Pumping Algae!
An Alternative Energy Future

Donald G. Redalje, The University of Southern Mississippi
John J. Cullen, Dalhousie University
Zackary I. Johnson, Duke University
Mark Huntley, Cellana
Gabriel de Scheemaker, Cellana and Royal Dutch Shell

Plus the 50 other members of the Cellana Team, including Xiaogang Chen, Egan Rowe, Merritt Tuel, Adam Boyette, Rebecca Schilling, Casey Smith and Matthew Stone.

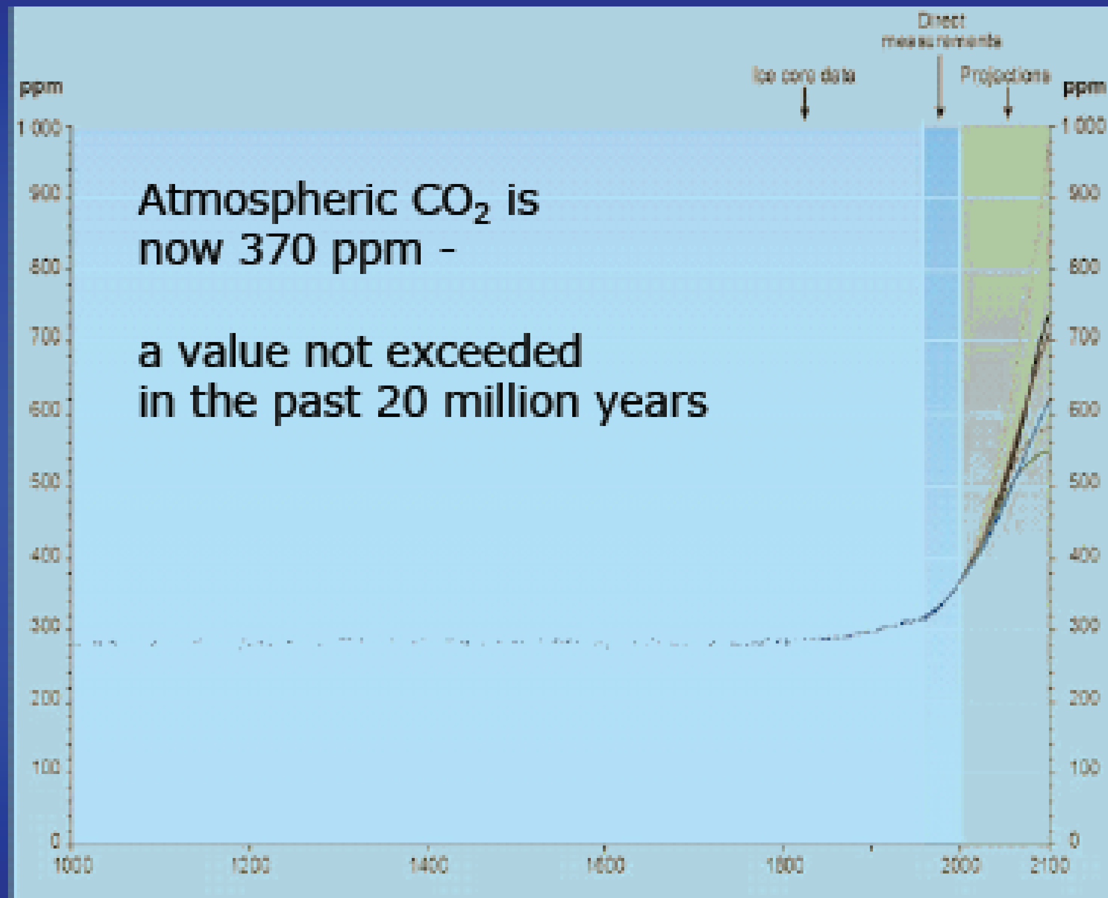
Supported by Cellana, a joint venture of Huntley-Raleigh BioPetroleum and Royal Dutch Shell

Northeast Algae and Energy Symposium
University of Vermont

Here is What I Want to Talk About Today:

- **Energy Status and CO_2 Emissions**
- **Our Options for Alternatives to Petroleum**
- **Corn was NOT the Answer!**
- **Marine Microalgae May Well be Our Best Chance**
- **The Hows and Whys of Growing Marine Microalgae**
- **Cellana and How We are Approaching the Issue**

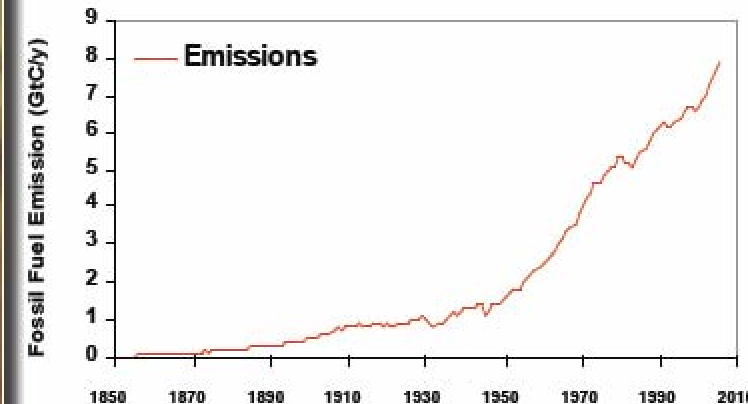
Increasing CO_2



Source: Intergovernmental Panel on Climate Change (IPCC) 2001

The emission rate is increasing fast:
Global Emissions from Fossil Fuel + Cement

2007 Fossil Fuel: 8.5 Pg C

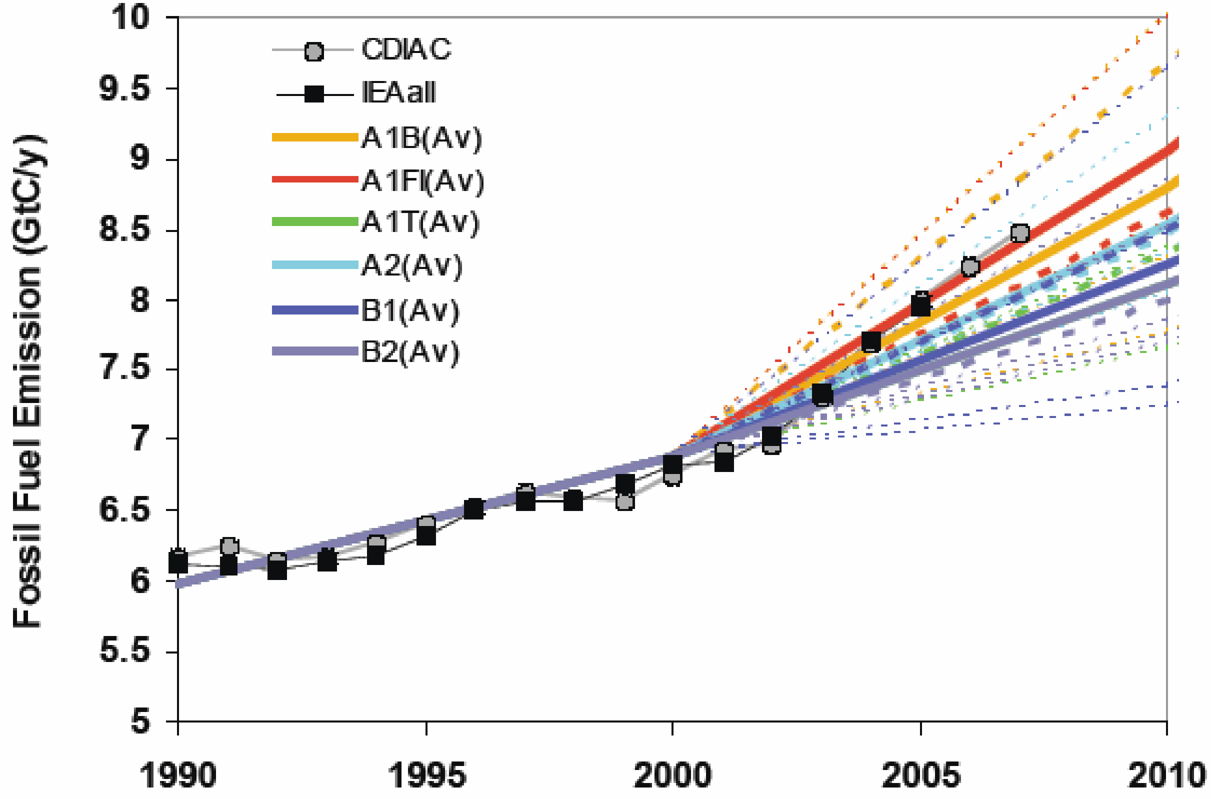


1990 - 1999: 0.9% y^{-1}

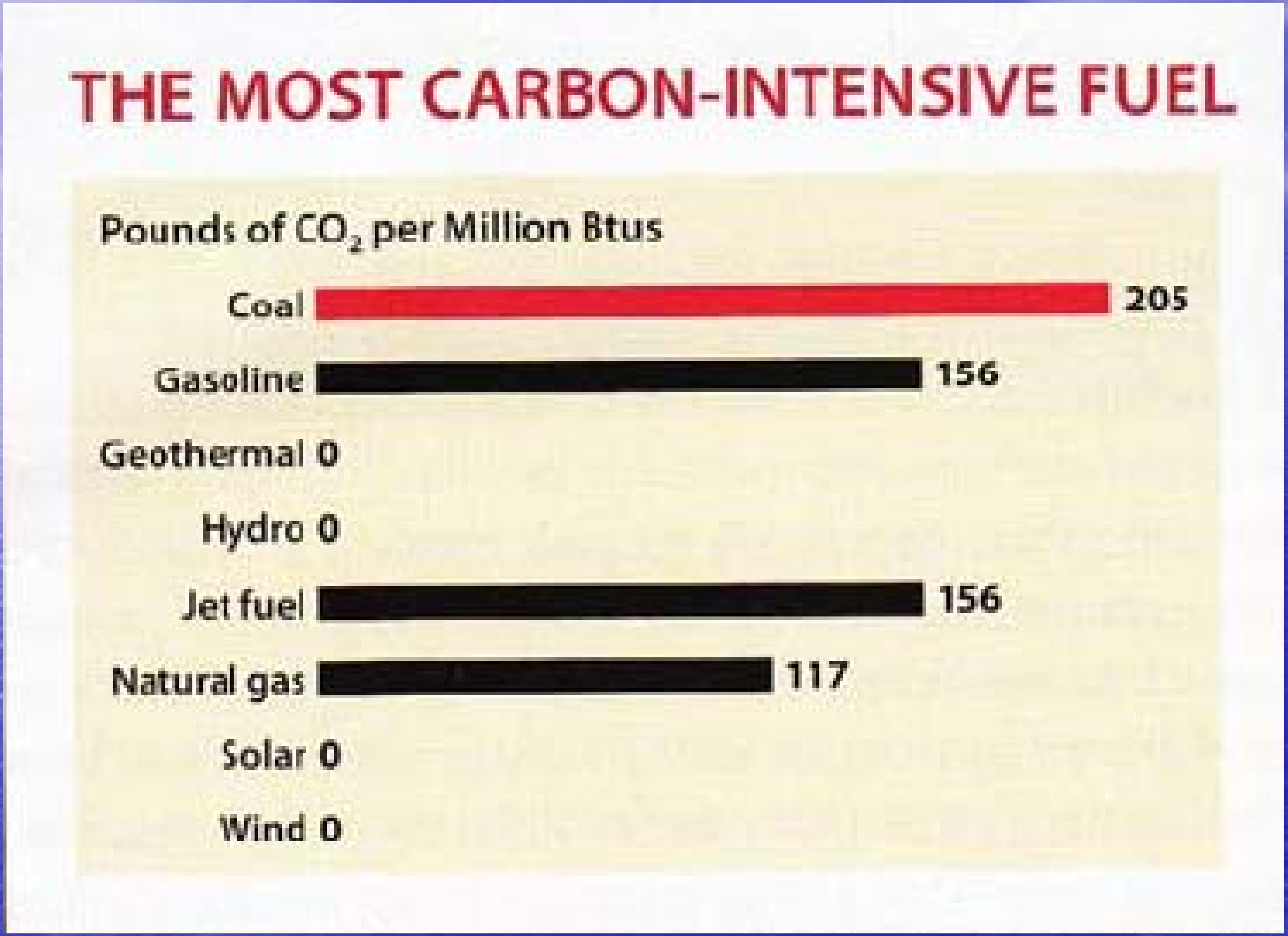
2000 - 2007: 3.5% y^{-1}

Global Carbon Project

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Raupach et al 2007, PNAS (updated)



Martelle, 2009

Carbon Emissions from Land Use Change

Borneo, Courtesy: Viktor Boehm

Tropical deforestation

13 Million hectares each year

	2000-2007
Tropical Americas	0.6 Pg C y^{-1}
Tropical Asia	0.6 Pg C y^{-1}
Tropical Africa	0.3 Pg C y^{-1}
	1.5 Pg C y^{-1}

[2007-Total Anthropogenic Emissions:8.5+1.5 = **10 Pg**]

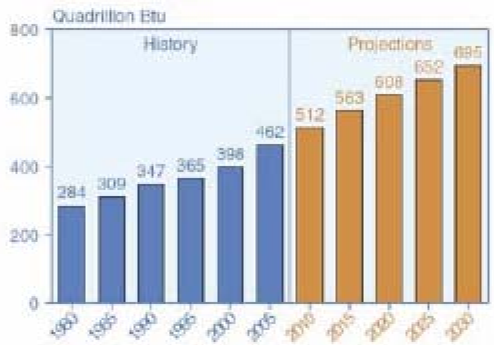
Canadell et al. 2007, PNAS; FAO-Global Resources Assessment 2005

"The world now consumes oil at the staggering rate of a thousand barrels a second" ***Tertzakian, 2007***

"By the year 2080, the world's supply of oil will be in steep decline" ***Martinez, 2002***

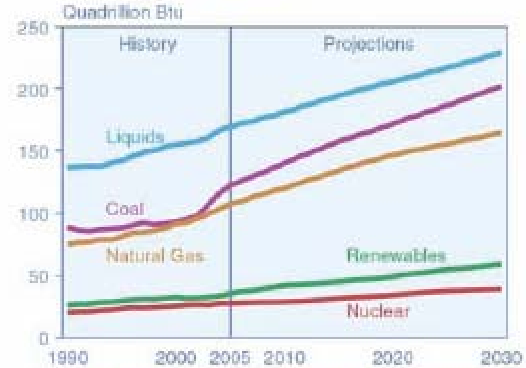
Increasing demand for fuel

Figure 9. World Marketed Energy Consumption, 1980-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2008).

Figure 12. World Marketed Energy Use by Fuel Type, 1990-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, World Energy Projections Plus (2008).

Oil and gas are getting harder to find

http://www.eia.doe.gov/oiaf/ieo/world.html

Our Options: Nuclear Power

Our Options: Hydroelectric Power

Our Options: Geothermal Power

Our Options: Solar Power

Our Options: Wind Power

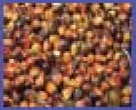
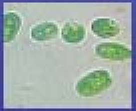
Our Options: Ethanol

Marine Algae
Compelling Advantages

- Saline water
- Non-arable land
- Algae consume a major greenhouse gas: CO_2
- *15x higher* productivity
- New, additional fuel feedstock
- New, additional animal feedstock

Bigelow Laboratory Phytopia

Reported yields for biomass crops

		Biomass (Mt/ha/yr)	Oil-content (% dry mass)	Bio-diesel (Mt/ha/yr)	Bio-diesel (bbl/ha/yr)
Soya		1-2.5	20%	0.2-0.5	1.4-3.5
Rapeseed		3	40%	1.2	8.2
Palmoil		19	20%	3.7	26.4
Jatropha		7.5-10	30-50%	2.2-5.3	16-38
Microalgae		140-255	35-65%	86.6	350-700

Not a new idea

ON THE MASS CULTURE OF ALGAE [1]

JACK MYERS, J. NEAL PHILLIPS, JR. AND
JO-RUTH GRAHAM

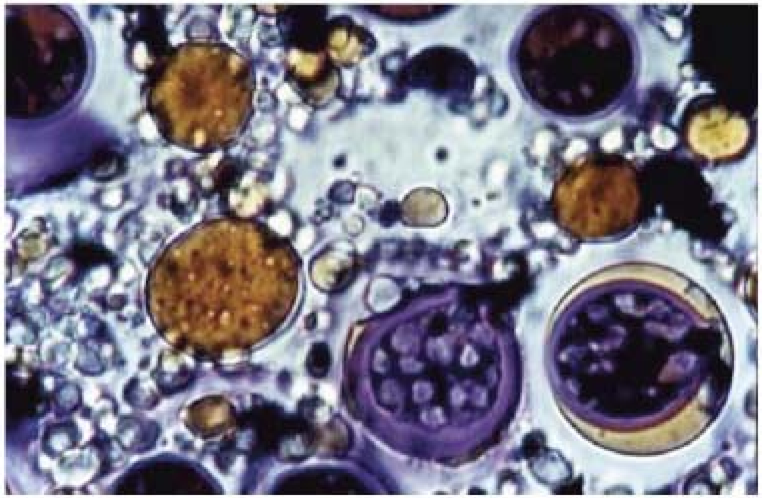
(WITH FOUR FIGURES)

Received January 9, 1951

Of the considerable body of literature variously concerned with the culture of algae there is relatively little work directed toward the particular problem of mass culture. VON WITSCH (10, 11) grew Chlorella in vertical glass cylinders of 3 cm. diameter and studied effects of carbon dioxide pro-

Studied for years

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



Biodiesel from Algae

July 1998

By

John Sheehan
Terri Dunahay
John Benemann
Paul Roessler

Open Ponds

www.seambiotic. com

Open Ponds

- Advantages
  - Economical
  - Relatively simple
  - High rates of production possible
- Disadvantages
  - Potential for contamination (competitors, invaders)
  - Less control on conditions (e.g., pH, Temp)

Photobioreactors

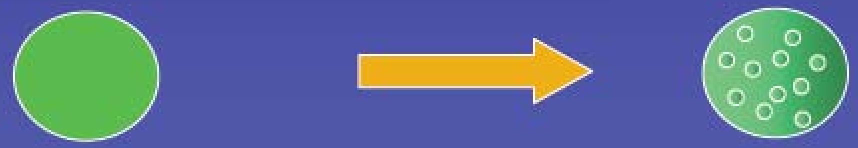
http://www.algaelink.com/algae-cultivation.htm

Photobioreactors

- Advantages
  - Controlled, optimized conditions
  - Contamination can be minimized
  - High rates of production
- Disadvantages
  - Expensive

Two-stage cultivation

PHOTO-BIOREACTORS + OPEN PONDS

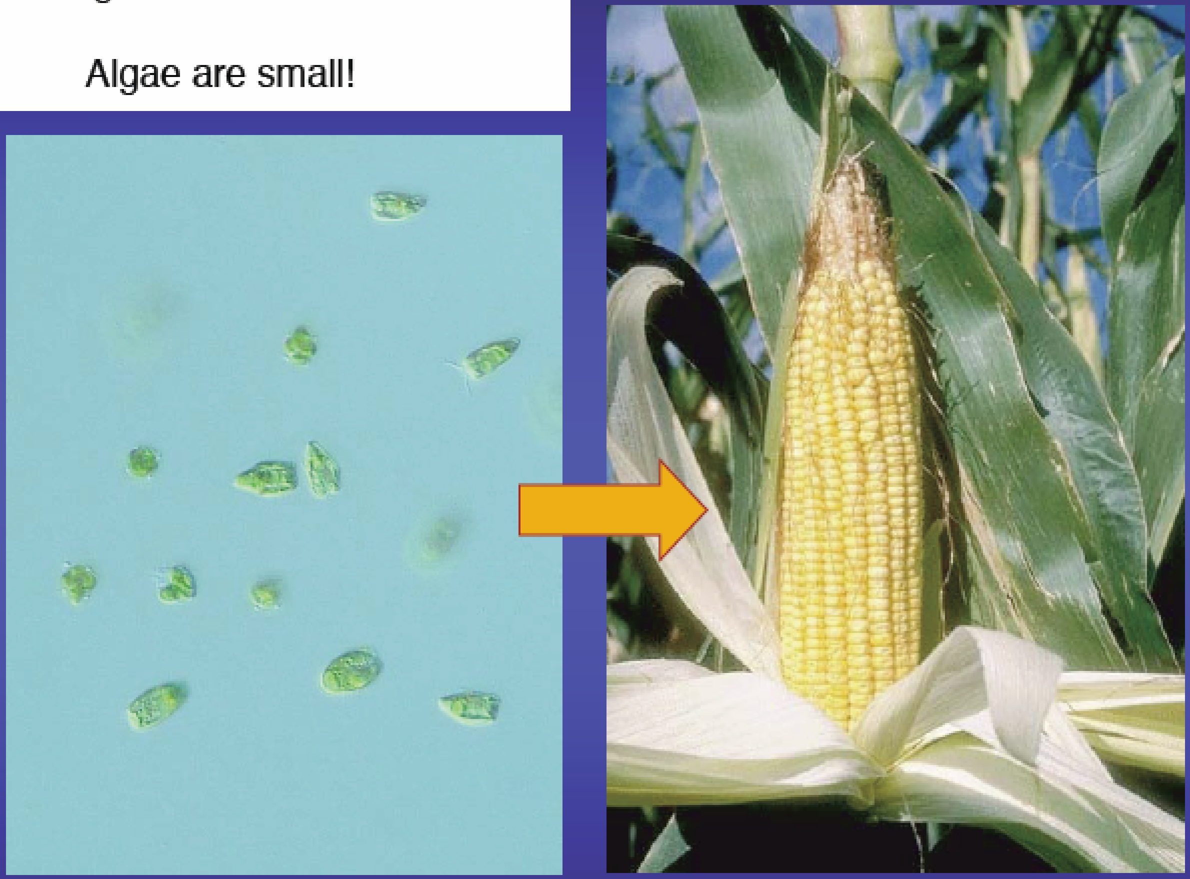


- Continuous
- Nutrient sufficient
- High yield
- Small area

- Batch
- Short residence time
- Large area

Harvesting:

Algae are small!



Cellana Group

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RESPONSIBLE ENERGY | INNOVATION | PRODUCTS & SERVICES | ABOUT SHELL

News & Media releases

Shell and HR Biopetroleum build facility to grow algae for biofuel

11/12/2007

Royal Dutch Shell plc and HR Biopetroleum today announced the construction of a pilot facility in Hawaii to grow marine algae and produce vegetable oil for conversion into biofuel.

The announcement is a further step in Shell's ongoing effort to develop a new generation of biofuels using sustainable, non-food raw materials. Algae hold great promise because they grow very rapidly, are rich in vegetable oil and can be cultivated in ponds of seawater, minimising the use of fertile land and fresh water.

Incorporated: 11 December 2007
Cellana LLC and Cellana BV
HRBP: algae cultivation
Royal Dutch Shell:
technology integration and scaling, network, project management.

Our vision: to be the world's preferred sponsor of commercial algae oil and protein facilities

Cellana Technology

Strain selection →	Cultivation Processing →	Integrating Scaling Templating
Dalhousie University University of Hawaii University of Southern Mississippi	… University … Research Institute	Shell Technology Suppliers
No GMOs	Photo Bio Reactors Open Ponds	2.5 ha 1,000 ha 20,000 ha

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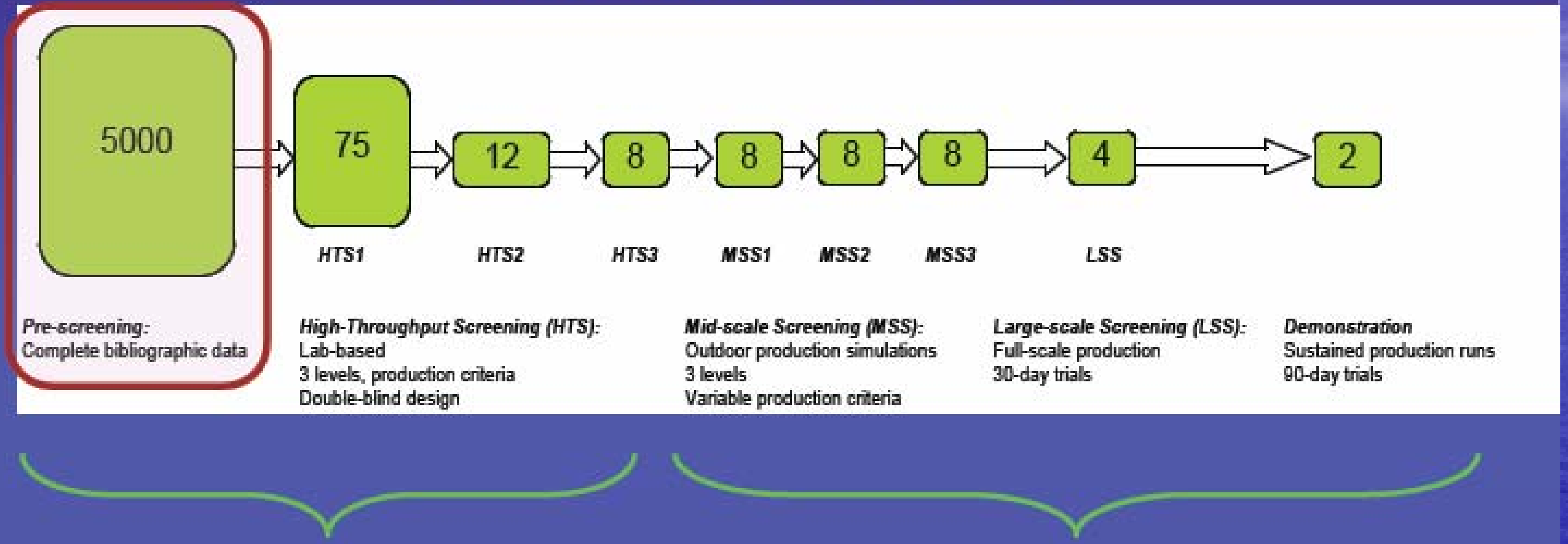
Strain Selection



Dalhousie University

University of Hawaii

University of Southern Mississippi

Kona Pilot Facility

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Which model is "better"?

Which model is "better"?

Finding the best strain

Sturdy with good capacity

Which model is "better"?

Finding the best strain

Sturdy and fast with good capacity

Fast and efficient?

No Genetically Modified Organisms (GMOs)

Sustained Production Rates (P) at Large Scale

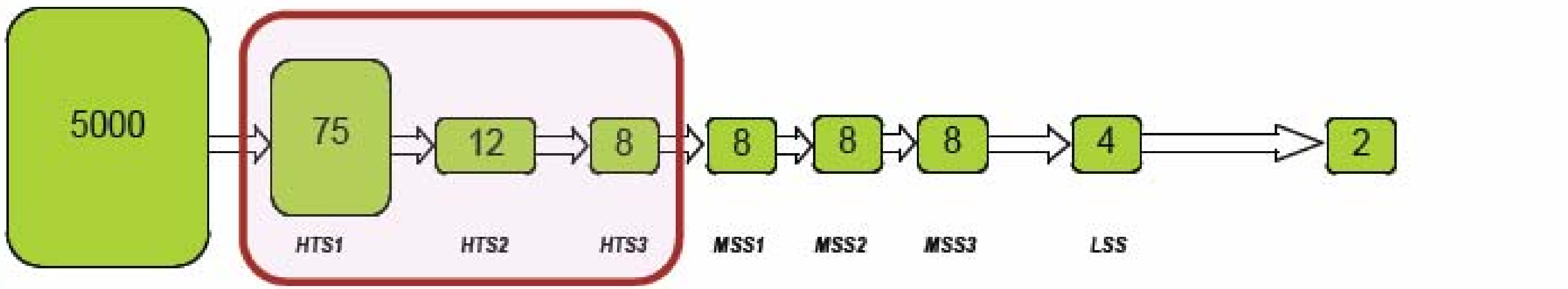
Species	P (g DW m^{-2} d^{-1})	Period (days)	Reference
Tetraselmis suecica	62	24	Laws et al. 1986
Skeletonema costatum	61.3	240	Kitto et al. 1999
Phaeodactylum tricornutum	81-96**	150	Acién-Fernandez et al. 1998

All in outdoor reactor systems, 5,000 to 50,000 L

*** Monthly average*

Isolation of new strains

High Throughput Screening for Production Potential



Pre-screening:
Complete bibliographic data

High-Throughput Screening (HTS):
Lab-based
3 levels, production criteria
Double-blind design

Mid-scale Screening (MSS):
Outdoor production simulations
3 levels
Variable production criteria

Large-scale Screening (LSS):
Full-scale production
30-day trials

Demonstration
Sustained production runs
90-day trials

Dalhousie University
University of Hawaii
University of Southern Mississippi

Kona Pilot Facility

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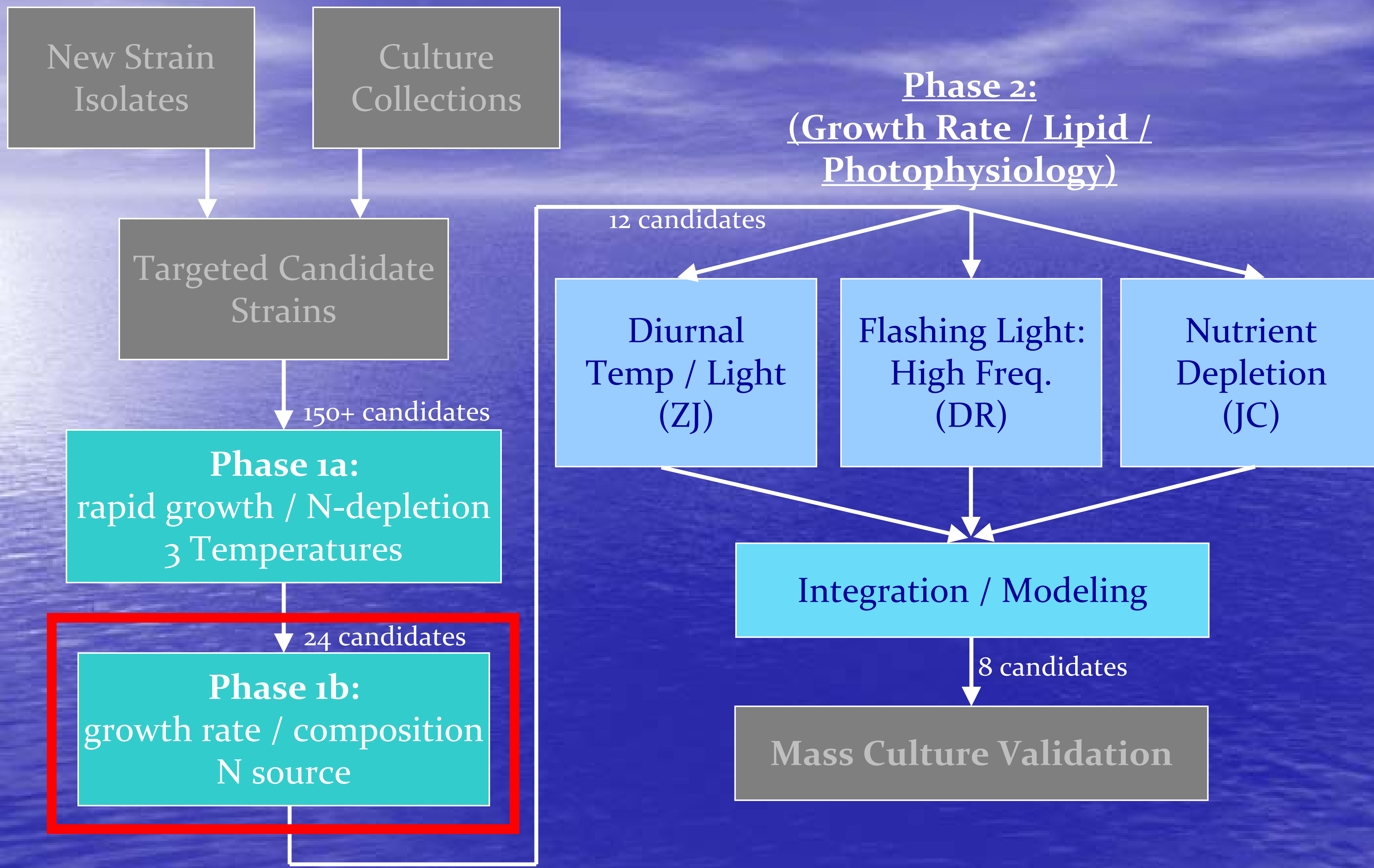
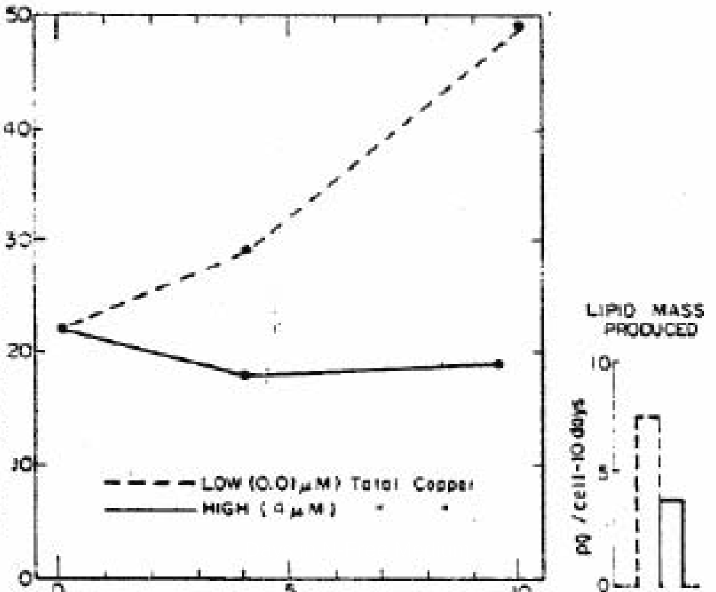

New Strain Isolates
Culture Collections
Targeted Candidate Strains
150+ candidates
Phase 1a:
rapid growth / N-depletion
3 Temperatures
24 candidates
Phase 1b:
growth rate / composition
N source
Phase 2:
(Growth Rate / Lipid / Photophysiology)
12 candidates
Diurnal Temp / Light (ZJ)
Flashing Light: High Freq. (DR)
Nutrient Depletion (JC)
Integration / Modeling
8 candidates
Mass Culture Validation

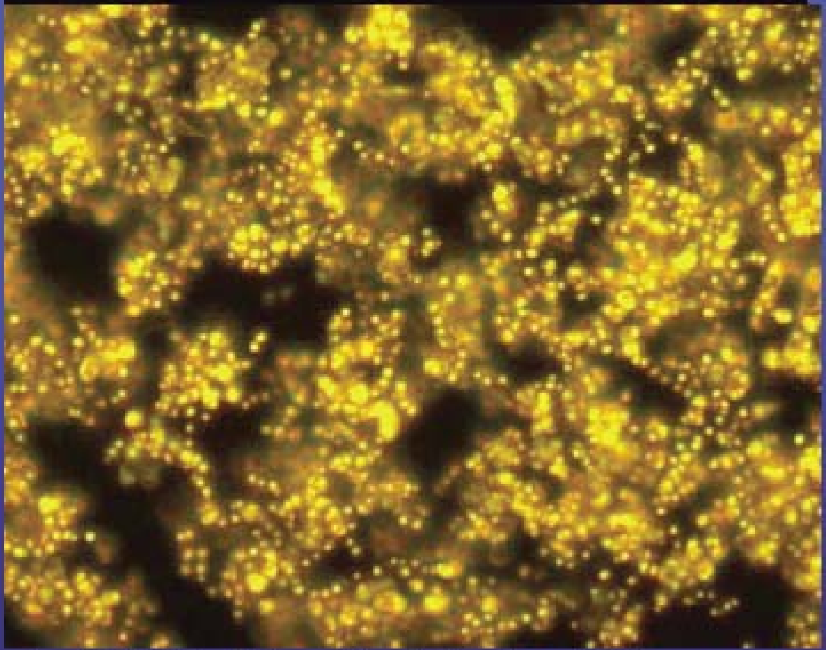
Exploiting Algal Physiology

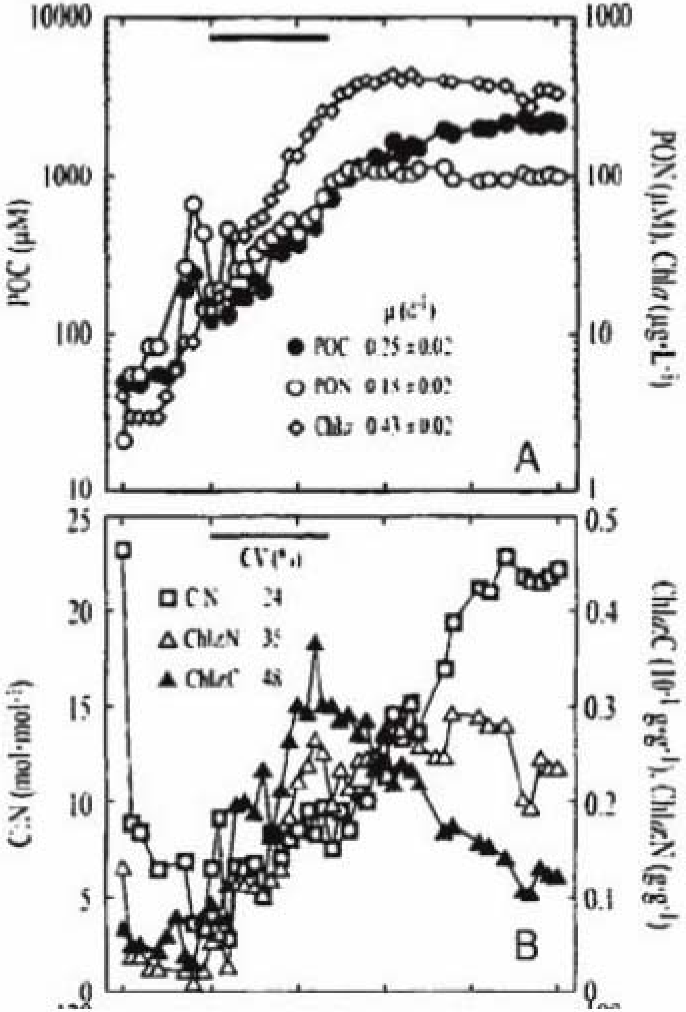
Algae Biomass
G. Shelef and C.J. Soeder, Editors

PHYTOPLANKTON LIPIDS: ENVIRONMENTAL INFLUENCES ON PRODUCTION AND POSSIBLE COMMERCIAL APPLICATIONS

NEIL S. SHIFRIN AND SALLIE W. CHISHOLM

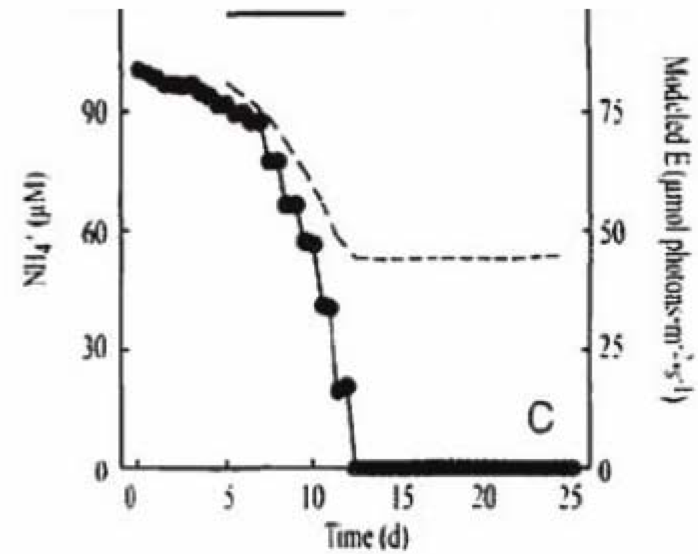




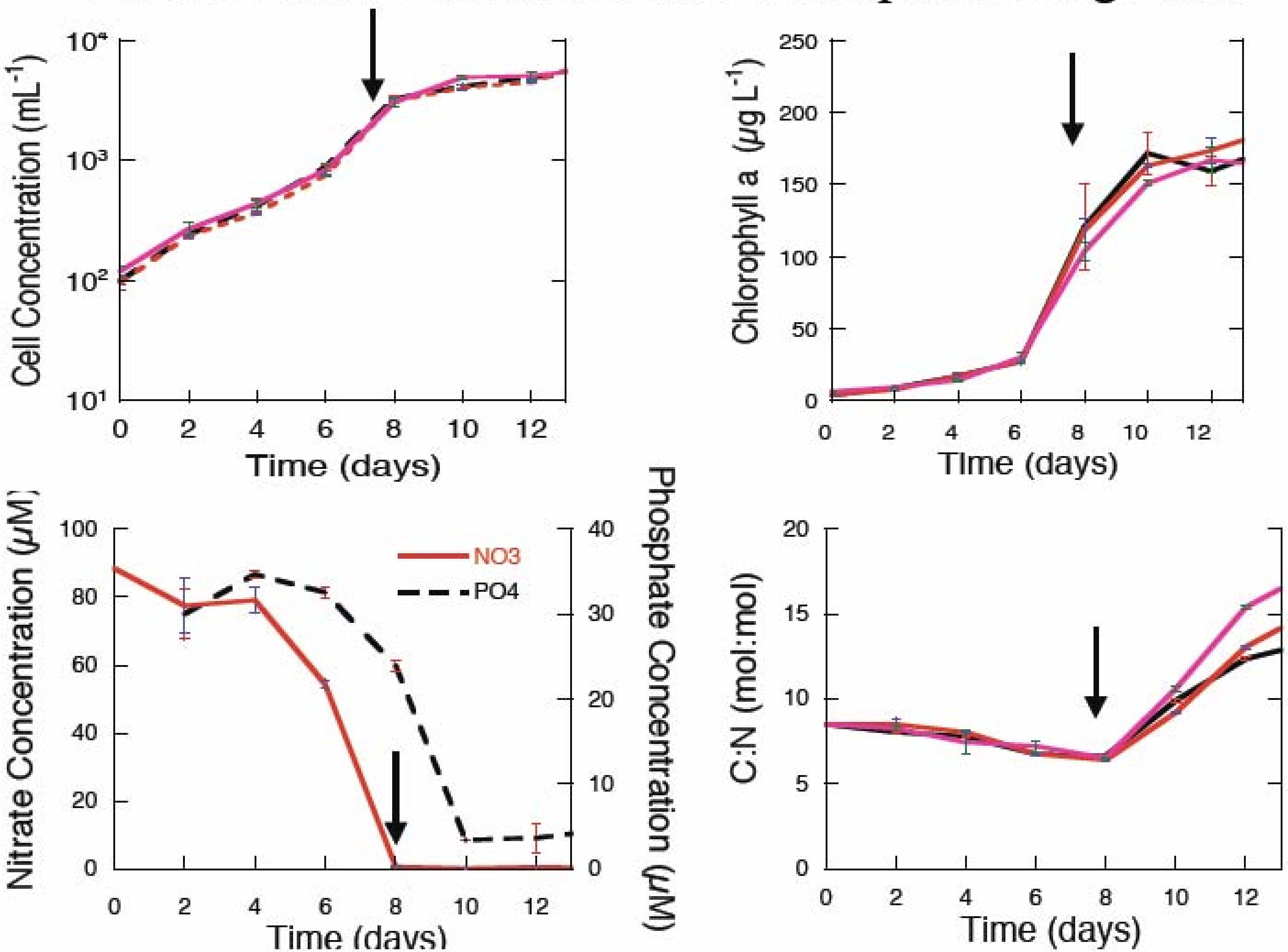


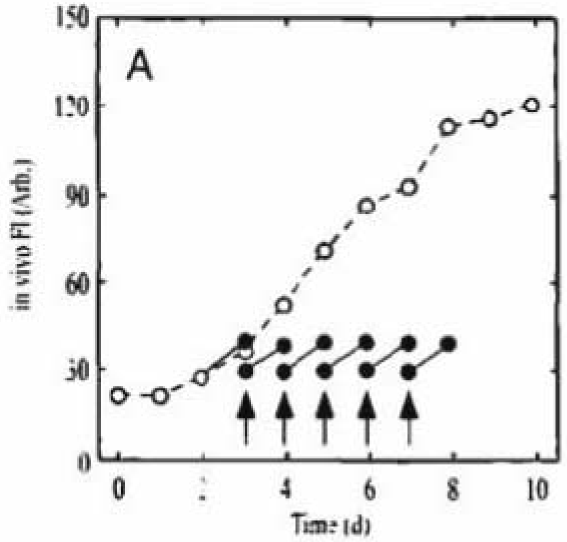
Conditions change very fast in batch cultures

Macintyre, H. L., and J. J. Cullen. 2005. Using cultures to investigate the physiological ecology of microalgae, p. 287-326. *In* R. A. Andersen [ed.], Algal Culturing Techniques. Academic Press.



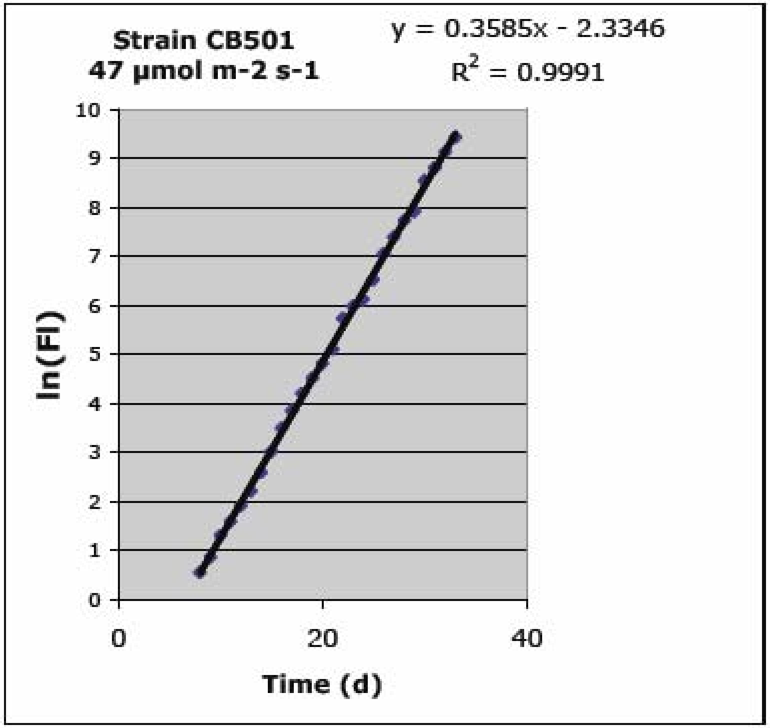
Batch Culture: not much time for exponential growth



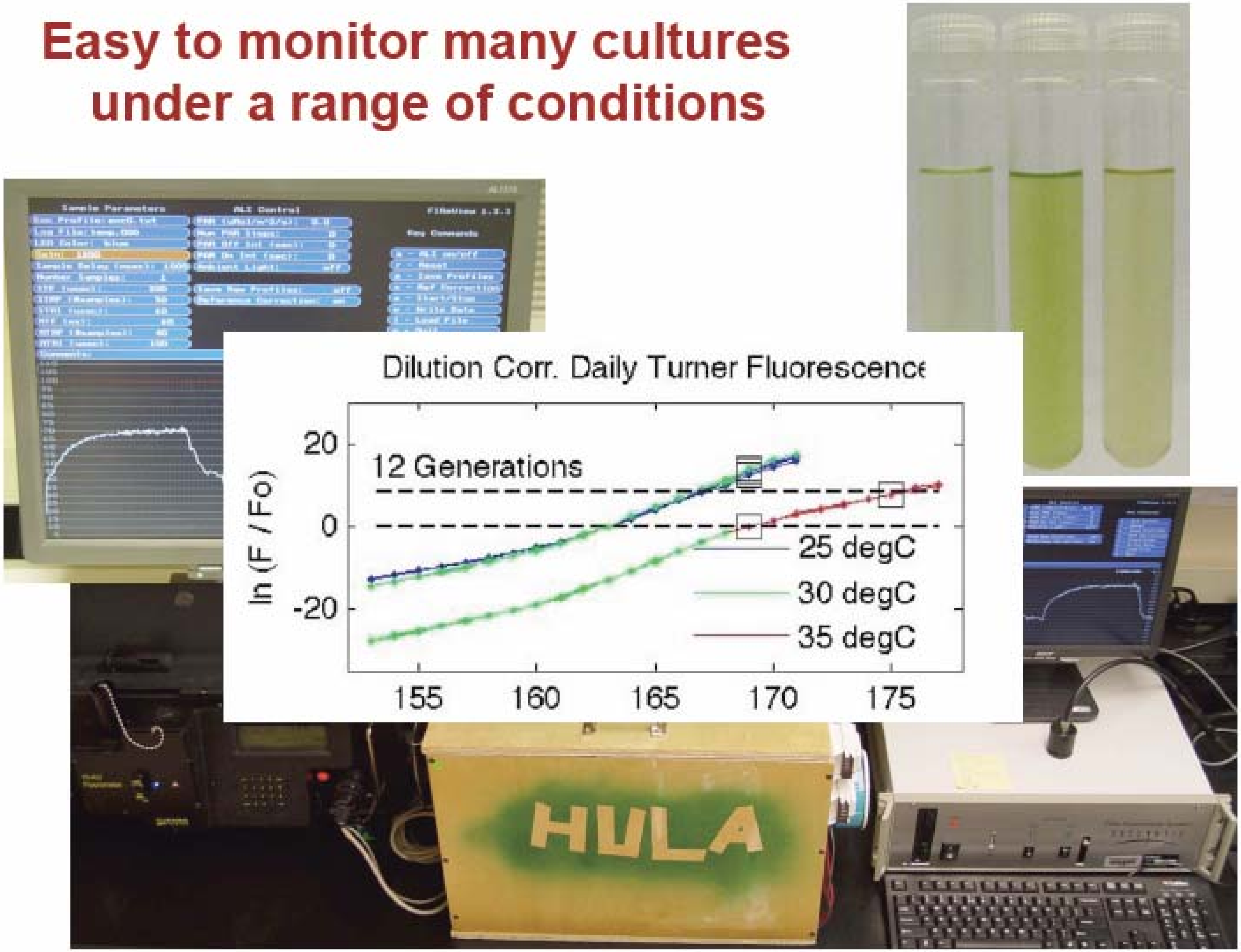


Acclimated conditions can be achieved through daily dilution

Brand, L. E., and R. R. L. Guillard. 1981. A method for the rapid and precise determination of acclimated phytoplankton reproduction rates. Journal of Plankton Research 3: 191-201.



Easy to monitor many cultures under a range of conditions



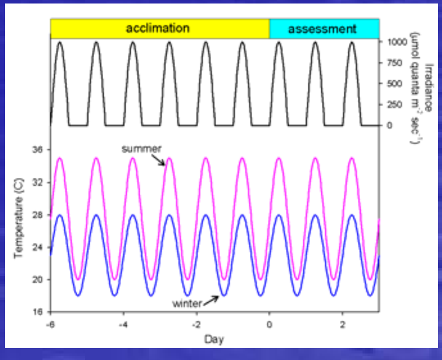
Phase 2: Plan

- Modified plan towards intensive characterization of representative strains with goal of providing link between phase 1 and ponds

  - 2A (Diel Light/Temperature): 2+ representative strains in detail: Photosynthesis/Irradiance, Respiration (O2), absorption, NPQ, nutrient replete (PBR concentrations)

  - 2B (Nutrient Limitation): original plan, (~12 strains and investigate the timing of nutrient limitation on lipid yield)
    - Proposed enhancements
      - Examine manipulations of silicate (diatoms)
      - Quantify carbohydrate synthesis
      - Complement production modeling if possible

  - 2C (Flashing Light): original plan, but with fewer strains



Photon
Systems
Instruments

Phototrophic Bioreactor – Fermentor

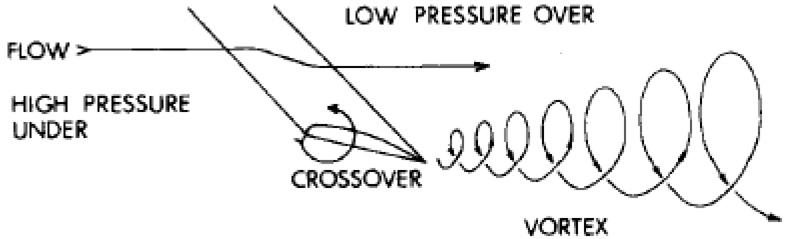


Figure 2. Design of a single foil indicating mechanism of vortex production.

From Laws et al., 1983

From Terry, 1986

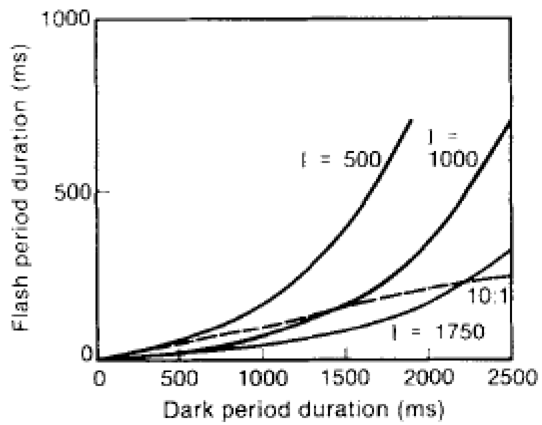
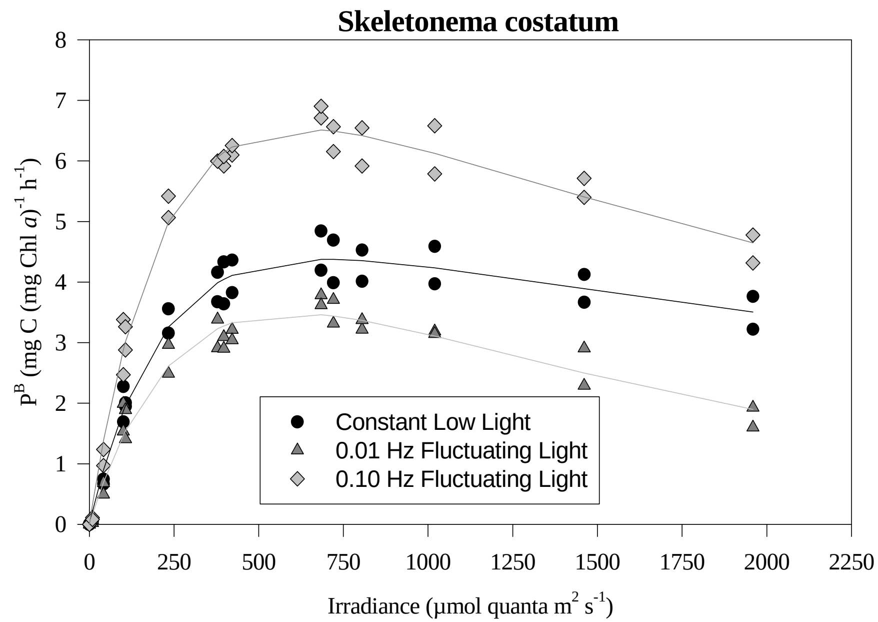


Figure 10. Optimum flash period length as a function of the dark period length for *Phaeodactylum tricornutum*. The three solid lines show optima for light intensities of 500, 1000, and 1750 μEinst/m²/s. The broken line indicates a light:dark ratio of 1:10.



From Bailey, 1997

Modeling the process

All day and night, top to bottom:

$$P_{Z,T}\ (\text{gC m}^{-2}\text{d}^{-1}) = \int_{t=0}^{T} \int_{z=0}^{\text{bottom}} [P(z,t) - R(t)] \cdot dt$$

Fully spectral with physiological parameters:

$$P(z,t) = \text{Chl} \cdot P_{\max}^{\text{B}} \cdot (1 - e^{-(\phi_{\max} \cdot \overline{a_{\phi}^{*}} \cdot E_{\text{PUR}}(z,t)/P_{\max}^{\text{B}})})$$

Choice of ways to parameterize respiration, e.g.:

$$R^{\text{B}}(t) = R_{\text{o}}^{\text{B}} + [F \cdot P^{\text{B}}(t)]$$

Tunable variables and parameters

Solar irradiance (including daylength and cloud factor)

Chlorophyll concentration

Photosynthetic quantum yield

Maximum rate normalized to Chl

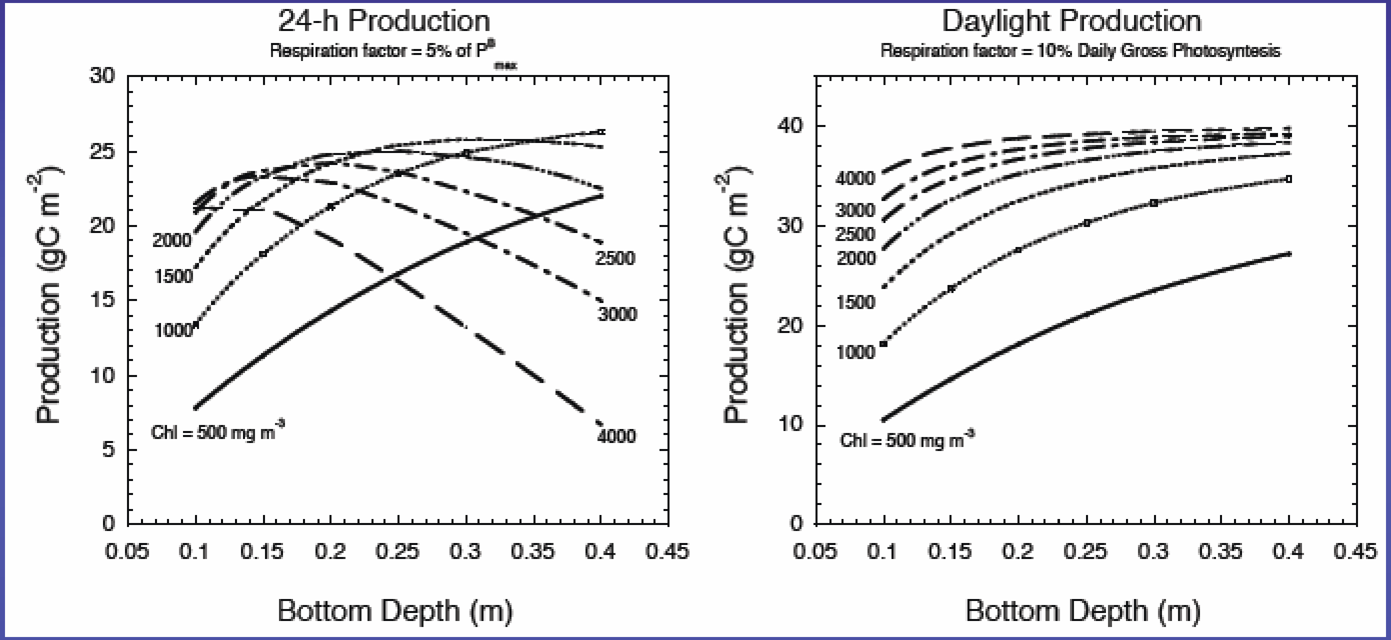
Absorption spectrum (packaging)

Can test genetically modified photosystem hypotheses

Bottom depth + reflectivity (pond liner)

Photosynthetic quotient must be added (N-source)
DW/C

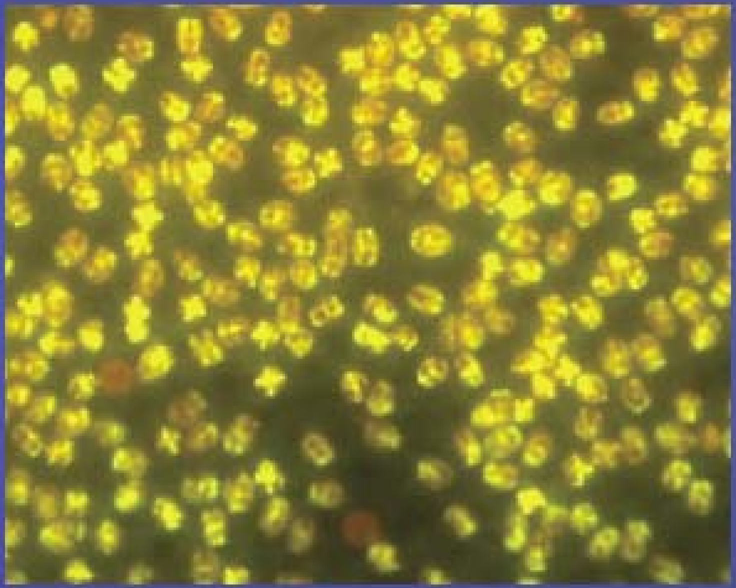
Preliminary Results



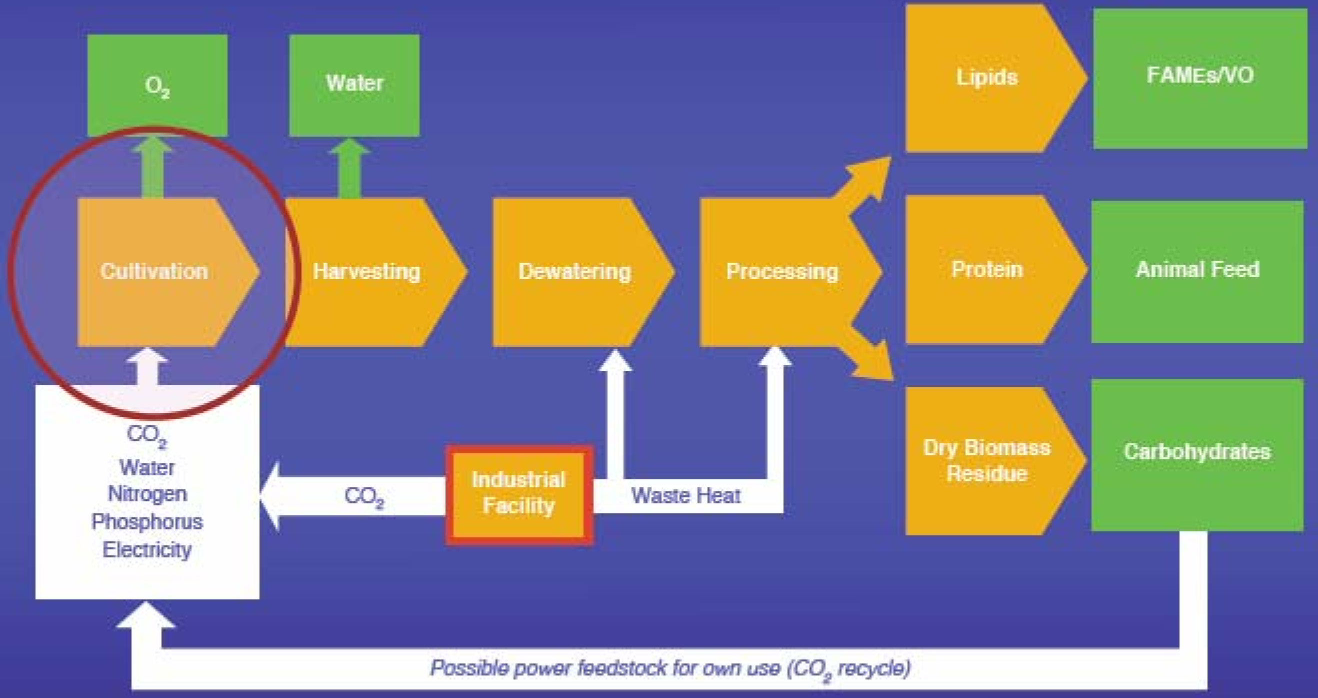
- High rates depend on high biomass
- Choice of respiration function has a huge influence
- Maximum production rate associated with moderate growth rates
- The key to high production is avoidance of down-regulation

Moving Toward Producing Billions of Liters of Fuel per Year

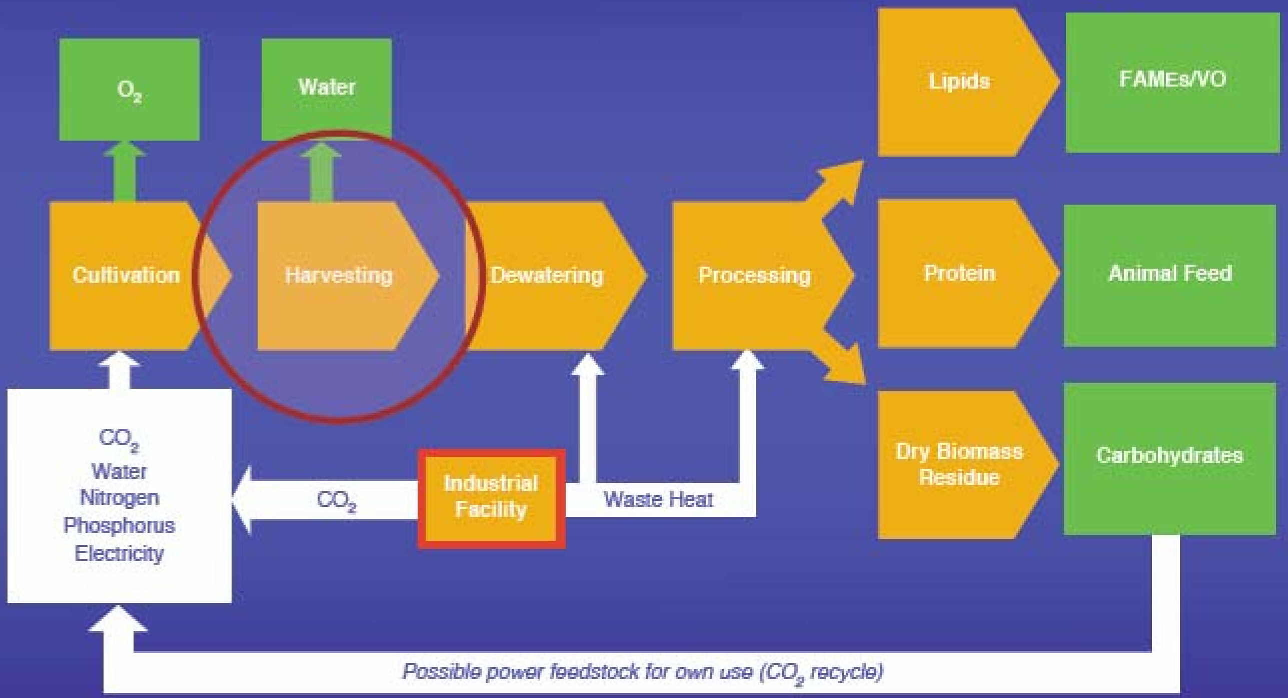
- Partnership
  - Science - Industry
- Technology
  - Upstream - Downstream
- Implementation
  - Business plan



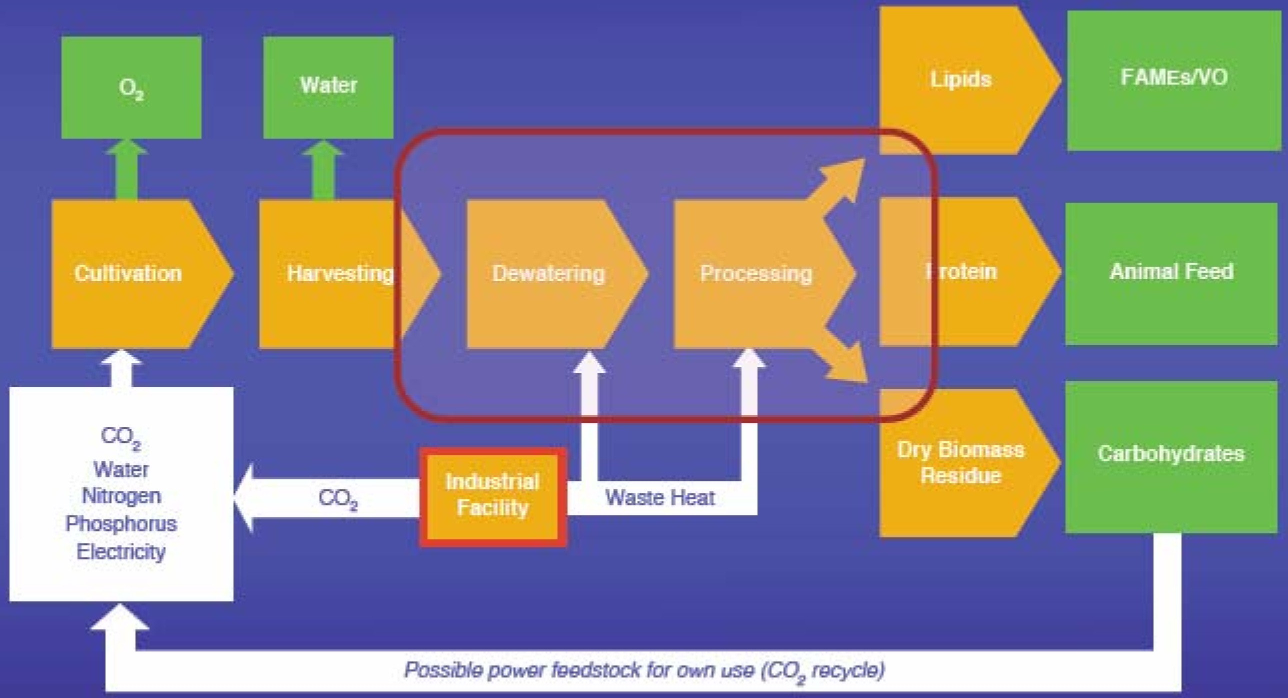
Cultivation and Processing



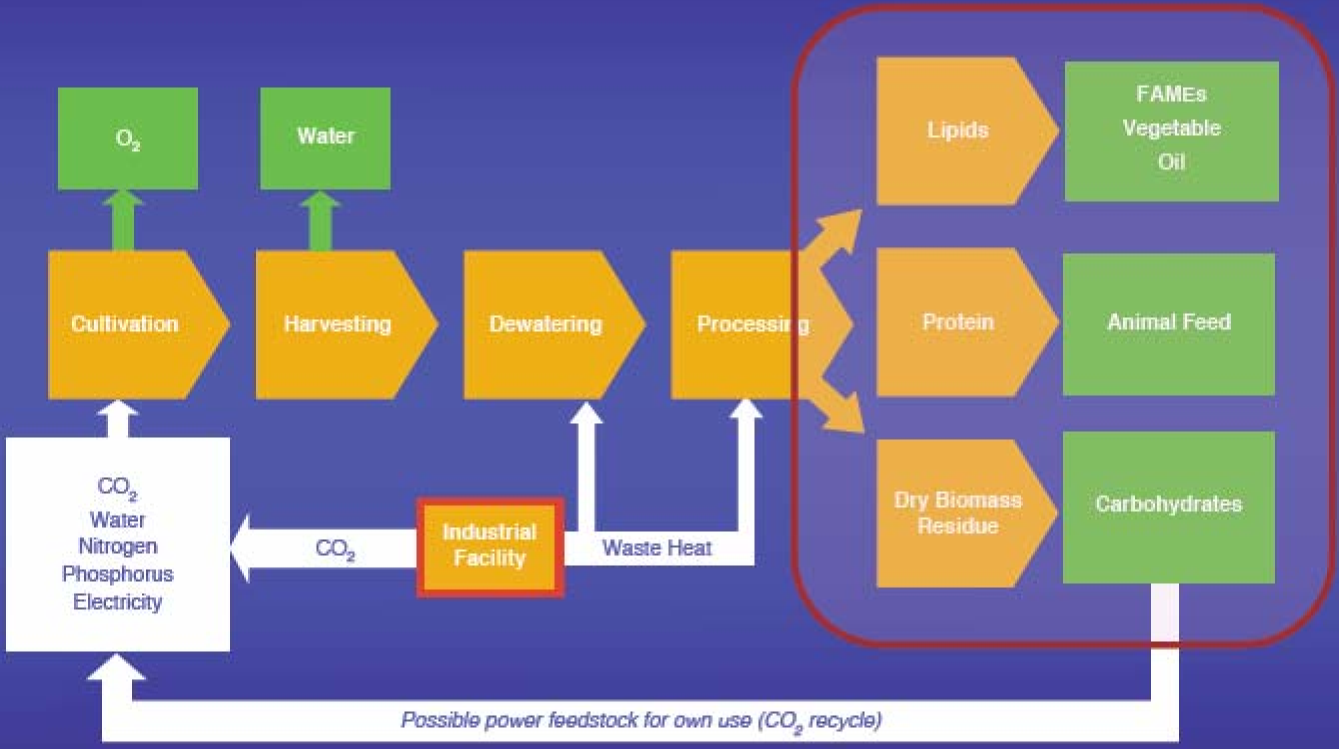
Cultivation and Processing



Cultivation and Processing



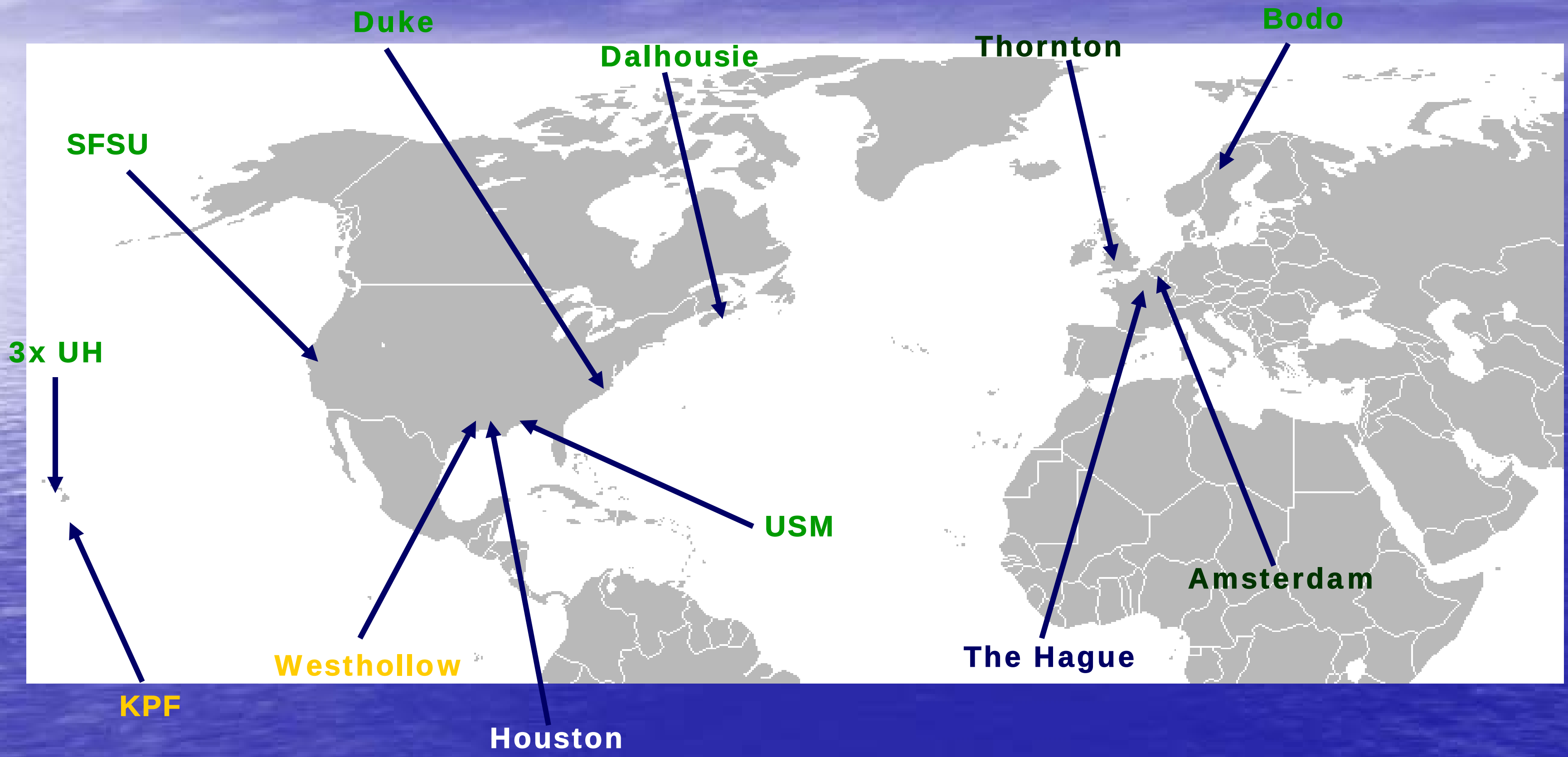
High Value Products for the World



Scaling and Integrating

- 2.5 ha → 1000 ha → 20,000 ha
- Leveraging Shell's expertise
  - Technology selection and due diligence
  - Integration of technologies
  - Design of large scale plants
  - Project management
  - Professional infrastructure
    - Health, Safety, Environment
    - Environmental Impact Assessment
    - Product Quality Management
    - Contracting & Procurement
  - Network, reach, etc.

Cellana Partners



- University research
- Shell research
- Cellana production facilities
- Cellana corporate

Kona Pilot Facility

"prove" the concept

- 2010
- 2.5 ha
- Freeze initial set of technologies
- Show that a facility can produce "large" amounts of algae and be…
  - Economically positive
  - Energy-positive
  - CO_2-positive

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First Commercial Plant

- The next stage
- 1000 ha
- Integrate and scale technologies
- Demonstrate acceptable technology risk

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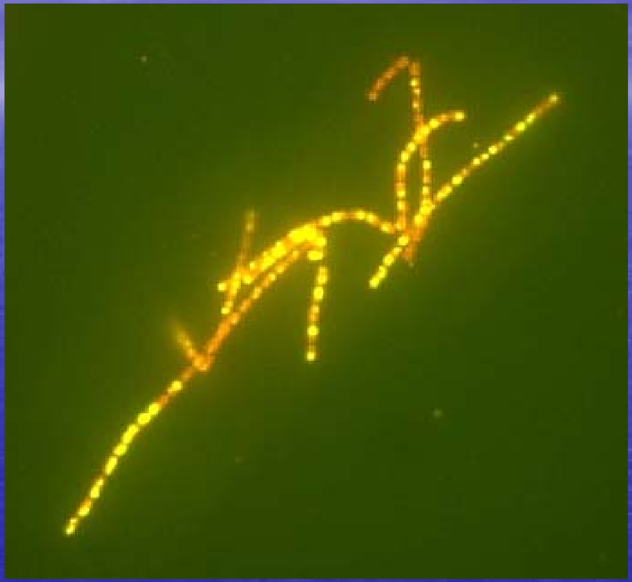
Today's status

- Operating since 1 January 2008...
  - on leased facilities
  - 7 strains cultivated
- Building the Kona Pilot Facility
  - 2009, 2.5 ha
  - Lab shake down
  - Q3 cultivation
  - Q4 first oil
- Designing the First Commercial Plant
  - site selection, design
  - start construction
  - 1000 ha (2km x 5km)
- Planning roll-out of Commercial Plants...
  - Economies of scale? 20,000 ha plants?
  - a material business



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Thank You – Questions?

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