National Renewable Energy Laboratory
Innovation for Our Energy Future

Development of Microalgal Biofuels: A National Laboratory Perspective

March 17, 2010

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Outline

Biofuel Challenges: Renewable Fuel Standard and Energy Density

Potential of Algal Biofuels: Myth vs reality

DOE's Aquatic Species Program: What's changed since 1996?

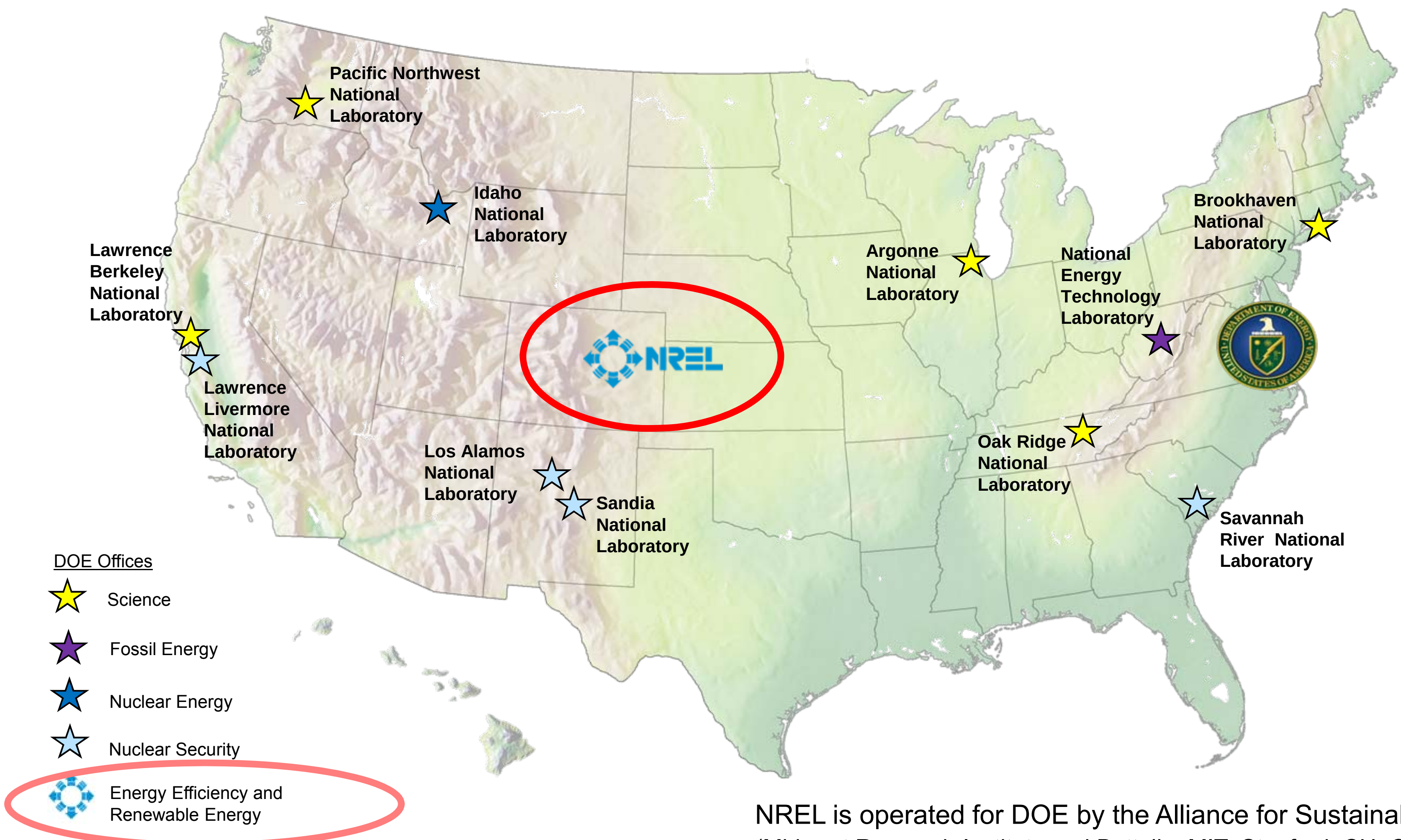
Role of the US Government in Developing Algal Biofuels

NREL's Microalgal Biofuels Program

Conclusions

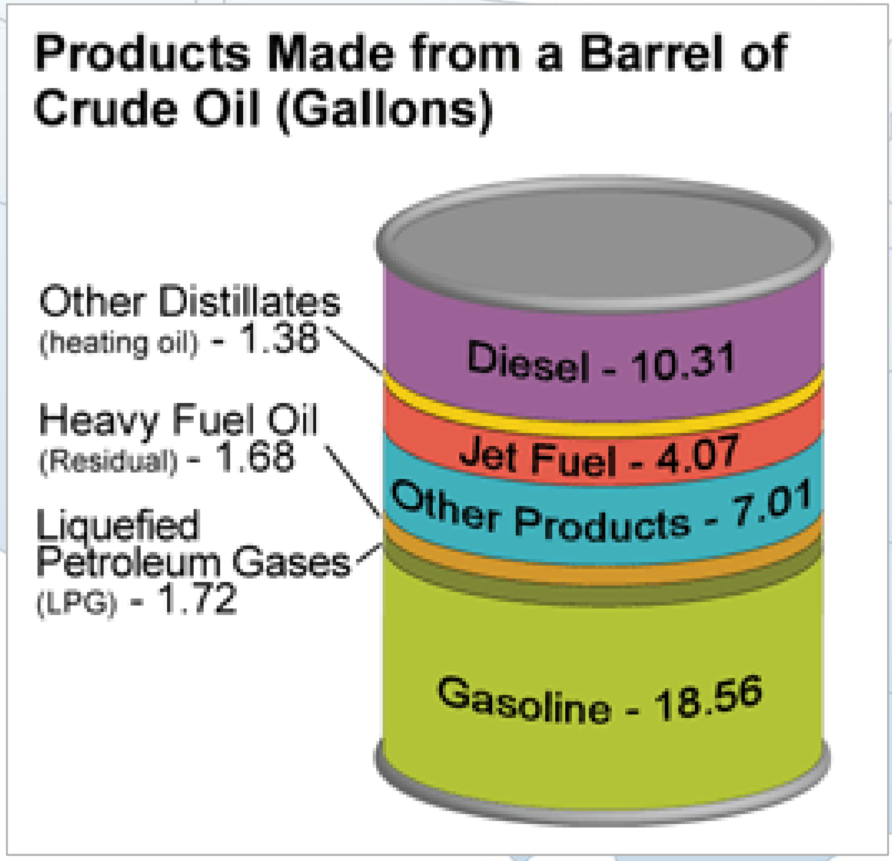
U.S. Dept of Energy National Labs

NREL is the only DOE National Laboratory dedicated to renewable and energy efficient technologies



NREL is operated for DOE by the Alliance for Sustainable Energy
(Midwest Research Institute and Battelle; MIT, Stanford, CU, CSU, CSM)

U.S. Petroleum Transportation Fuels



U.S Annual Consumption

Highway
Gasoline: 140 bgy
Diesel: 60 bgy

Non-Highway
Jet Fuel: 25 bgy
Water: 10 bgy
Rail/Other: 10 bgy

U.S. Biofuels Current Status

U.S. Consumption
Gasoline: 140 bgy
Diesel: 60 bgy

Biodiesel [1]

- ~175 commercial plants
- 2.7 bgy capacity (2009)
- 0.5 bg produced (2009)

Corn Ethanol [2]

- ~200 commercial plants
- 13.0 bgy capacity (+ 1.4 bgy planned) (2009)
- 10.5 bg produced (2009)

Cellulosic Ethanol [3]

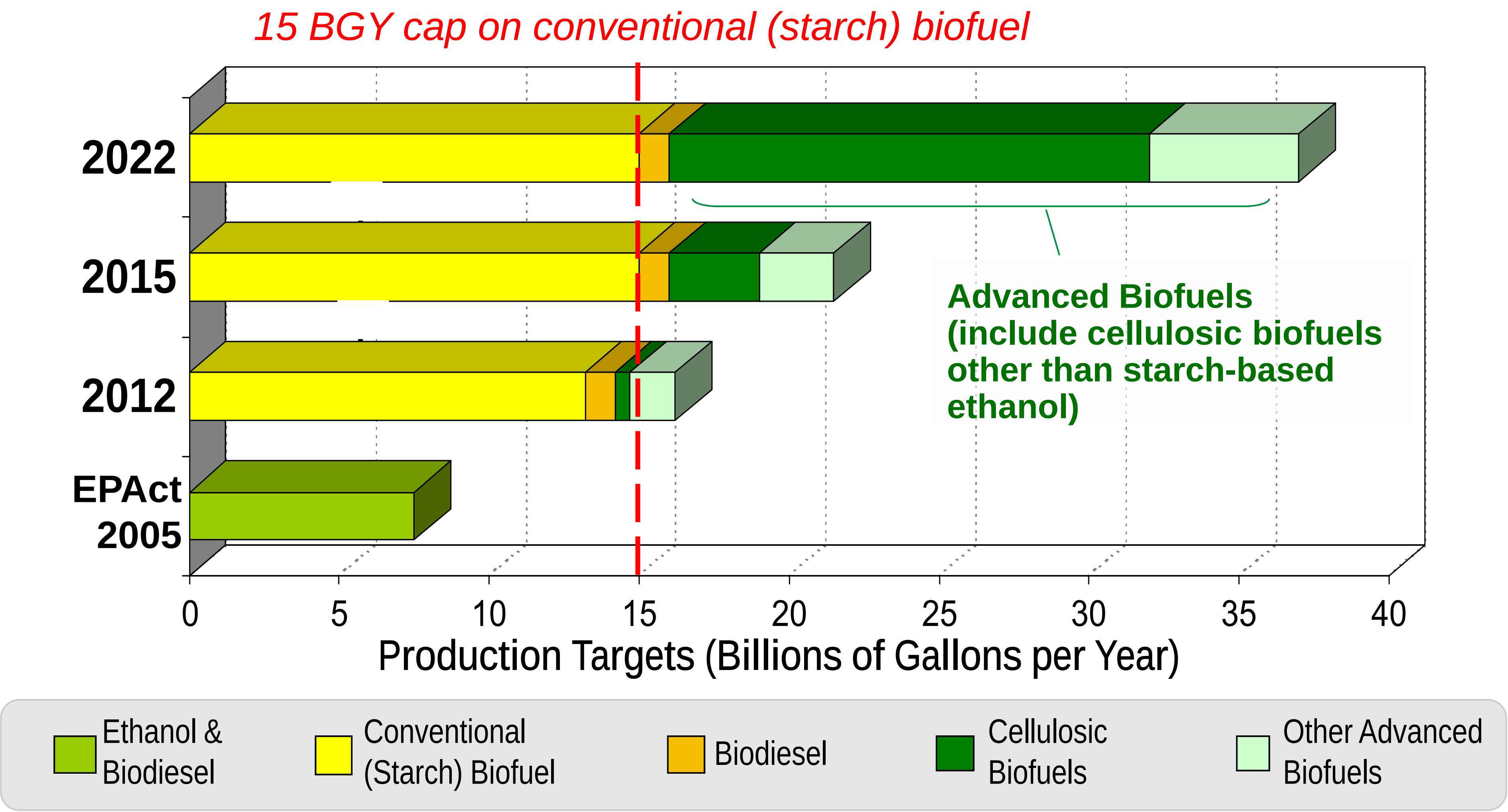
- 30 demo plants DOE-funded
- ~.250 bgy capacity projected
- Additional industry-only funded plants

bg = billion gallons; bgy = billion gallons per year

Sources: 1- National Biodiesel Board, 2- Renewable Fuels Association, 3- DOE Biomass Program

~2,000 E85 stations

U.S. Renewable Fuel Standard (RFS)



RFS in the Energy Independence and Security Act (EISA) of 2007

Major DOE Biofuels Project Locations

Geographic, Feedstock, and Technology Diversity

Biofuel Challenges: Energy Density

Cellulosic ethanol addresses the gasoline market

- U.S. gasoline usage: 140 billion gallons/year (bgy)

Does not address need for higher-energy density fuels

- U.S. diesel usage: 60 bgy
- U.S. jet fuel usage: 25 bgy

Energy Densities

Ethanol	Gasoline	Biodiesel	Diesel/Jet Fuel
76,330 Btu/gal	116,090 Btu/gal	118,170 Btu/gal	128,545/135,000 Btu/gal

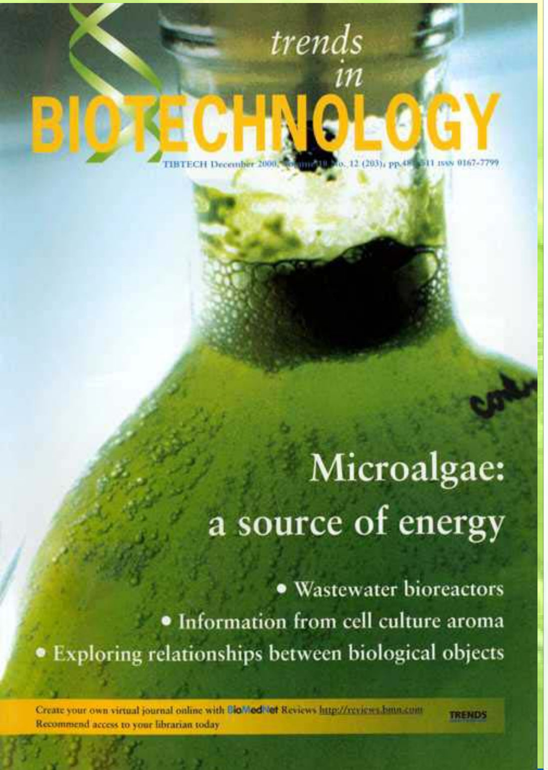
Dilemma: Biodiesel from current oilseed crops cannot come close to meeting U.S. diesel demand (60 billion gal/year)

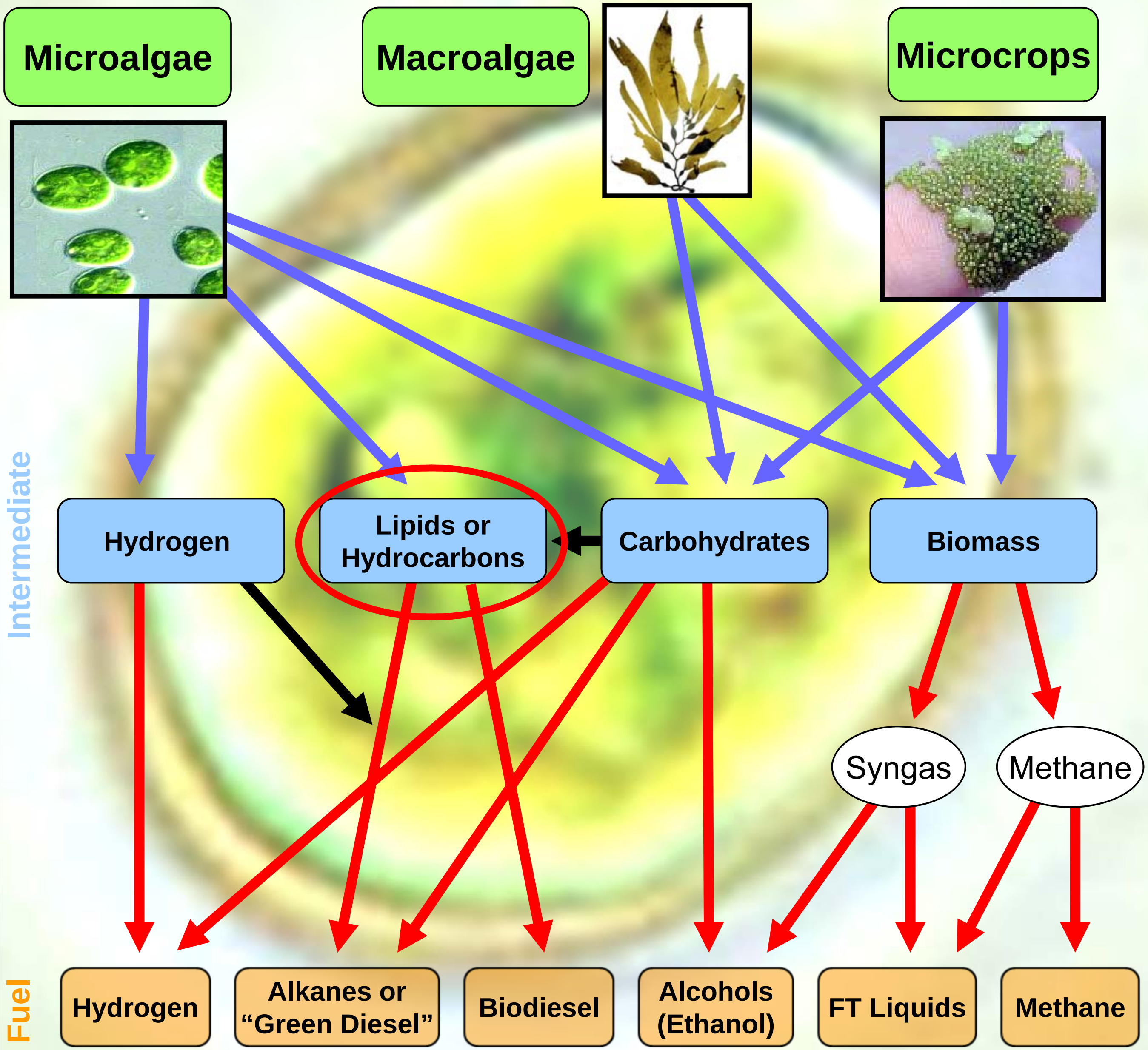
- **0.5 bgy biodiesel (2009) – uncertainty exists**
- **Soy oil (2.75bg; 2007); replaces <5% of demand**

Alternative sources of oils are needed!

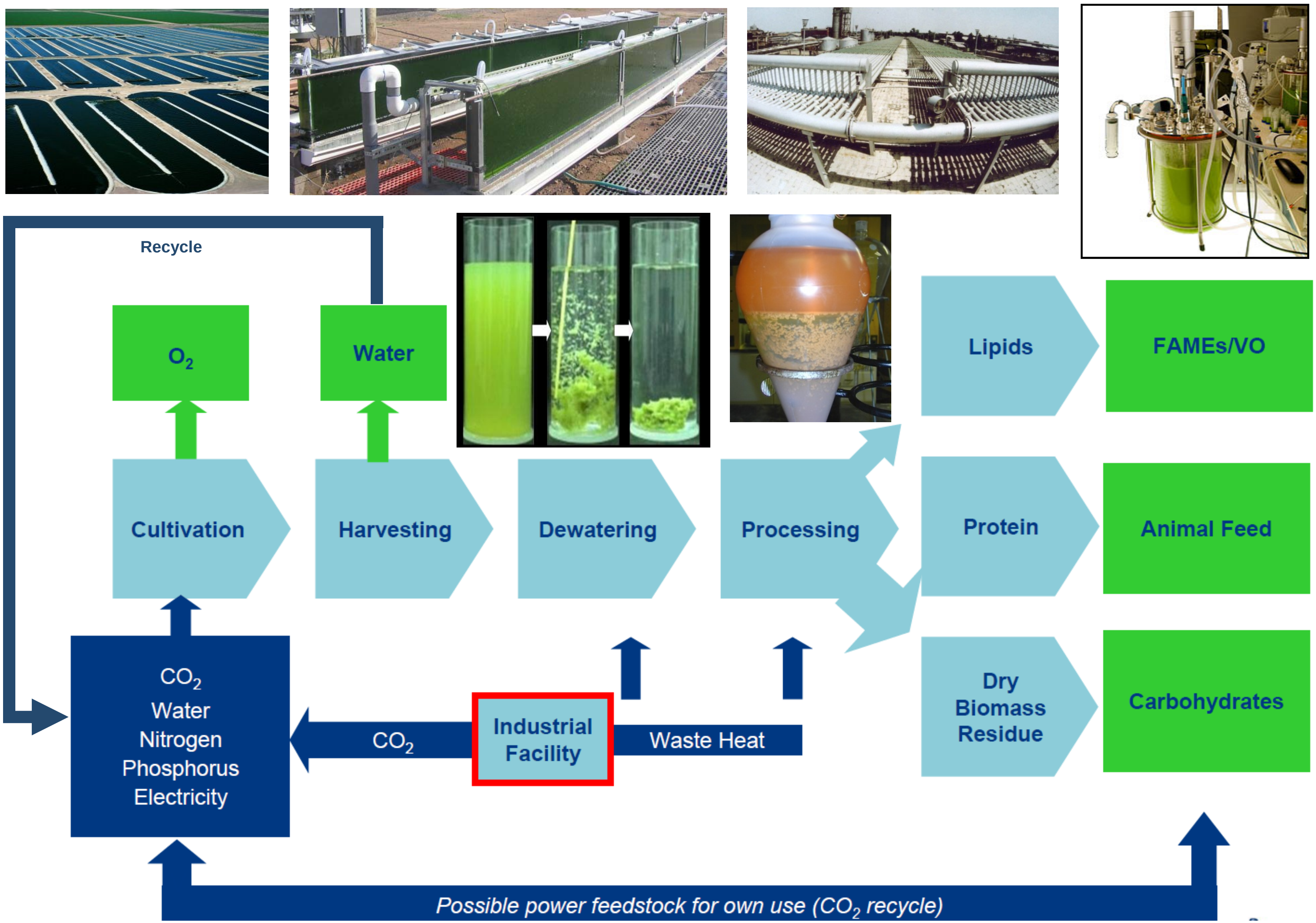
Routes to Algal Biofuels

Defining a Biofuels Portfolio From Microalgae

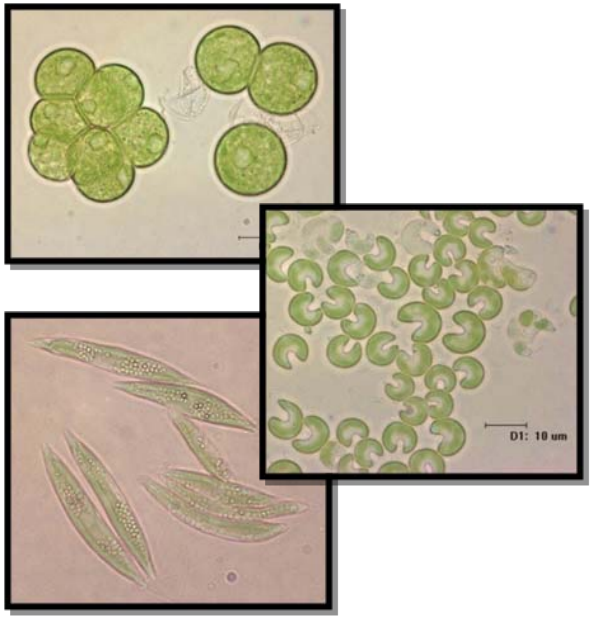




General Cultivation Processing Flow Sheet



Why Fuels from Algal Oil?



- **High-lipid content (up to 50%); rapid growth; more lipids than terrestrial plants --*10x - 100x***
- Can use non-arable land; growth possible in fresh, brackish, saline and wastewater
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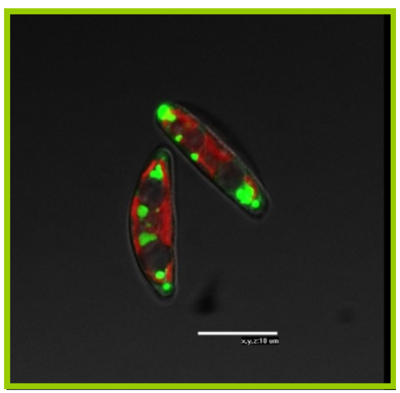
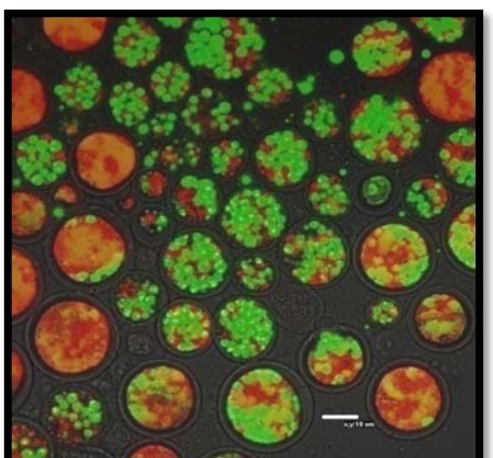


Fluorescence micrograph showing stained algal oil droplets (green)



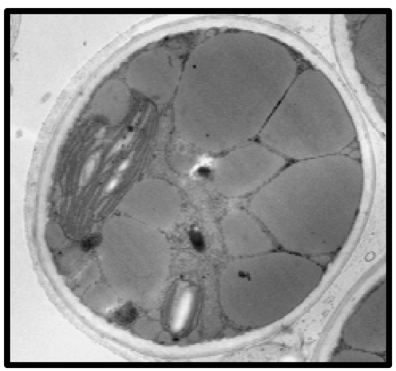
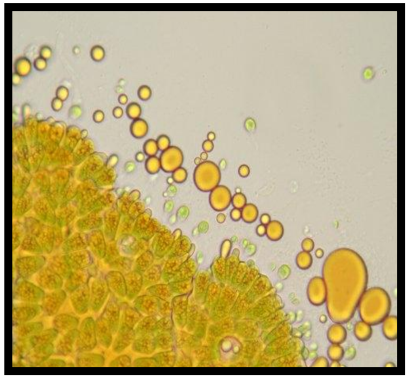
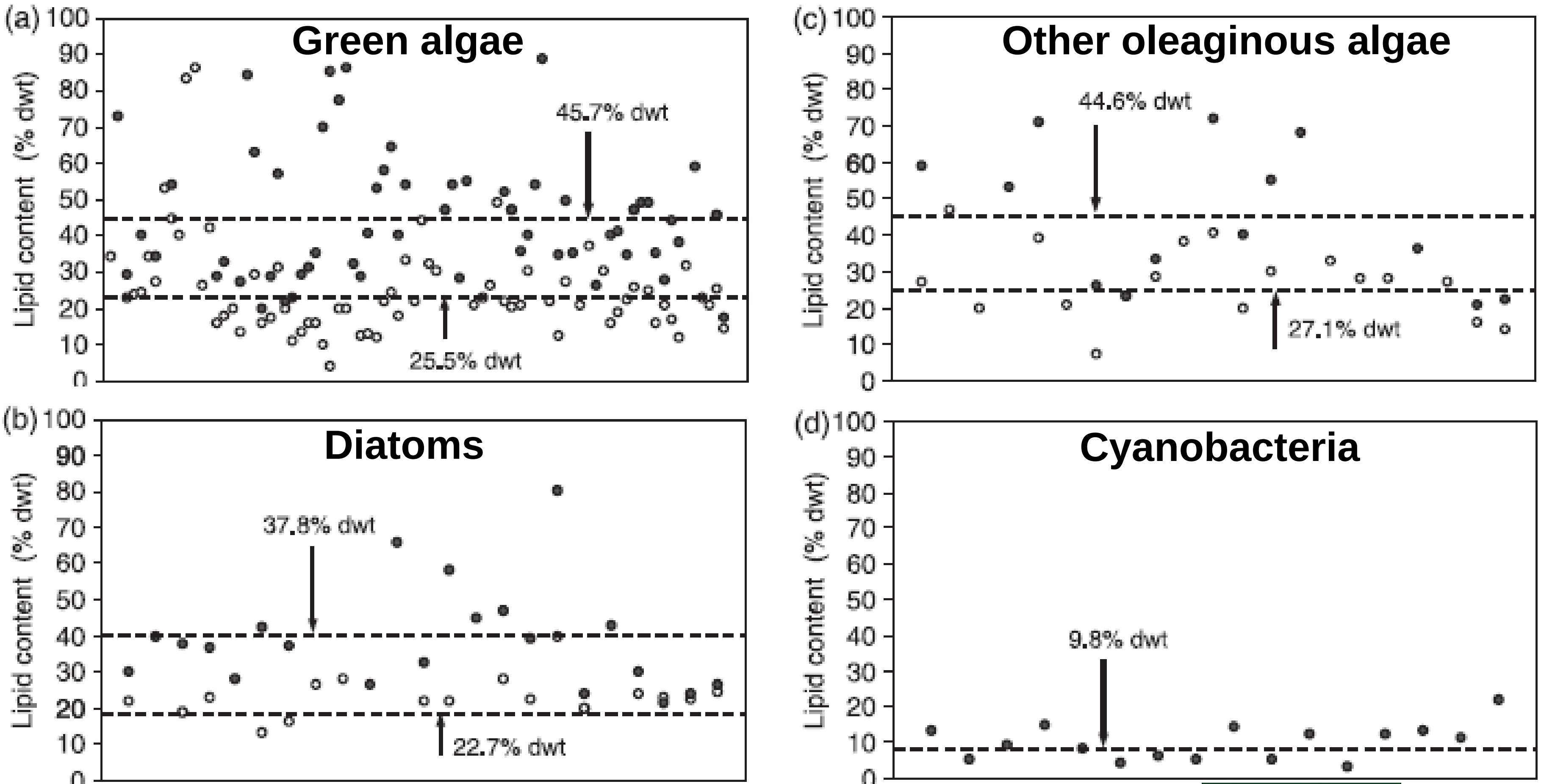


Image courtesy: Q. Hu, ASU



Cellular Lipid Content of Algae



Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M. and Darzins, A. *(2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. The Plant Journal 54:621-639.*

Superior Oil Yields

Crop	Oil Yield Gallons/acre
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed	127
Jatropha	202
Oil palm	635
Algae (20g/m^2/day-15%)	1267

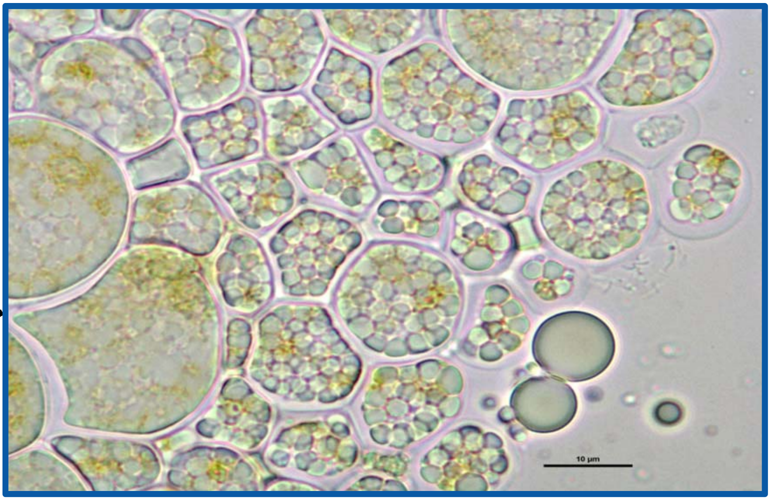
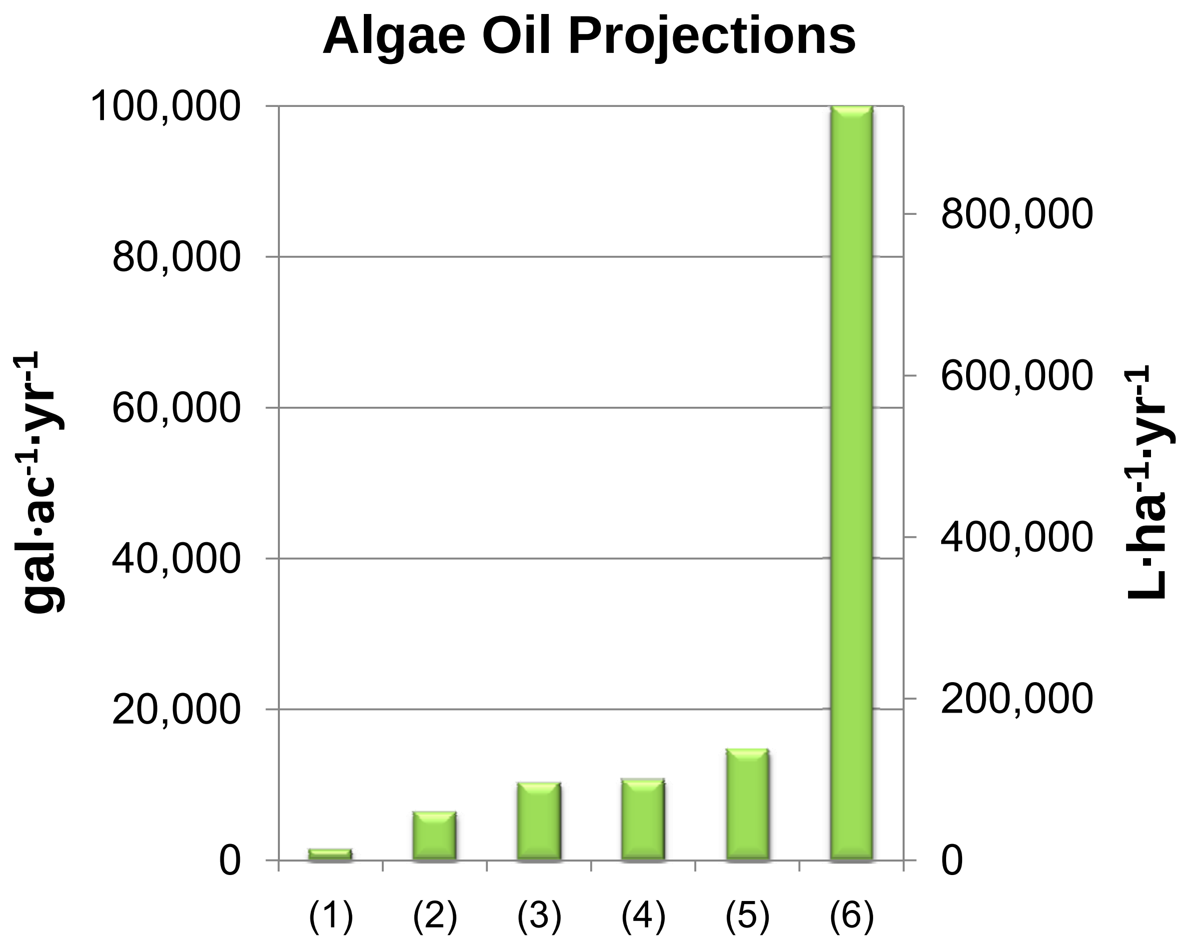


Image courtesy of Lee Elliott, CSM

Myth vs Reality

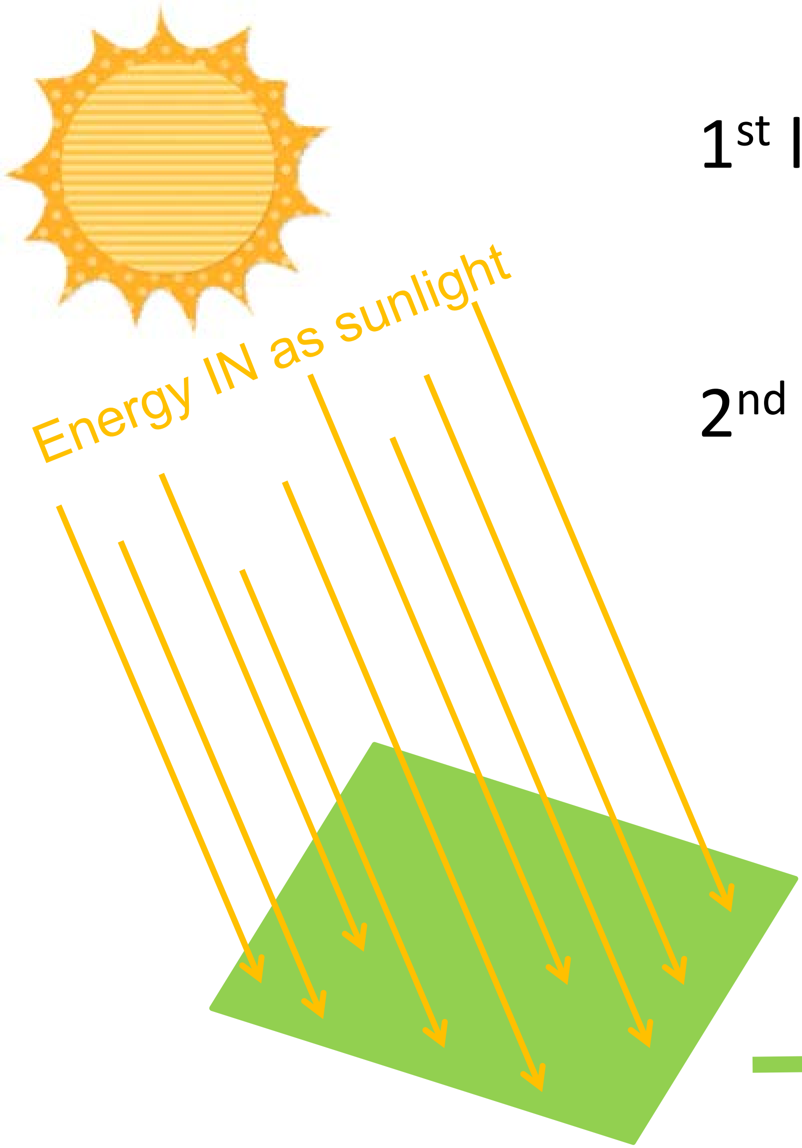


Wide range of projections…

What is the ultimate upper limit?

(1) Schenk, 2008
(2) Chisti, 2007 **(30% oil)**
(3) NREL ASP, Sheehan et al., 1998
(4) Schenk, 2008
(5) Chisti, 2007 **(70% oil)**
(6) Report on CNN, Apr 4, 2008

Need to Obey Laws of Thermodynamics



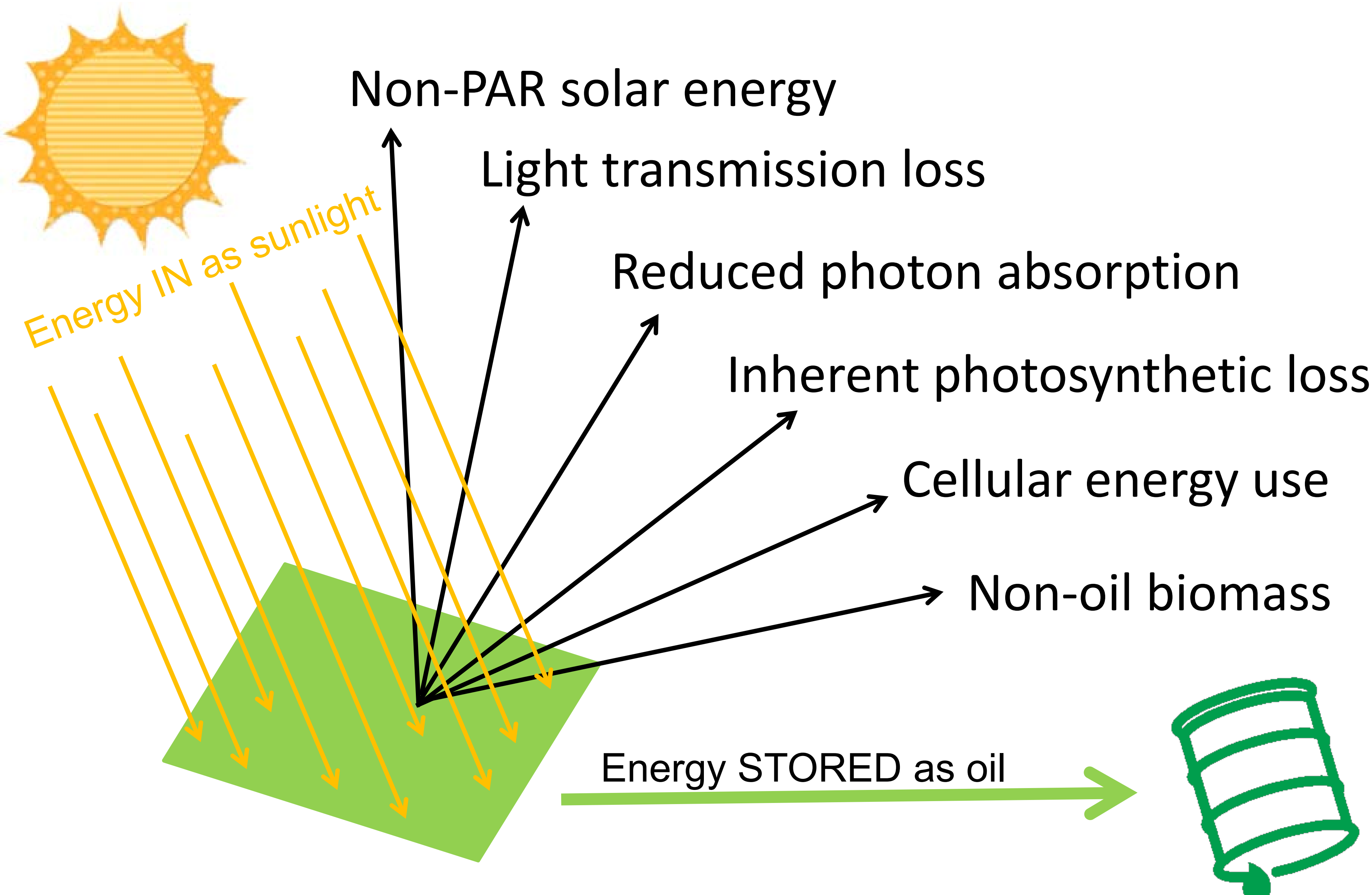
1st law: conservation of energy

$$E_{in} - E_{out} = E_{stored}$$

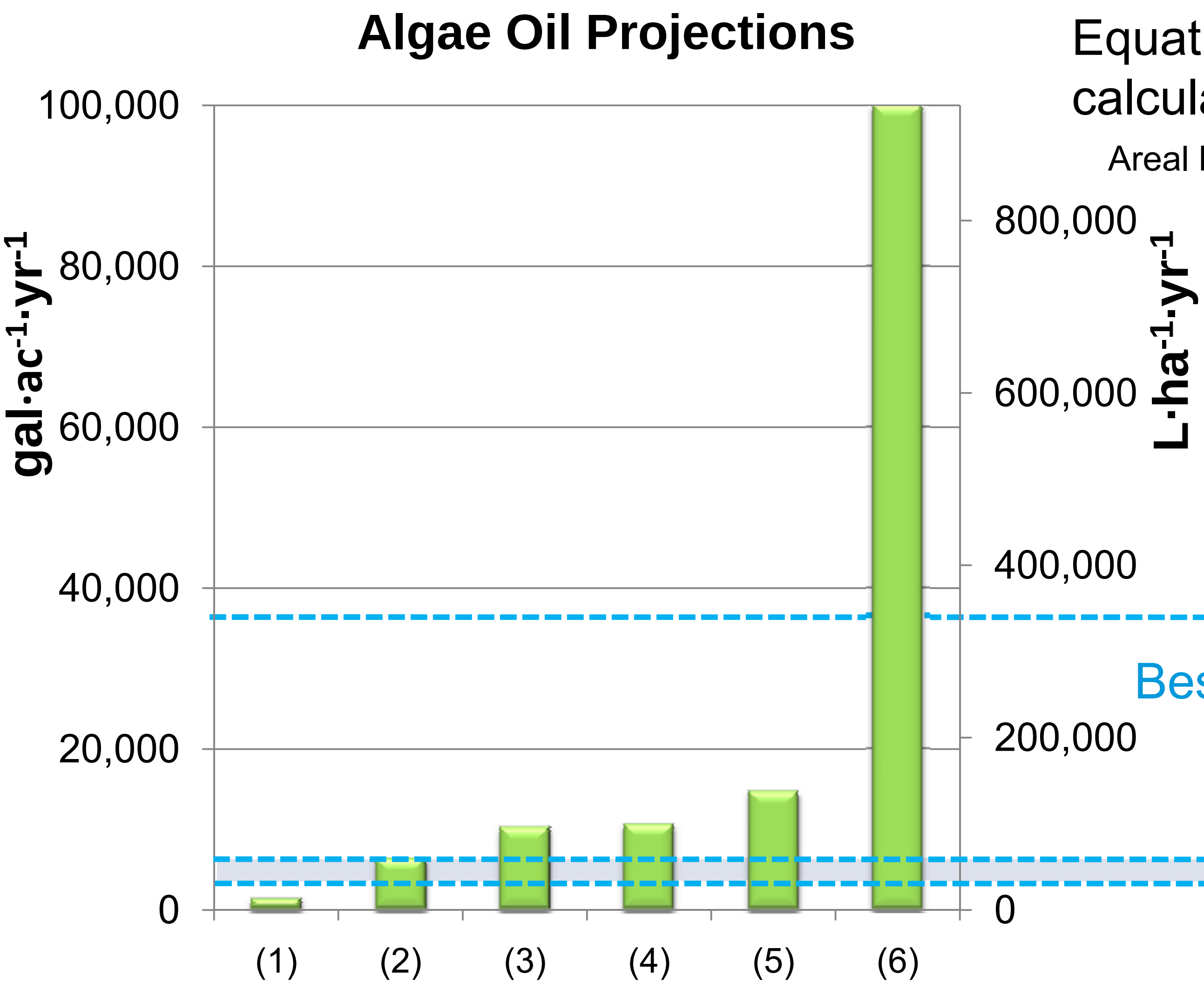
2nd law: 100% efficiency is not possible

$$E_{in} > E_{stored}$$

Inefficiences galore.....



Industry needs to well grounded….



Equation using 11 terms to calculate volume/area/year

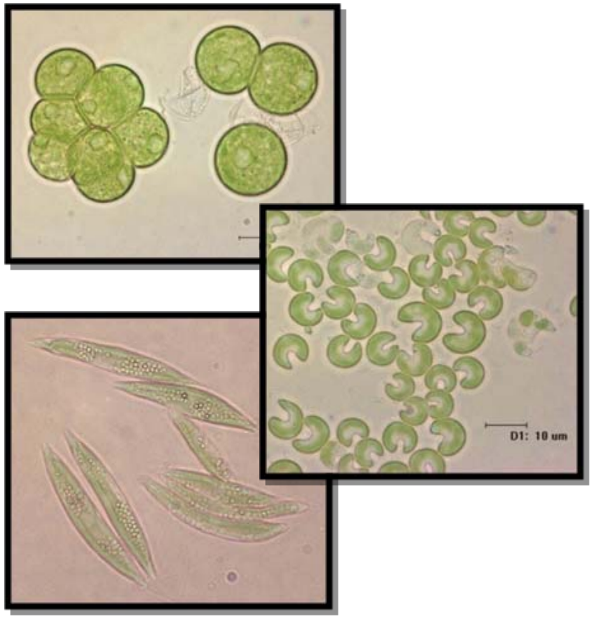
Areal Productivity: 38-47 gm/m^2/day

Theoretical maximum oil production @ 50% oil; at the equator: **38,000** gal·acre^{-1}·yr^{-1}

Best case range @ 50% oil: **4,350 – 5,700** gal·acre^{-1}·yr^{-1}

Weyer, K., Bush, D., Darzins, A. and Willson, B. (2009). Theoretical Maximum Algal Oil Production. (BioEnergy Research, Online First [Open Source])

Why Fuels from Algal Oil?



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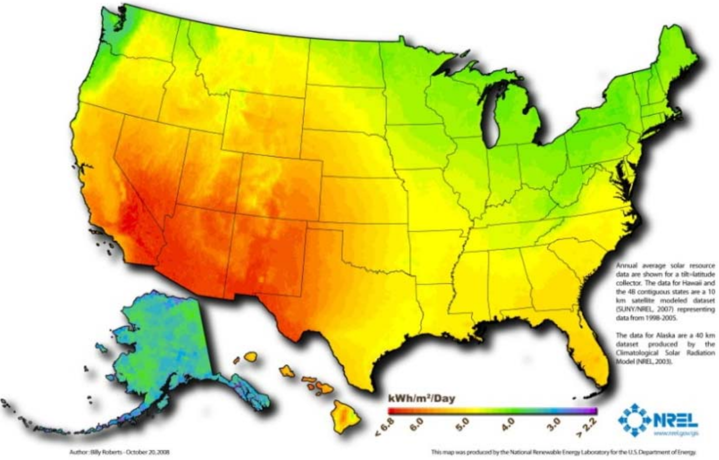
- Utilize large waste CO_2 resources (i.e., flue gas)
- Potential to displace significant U.S. petroleum fuel usage – requires existing infrastructure



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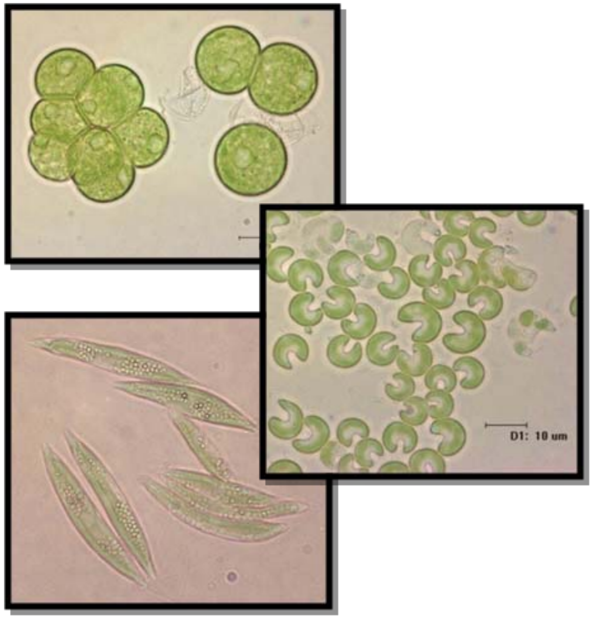

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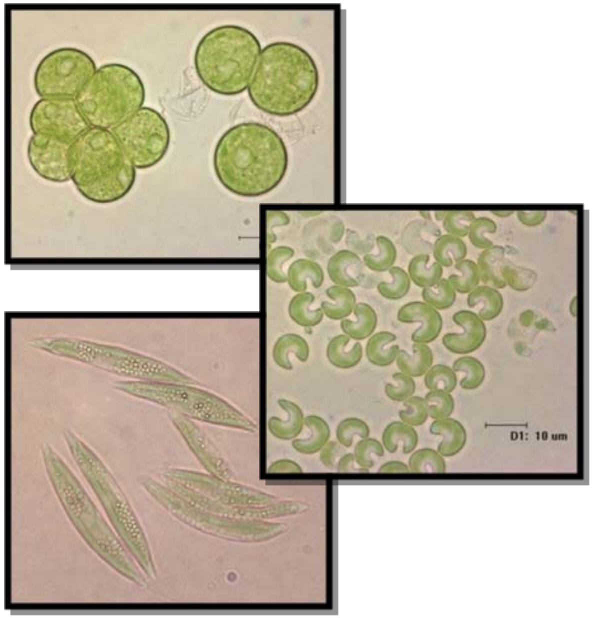

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Seambiotic: Ashkelon, Israel

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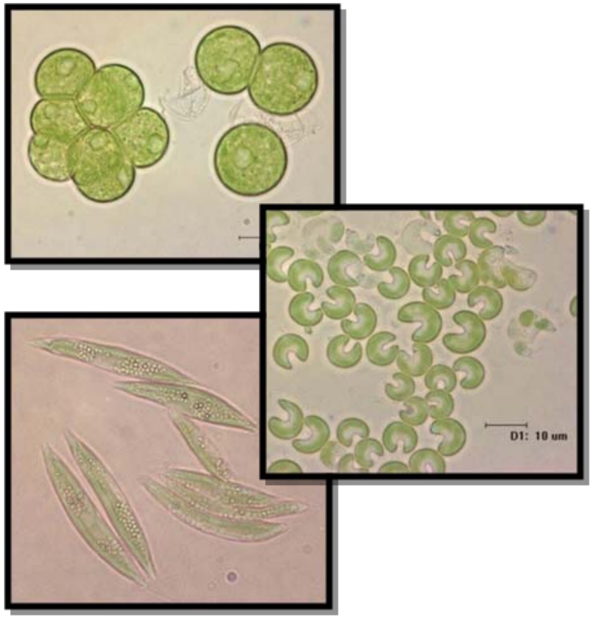

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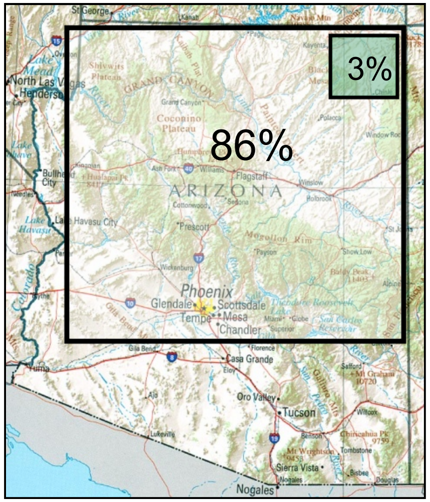
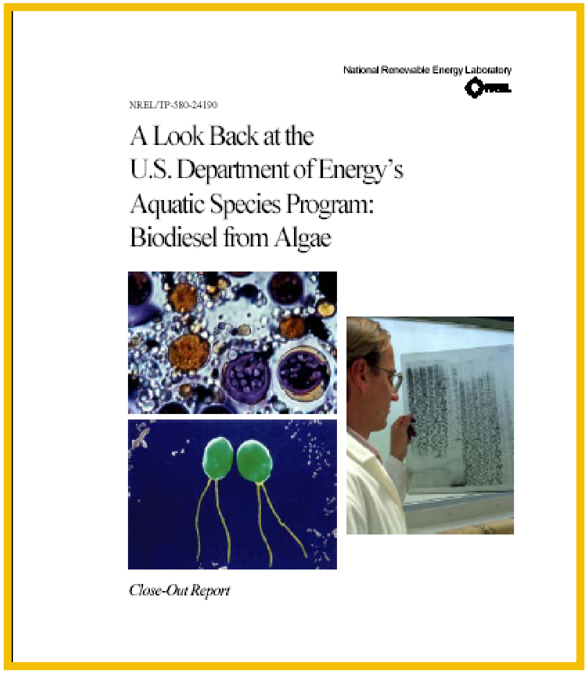
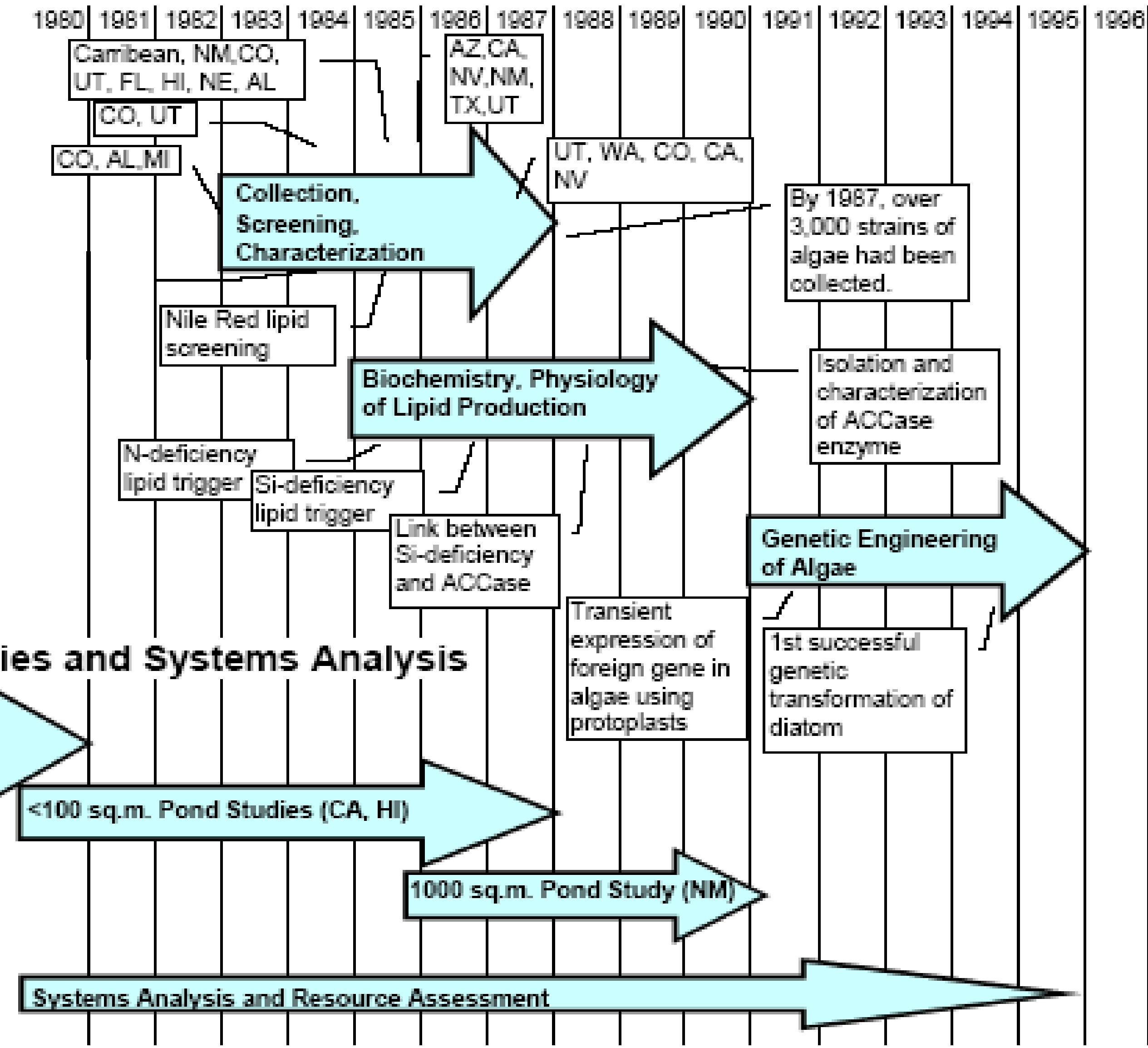
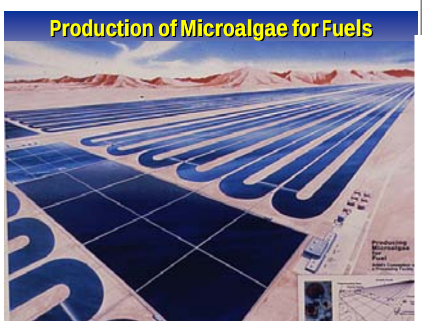
	Soybean	Algae
gal/year	3 billion	3 billion
gal/acre	48	1267
Total acres	62.5 million	2.4 million



DOE's Aquatic Species Program







What's Changed Since 1996?

- **Record oil prices; increasing worldwide demand for energy**
- **CO_2 capture, GHG reduction; energy security**
- **Industrial interest (>150 algal companies)**
- **Interest by oil industry, venture capital, end users, utilities and governments**
- **Explosion in biotechnology**

ExxonMobil

Chevron

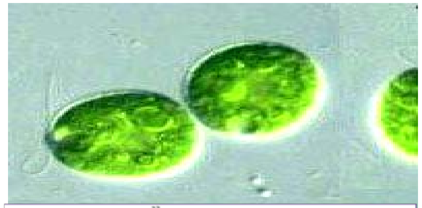
OFFICE OF SCIENTIFIC RESEARCH AIR FORCE UNITED STATES AIR FORCE

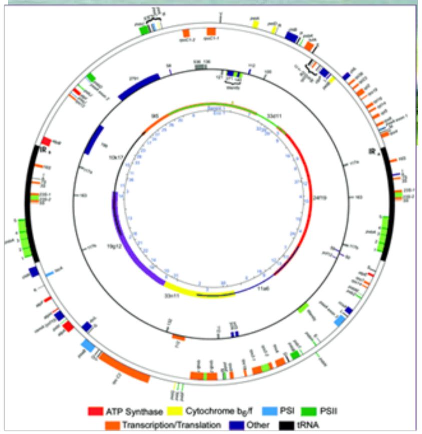
VALERO

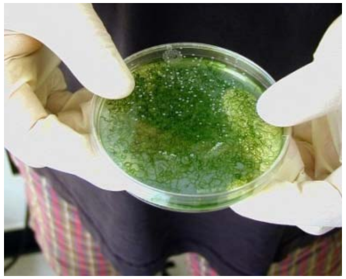
DARPA

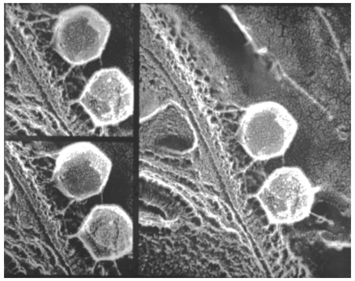
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

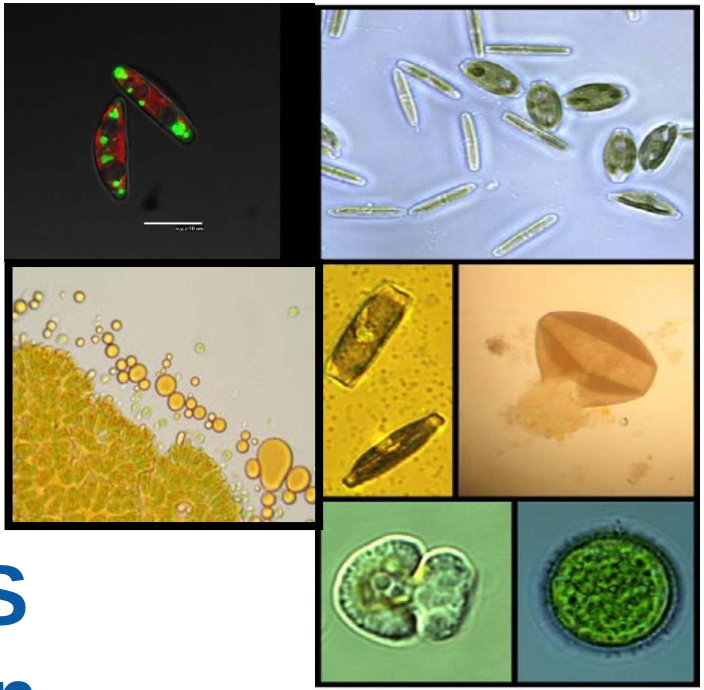
ConocoPhillips



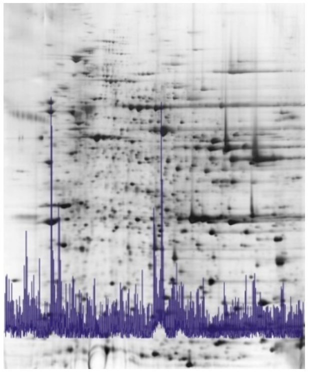


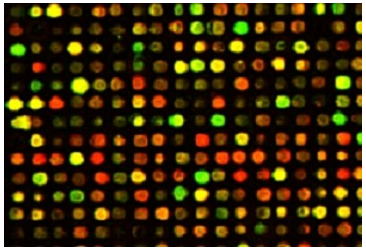


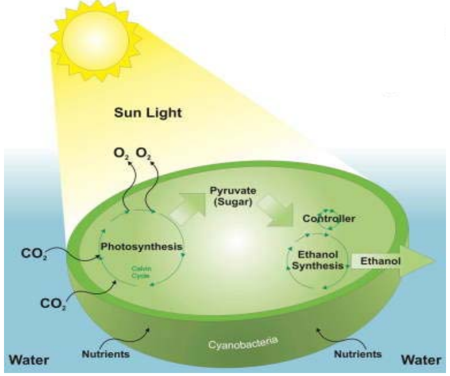


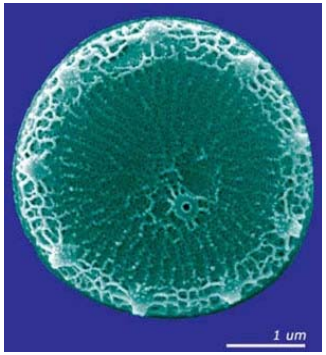


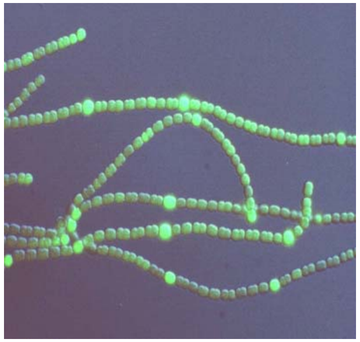
Role of the US Government in developing algal biofuels











Congressional Algae Report

Microalgae Feedstocks for Biofuels Production

Report to Congress

Microalgae Feedstocks for Biofuels Production
(EISA 2007 – Section 228)

March 14, 2008

U.S. Department of Energy

Report Outline

- Executive Summary
- Introduction
- Historical Review of Technical Progress
- Microalgae Oil Production: Biology and Physiology
- Microalgae Oil to Biofuels
- Current Activities/Funding Support for Algae Biofuels
- Resource and Technoeconomic Assessment
- Conclusions and Recommendations

National Renewable Energy Laboratory
and
Air Force Office of Scientific Research
Joint Workshop
on
Algal Oil for Jet Fuel Production

February 19-21, 2008

Arlington, VA

http://www.nrel.gov/biomass/algal_oil_workshop.html

Algal Biofuels Technology Roadmap Workshop

Sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of the Biomass Program

- **Venue**: Univ. of Maryland Dec 9-10, 2008
- **Participants**: ~200 scientists, engineers and other experts and stockholders
- **Goal**: Define activities needed to resolve barriers associated with commercial scale algal biofuel production
- **Workshop**: plenary talks and breakout sessions covering technical, industrial, resource, and regulatory aspects
- **Information**: http://www.orau.gov/algae2008/

  http://www.orau.gov/algae2008pro
- **Progress**: First draft of Roadmap complete; Request for Information (RFI)

Biomass Program

Growing America's Energy Future

Algal Biofuels

Biofuels made from microalgae hold the potential to solve many of the sustainability challenges facing other biofuels today.

Algal biofuels are generating considerable interest around the world. They may represent a sustainable pathway for helping to meet the U.S. biofuel production targets set by the Energy Independence and Security Act of 2007.

Microalgae are single-cell, photosynthetic organisms known for their rapid growth and high energy content. They are capable of doubling their mass several times per day, and more than half of that mass consists of lipids or triacylglycerides— the same material found in vegetable oils. These bio-oils can be used to produce such advanced biofuels as biodiesel, green diesel, green gasoline, and green jet fuel.

Renewed Interest and Funding

Higher oil prices and increased interest in energy security have stimulated new public and private investment in algal biofuels research. The Biomass Program is reviving its Aquatic Species Program at the National Renewable Energy Laboratory (NREL) to build on past successes and drive down the cost of large-scale algal biofuel production. Private investors as well as programs within the Defense Advanced Research Projects Agency (DARPA) and Air Force Office of Scientific Research (AFOSR) are also sponsoring research at NREL, Sandia, and other laboratories. Substantial research and development challenges remain.

Benefits of Algal Biofuels

Impressive Productivity:
Microalgae, as distinct from seaweed or macroalgae, can potentially produce 100 times more oil per acre than soybeans—or any other terrestrial oil-producing crop.

Non-Competitive with Agriculture:
Algae can be cultivated in large open ponds or in closed photobioreactors located on non-arable land in a variety of climates (including deserts).

Undemanding of Fresh Water:
Many species of algae thrive in seawater, water from saline aquifers, or even wastewater from treatment plants.

Mitigation of CO2:
During photosynthesis, algae use solar energy to fix carbon dioxide (CO_2) into biomass, so the water used to cultivate algae must be enriched with CO_2. This requirement offers an opportunity to productively use the CO_2 from power plants, biofuel facilities, or other sources.

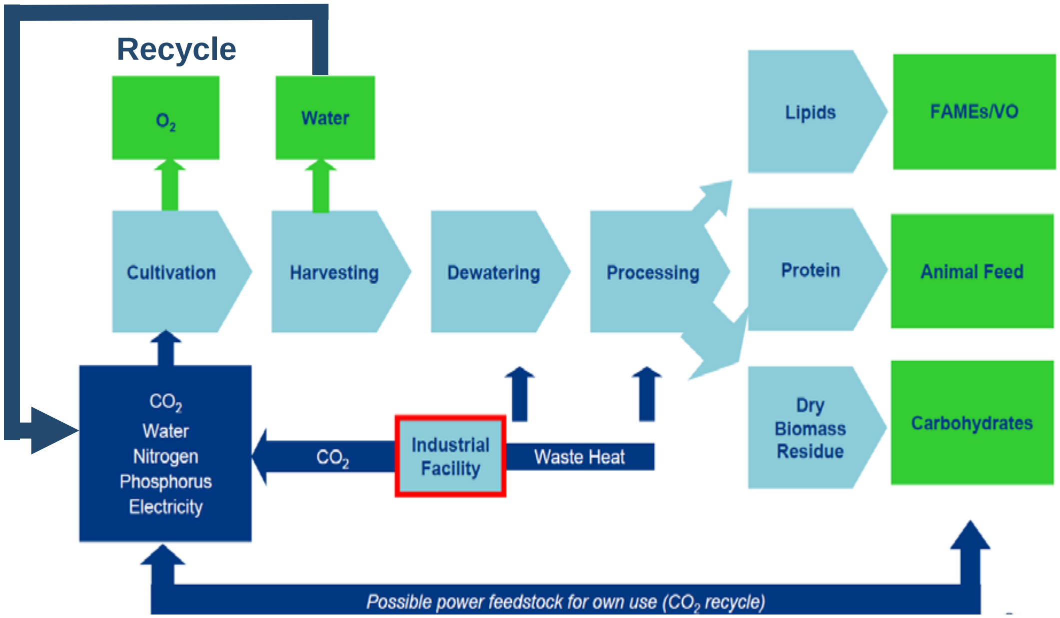
Broad Product Portfolio:
The lipids produced by algae can be used to produce a range of biofuels, and the remaining biomass residue has a variety of useful applications:

- combust to generate heat
- use in anaerobic digesters to produce methane
- use as a fermentation feedstock in the production of ethanol
- use in value-added byproducts, such as animal feed

http://www1.eere.energy.gov/biomass/pdfs/algalbiofuels.pdf

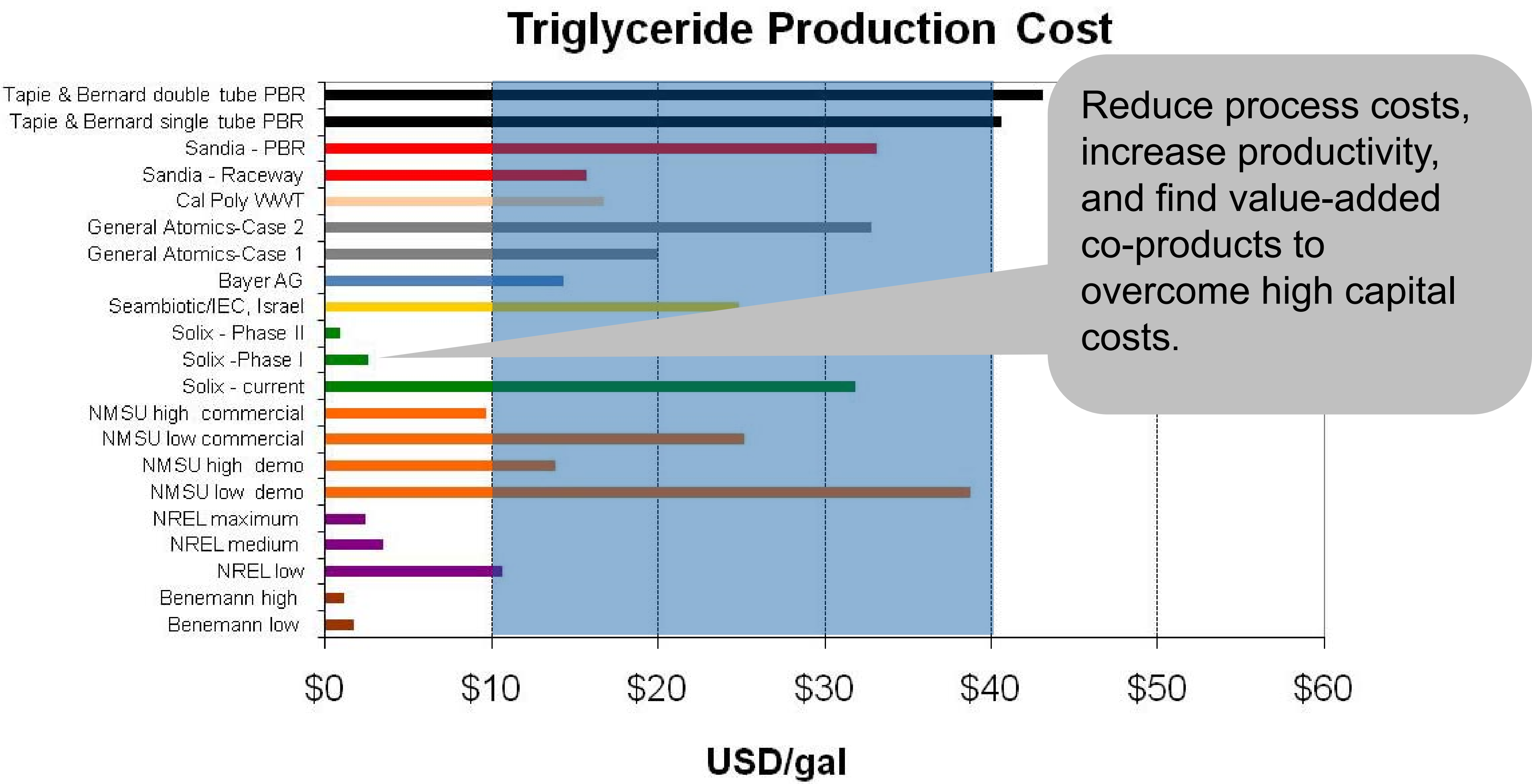
*Funding opportunity DE-PS36-09GO39010-RFI

Fundamental and applied research needed to resolve uncertainties associated with commercial-scale algal biofuel production:



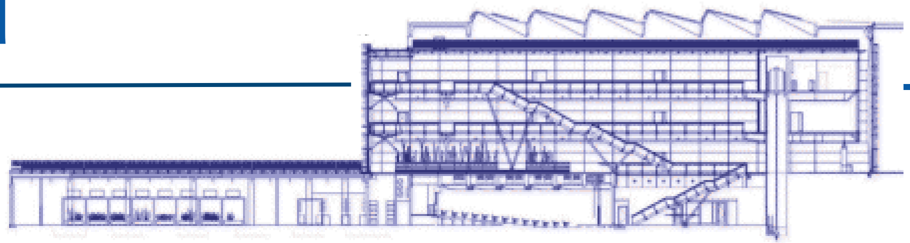
- Algal Biology
- Cultivation
- Harvest/dewatering
- Extraction/fractionation
- Conversion to fuels
- Co–products
- Systems integration
- Siting & Resources
- Regulation & Policy

Technoeconomic Analysis



Photobioreactors Haven't Been Ruled Out

Algal Biofuels Award



Awarded to:

National Alliance for Advanced Biofuels and Bioproducts (NAABB)

Leader:
Donald Danforth Plant Science Center

With Partners:
2 national laboratories, 10 university and 13 industry partners

$44M DOE + $11M cost share

Objectives and Approach:

- Develop a systems approach for sustainable commercializ[...]el (such as renewable ga[...] jet fuel) and bioproducts.
- Integrate res[...]nies, universities, a[...]tories to overcome the critical barriers
- Develop and demonstrate the science and technology necessary to significantly increase production of algal biomass and lipids
- Explore co-products, including animal feed, industrial feedstocks, and additional energy generation.
- Multiple test sites will cover diverse environmental regions to facilitate broad deployment.

+ $35M in FY10 appropriation

NREL’s Algal Biofuels Program

Rebuilding NREL Algae Program

In 2006, recognizing the limitations on biofuels based on terrestrial biomass, NREL began a strategic initiative to revive its program in algal biofuels.

Leveraging research funding from a number of sources to revive a program dormant for more than a decade

- Partnerships with industry and academia
- International partnerships
- Internal funding
- DOE
- DOD

Chevron Algae CRADA

2nd Collaborative Research and Development Agreement (CRADA) under Chevron/NREL Alliance

Goal: Identify and develop algae strains that can be economically harvested and processed into finished transportation fuels

DOE US - Israel Collaboration

Development of Novel Microalgal Production and Downstream Processing Technologies for Alternative Biofuels Applications

Joint NREL/SNL/Israel-US Private Industry Collaboration

Tasks:

- Develop extraction methods
- Thermochemical conversion of algal feedstocks
- Physics-based modeling/analysis
- Life Cycle Analysis (LCA)

Seambiotic

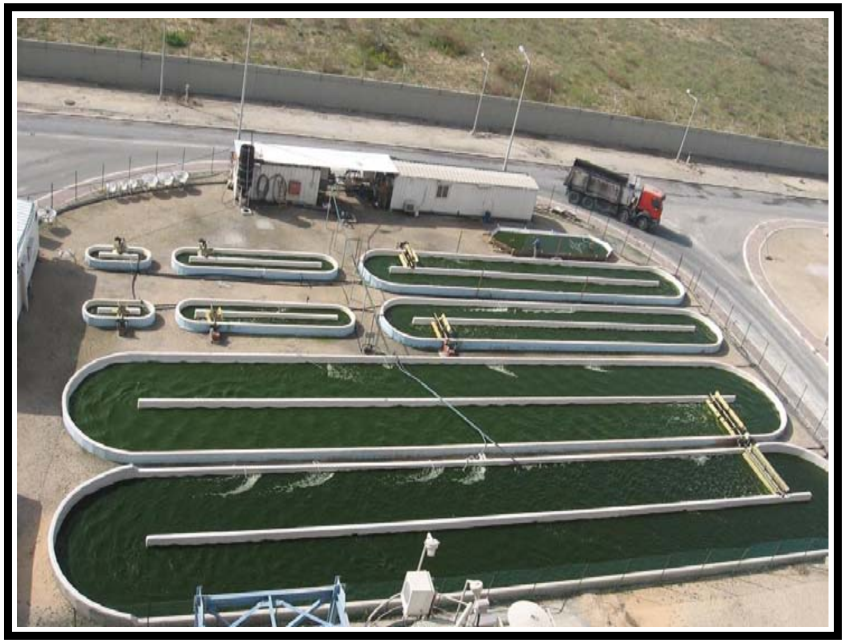


Image courtesy: A. Ben-Amotz, Seambiotic

DOE US - Canada Collaboration

Isolation and preliminary characterization / assessment of scale-up potential of photosynthetic microalgae for the production of both biofuels and bio-active molecules in the US and Canada

Joint NREL/SNL/NRC Partnership

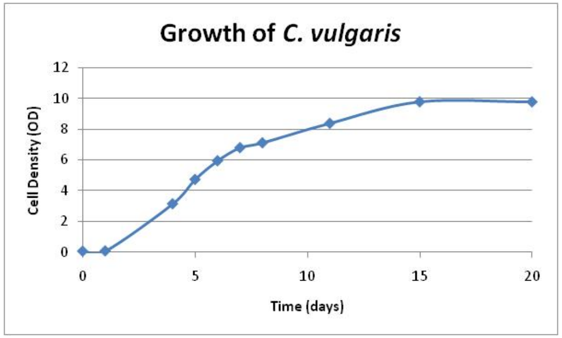
Tasks:

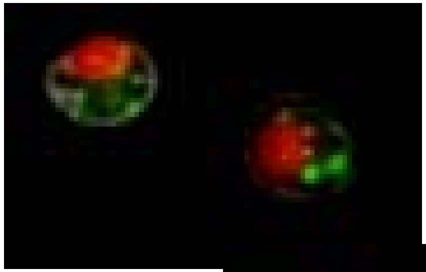
- Bioprospecting for strains with suitable characteristics for cultivation in northern latitudes – marine environments
- Evaluation of strains for lipid productivity and bio-active molecule production
- Siting analysis for selected regions of Canada and northern US
- Techno-economic modeling

Chlorella vulgaris: NREL Model System

Chorella vulgaris UTEX395

- Rapid growth to high cell density
- Visible accumulation of oil after N depletion
- High fatty acid content after N starvation
- Capable of heterotrophic growth
- Reports of successful genetic manipulation



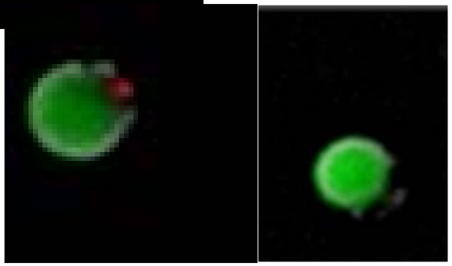


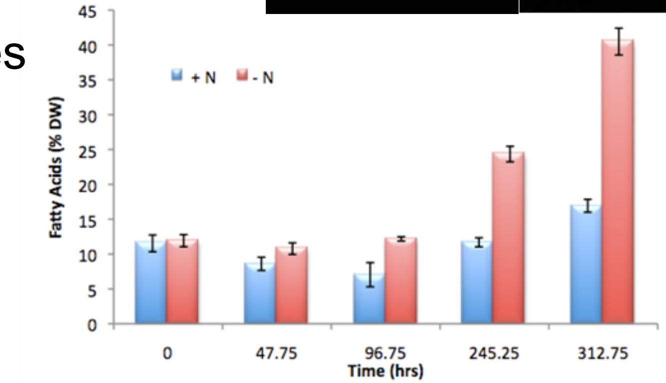
+N

Projects currently underway

- Digital gene expression (Transcriptomics)
- Proteomics (AFOSR)
- Development of novel harvest methodologies
- Development of transformation methodologies
- Regulated enzymatic disruption of algal cell walls as an oil extraction technology
- Identification of novel promoters

-N

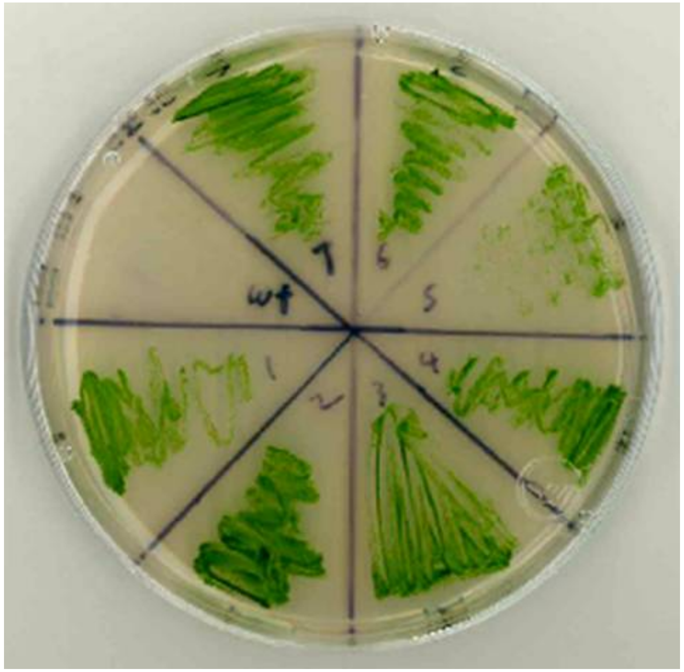


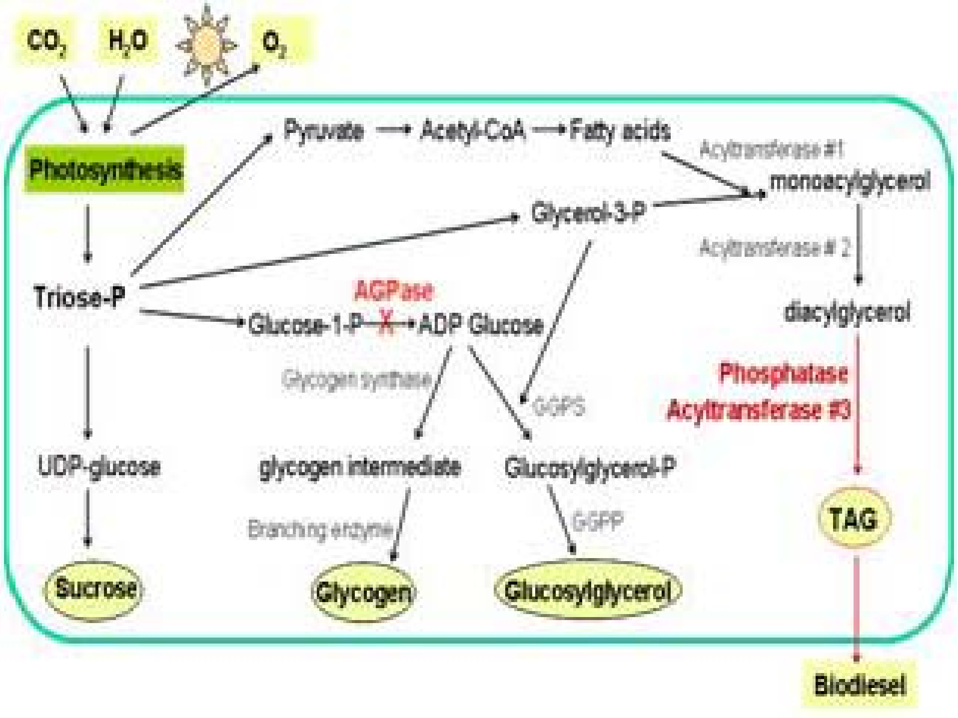


Pathway Engineering in Cyanobacteria

- Biodiesel from Cyanobacteria (*Synechocystis* PCC 6803)

- Development of Novel Cyanobacterial Biofuels





C2B2 Colorado Center for Biorefining and Biofuels

Establishment of a Bioenergy-Focused Microalgal Strain Collection Using High-Throughput Methodologies

Colorado Renewable Energy Collaboratory
Partners for Clean Energy

Current Corporate Sponsors (21)

Catchlight Energy
Ceres
Chevron
Cobalt Biofuels
ConocoPhillips
Ecopetrol
Flad Architects

General Motors
Genesis Biofuel
Gevo
GICON
Kimberly-Clark
Korth O'Neil Engineering
LiveFuels

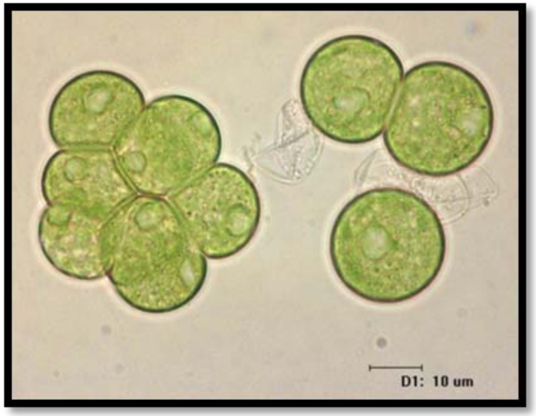
Mascoma
OpX Bioproducts
Shell Global Solutions
Solix Biofuels
Sundrop Fuels
Valero
ZeaChem

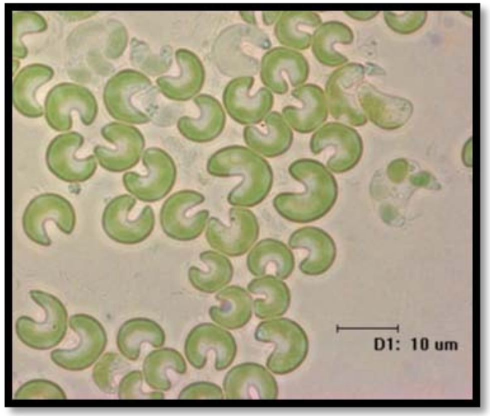
C2B2 Colorado Center for Biorefining and Biofuels

Project Description

Goal: Isolate and characterize 500 microalgal strains utilizing rapid, high-throughput methodologies

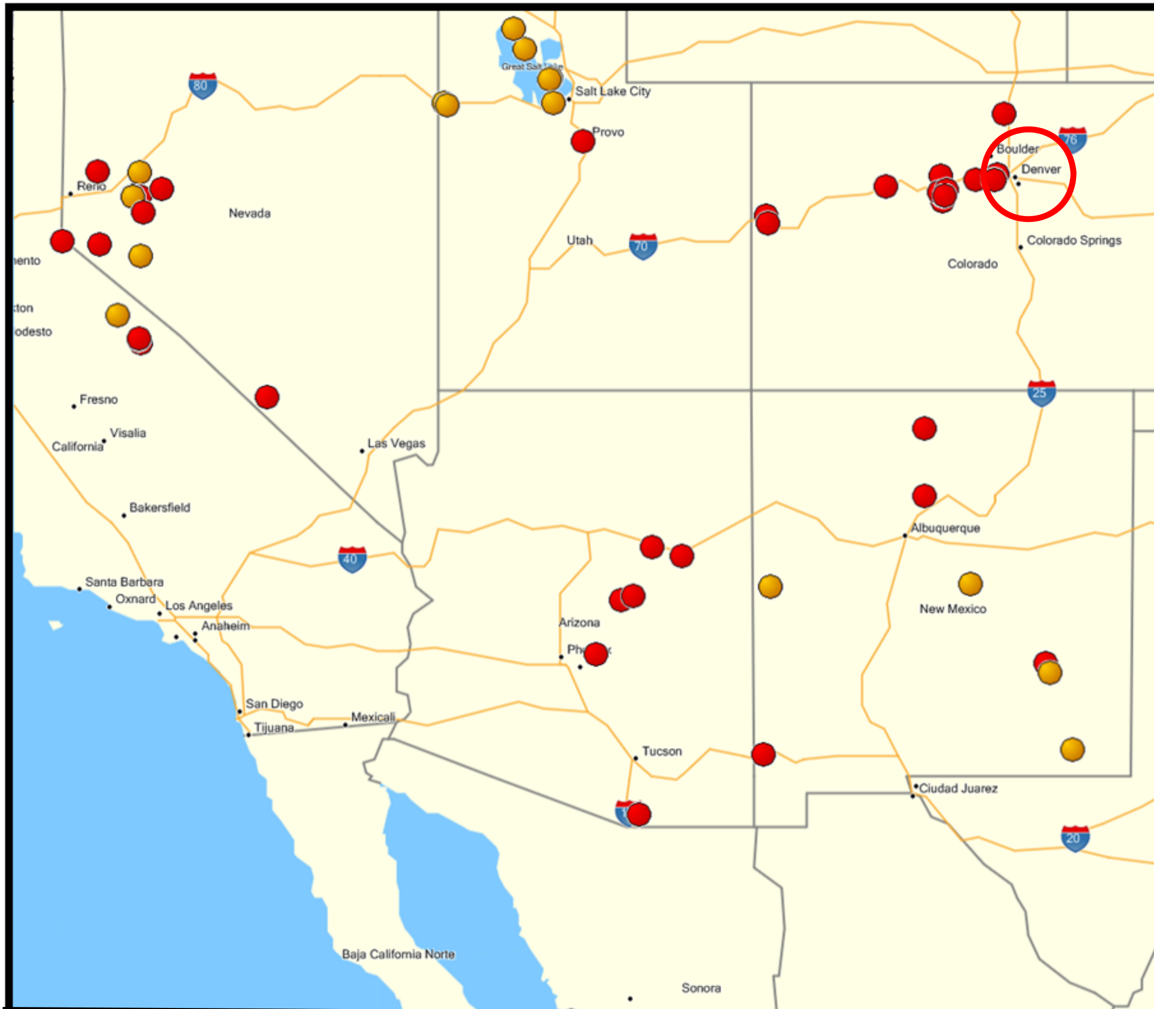
- Sample unique aquatic environments in the US Southwest.
- Sort microalgal cells using Fluorescent Activated Cell Sorting (FACS).
- Characterize algae based on morphology and lipid accumulations
- Cryopreserve microalgae isolates for long-term storage.





Locations of Sample Collection Sites

- Targeted sites from diverse locations in the Southwest
- Site determination
  - **Locally**: Based on visible algal growth
  - **Regionally**: Documentation of productivity and visible growth
- 69 samples collected:
  - 31 from Colorado
  - 9 from Utah
  - 8 from New Mexico
  - 6 from Arizona
  - 5 from California
  - 10 from Nevada



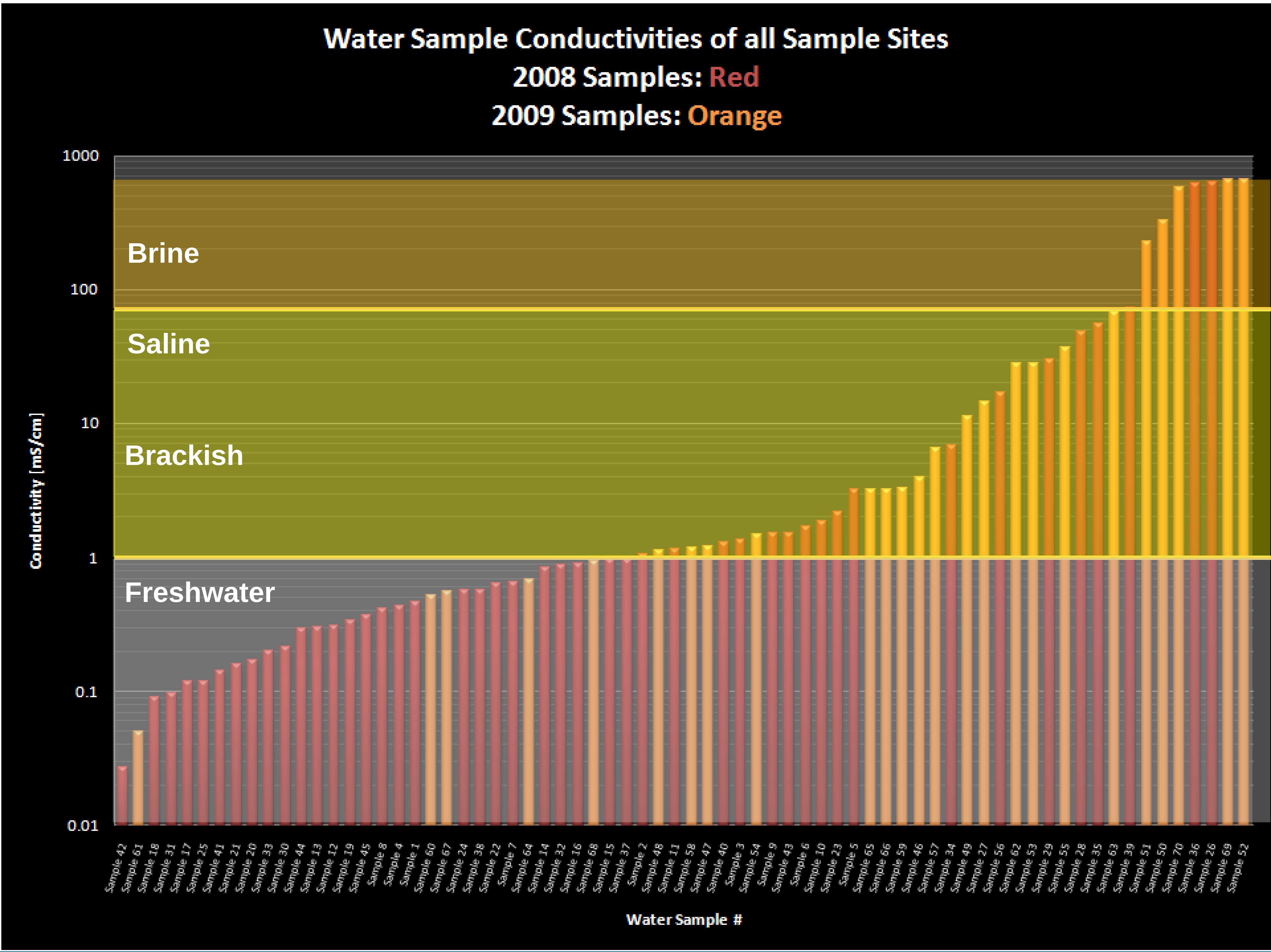
Red: 2008 sampling trip **Orange**: 2009 sampling trip

Specific Conductivity and Water Quality

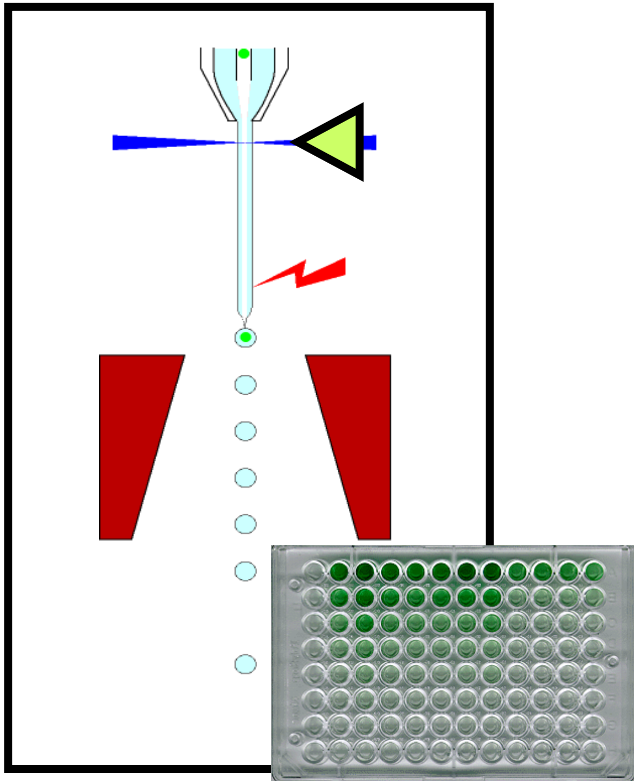
- Typical specific conductivity ranges for water from fresh to brine and the corresponding salinity ranges.
  - Conductivity measures the ionic activity of water.
  - Conductivity is a very good measure of TDS and salinity.
  - Most influential ions contributing to conductivity: Na+, Cl-, Ca2+, K+, Mg2

Water Type	*Specific Conductivity (mS/cm)	Salinity (ppt)
Fresh Water	<1.0	<0.5
Brackish Water	1.0-47.0	0.5-30
Saline Water	47.0-73.0	30-50
Brine	>73.0	>50
Sea Water (Boothbay Harbor, Maine)	65.4	42.78

Specific conductivity is normalized at 25 degrees Celsius.
Source: http://www.ourlake.org/html/specific_conductivity.html

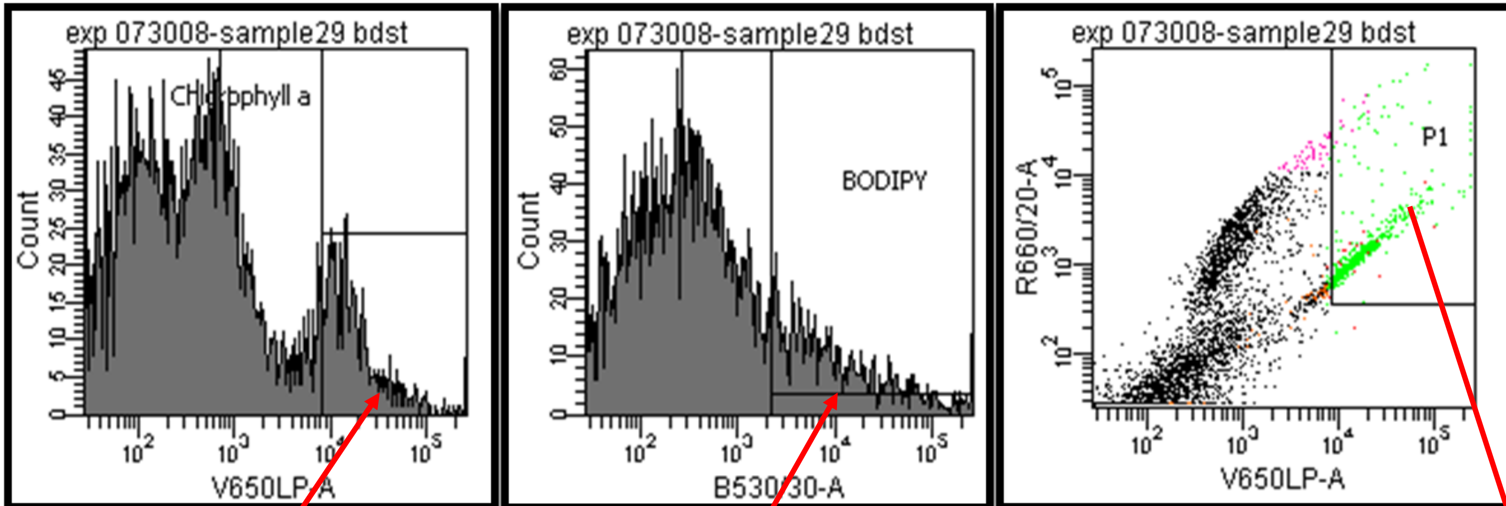

Water Sample Conductivities of all Sample Sites
2008 Samples: Red
2009 Samples: Orange
Brine
Saline
Brackish
Freshwater
Conductivity [mS/cm]
1000
100
10
1
0.1
0.01
Water Sample #
Sample 42
Sample 61
Sample 18
Sample 31
Sample 17
Sample 25
Sample 41
Sample 21
Sample 20
Sample 33
Sample 30
Sample 44
Sample 13
Sample 12
Sample 19
Sample 45
Sample 8
Sample 4
Sample 1
Sample 60
Sample 67
Sample 24
Sample 38
Sample 22
Sample 7
Sample 64
Sample 14
Sample 32
Sample 16
Sample 68
Sample 15
Sample 37
Sample 2
Sample 48
Sample 11
Sample 58
Sample 47
Sample 40
Sample 3
Sample 54
Sample 9
Sample 43
Sample 6
Sample 10
Sample 23
Sample 5
Sample 65
Sample 66
Sample 59
Sample 46
Sample 57
Sample 34
Sample 49
Sample 27
Sample 56
Sample 62
Sample 53
Sample 29
Sample 55
Sample 28
Sample 35
Sample 63
Sample 39
Sample 51
Sample 50
Sample 70
Sample 36
Sample 26
Sample 69
Sample 52

Fluorescence Activated Cell Sorter (FACS)



- NREL's Custom BD FACS*Aria™*
  - ➢ analyzes particle fluorescence and sorts microalgae based on pre-set parameters.

High-Speed FACS Sorting

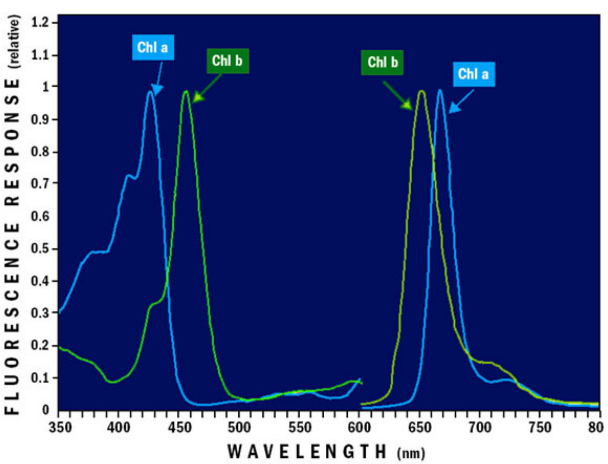


Positive chlorophyll population

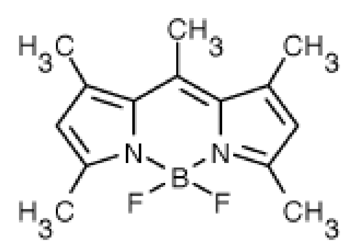
Positive BODIPY population

Population	%Parent	%Total
All Events	####	100.0
Chlorophyll a	12.9	12.9
BODIPY	88.2	11.4
P1	98.8	11.2

96 well plate



- Chlorophyll *a* excitation, 405nm, emission at >650nm.
- Non-polar lipid probe Bodipy excitation, 488nm, emission at 530/30nm.

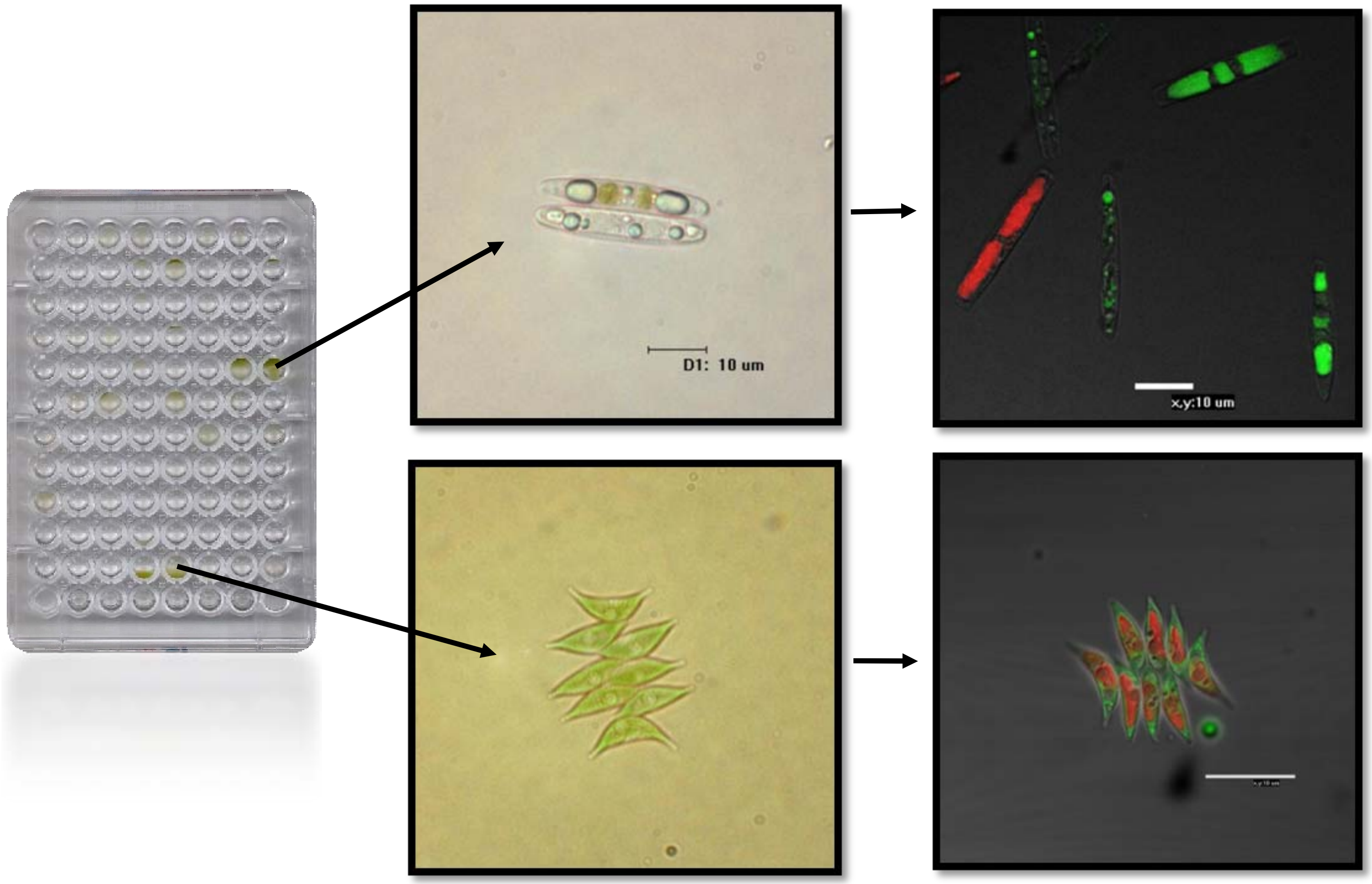


Sort single events in population P1 which are positive for ***both*** chlorophyll ***and*** BODIPY

Clonal Isolate Characterization

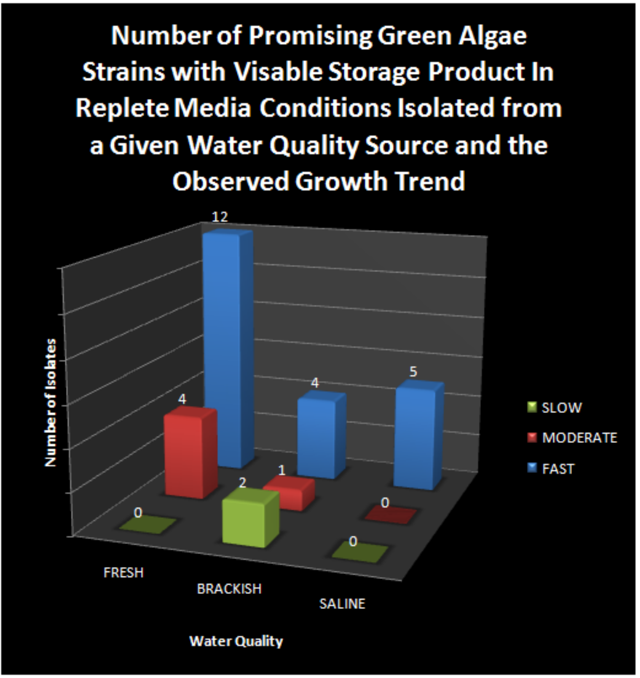
Step 1: Image positive wells with brightfield microscopy; compare morphologies and transfer unique isolates into fresh media.

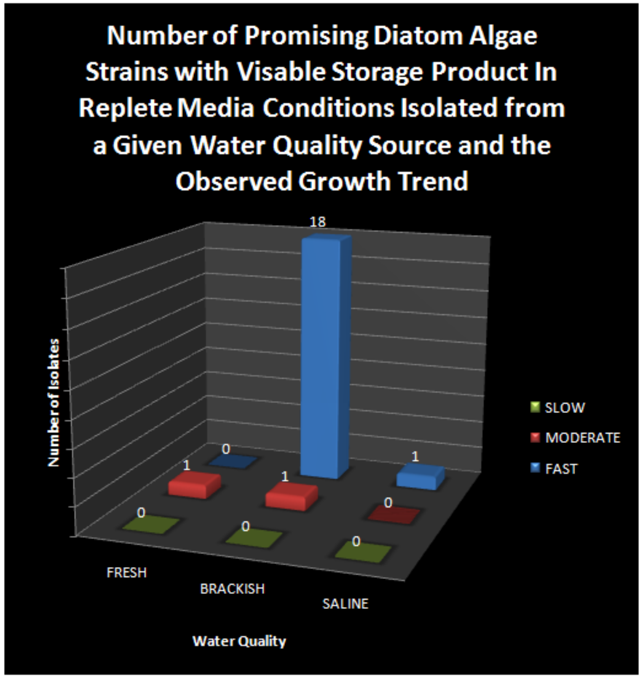
Step 2: Stain cells with fluorescent lipophilic probe (Bodipy) and image intracellular non-polar lipid distribution by confocal microscopy.

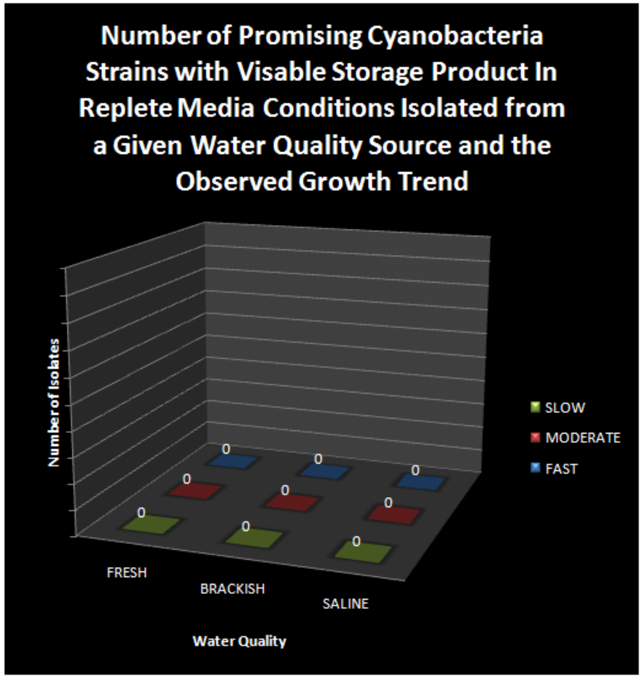


Population Analysis

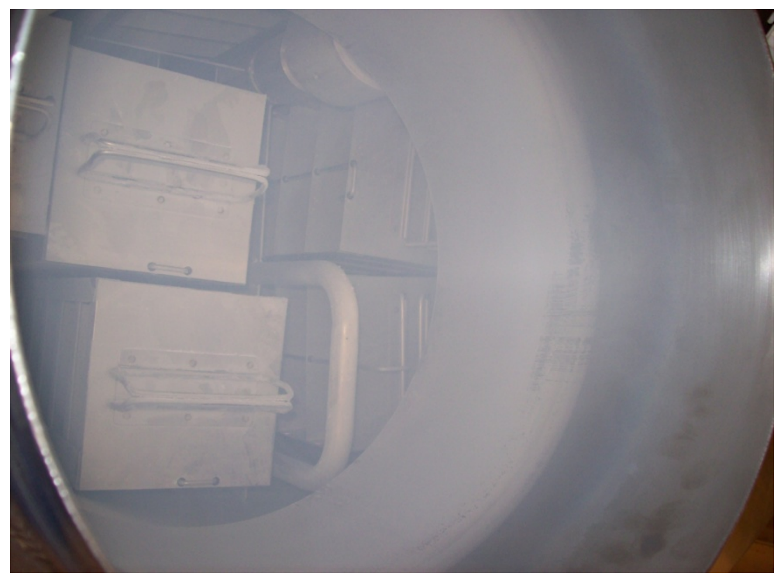
Green algae and diatoms from fresh, brackish and saline environments identified as potential bioenergy-feedstock strains







Algal Cryopreservation System



Chart® MVE 800 Series-190
vapor-phase LN_2 cryopreservation tank

Cryopreservation of Isolated Strains

- 91% of strains successfully cryopreserved in 5% MeOH in growth media
  - Protocol adapted from UTEX

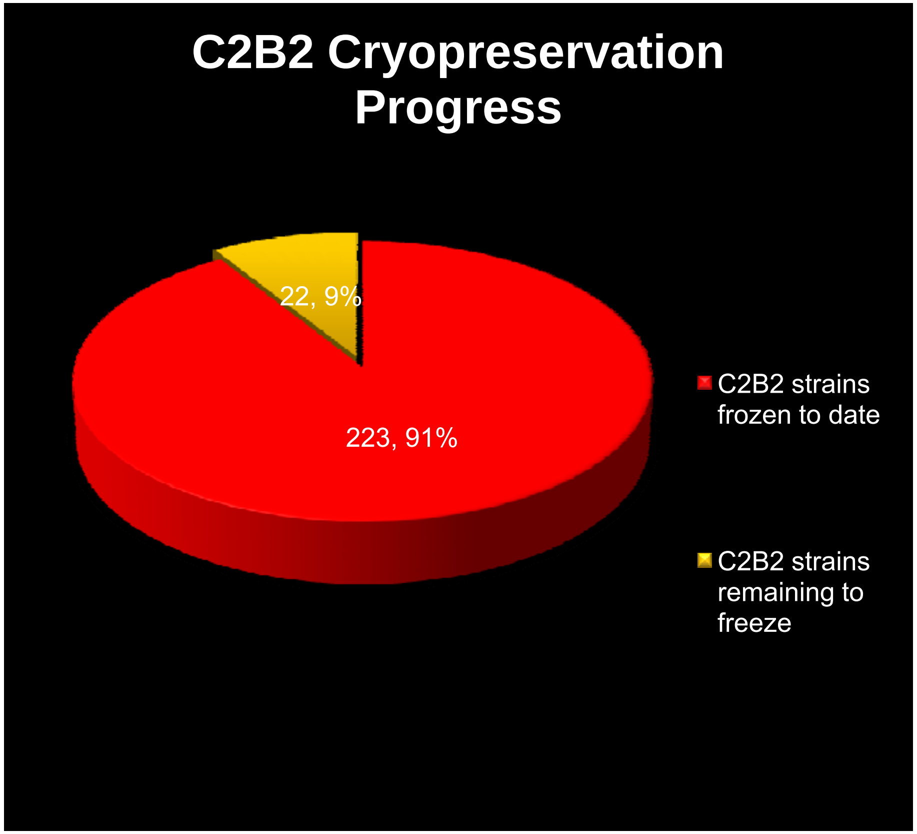


Plate A OD(λ=750) initial measurement

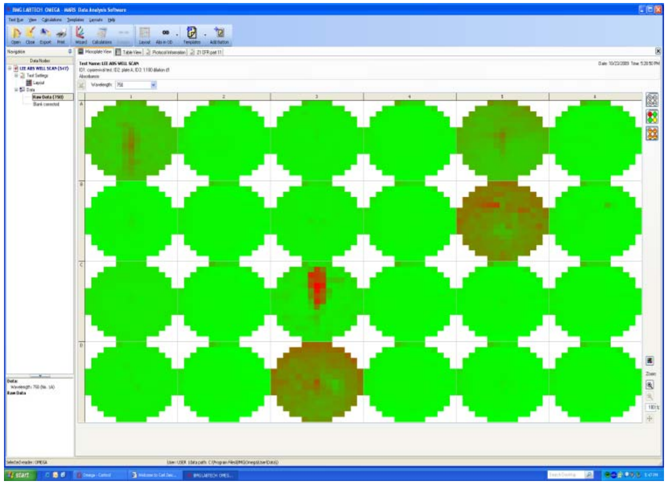
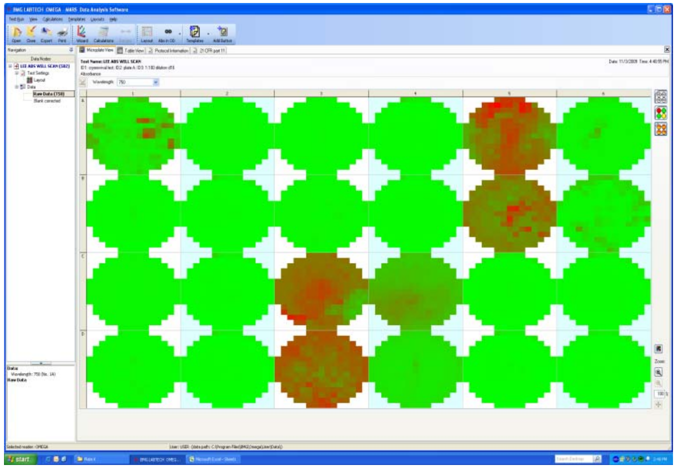


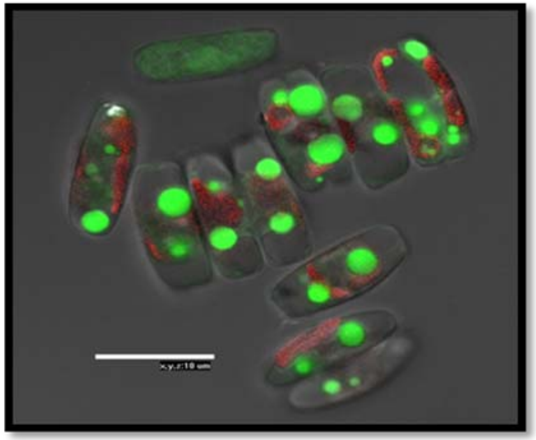
Plate A OD(λ=750) final measurement

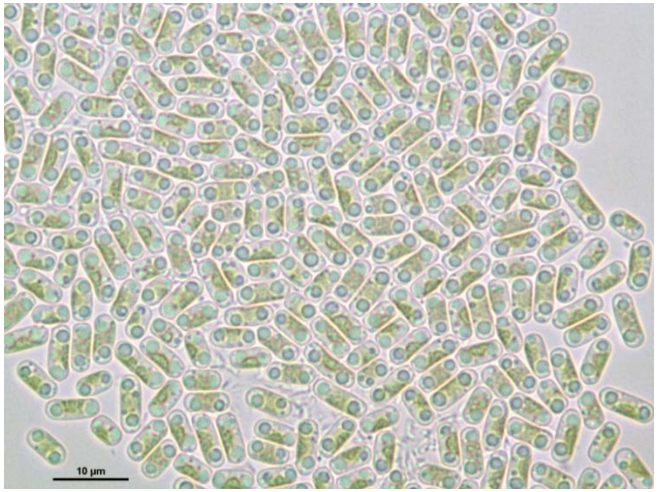


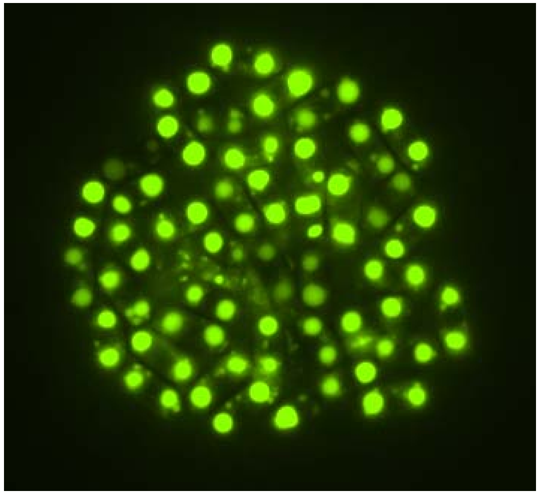
Future work

Phase II: Detailed Lipid Production Analysis of Most Promising Strains

- Screen/select most promising strains
- Optimize lipid productivity
- Obtain fatty acid methyl ester profiles
- Determine taxonomic classifications
- Rapidly quantitate lipid content and profile.



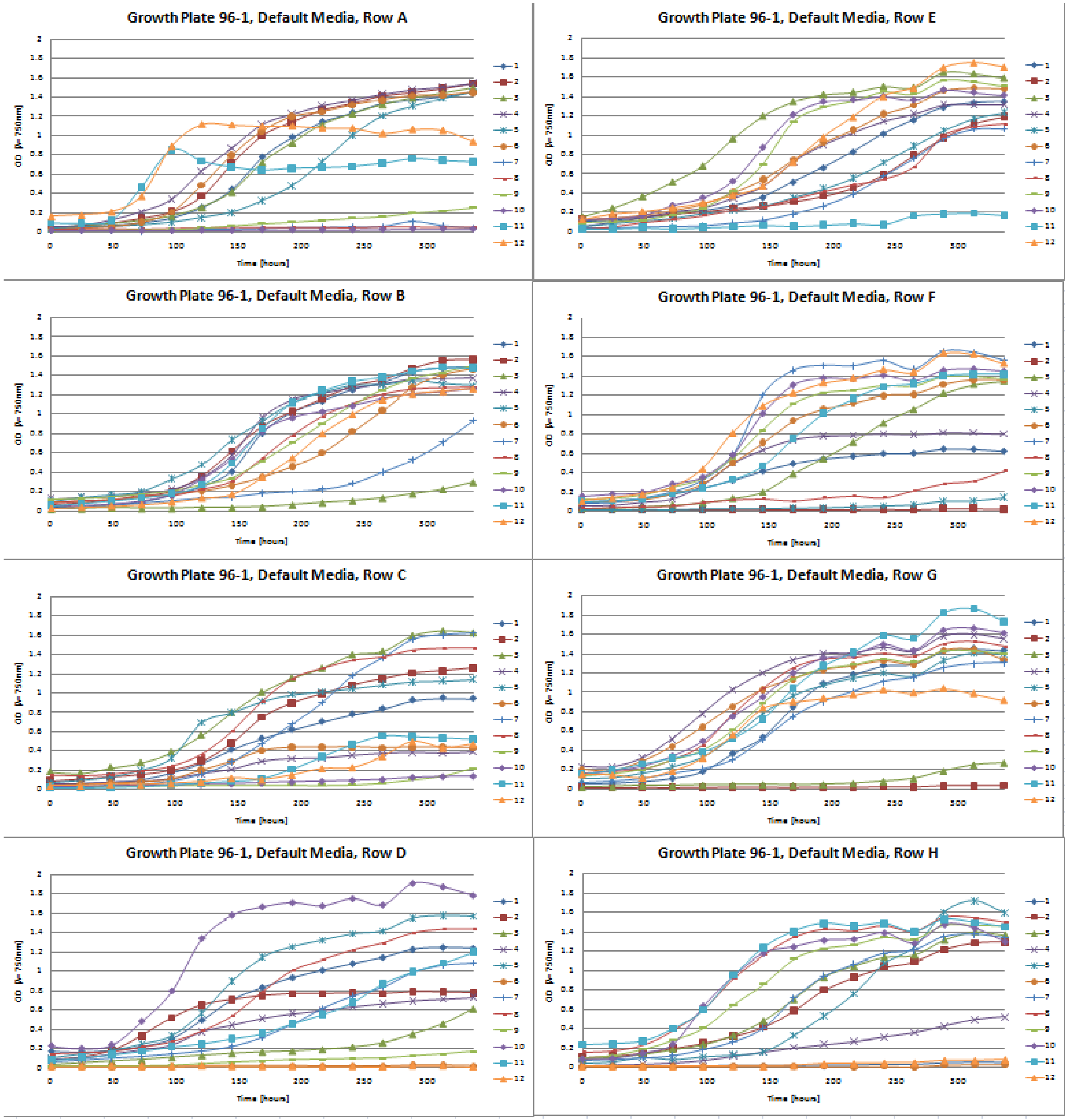




High Throughput Growth Screening

- Tracked growth of the entire culture collection in a 96 well plate format to get a quantitative picture of the growth of all strains over a 14 day period

- Goal: Identify strains that should be examined more closely



NREL Funded Algal Biofuels Projects

Laboratory Directed Research & Development (LDRD) Awards

"Development of a Comprehensive High-Throughput Technique for Assessing Lipid Production in Algae"

"Use of Digital Gene Expression (DGE): Tag Profiling for High Throughput Transcriptomics in Microbial Strains Involved in Advanced Biofuel Production"

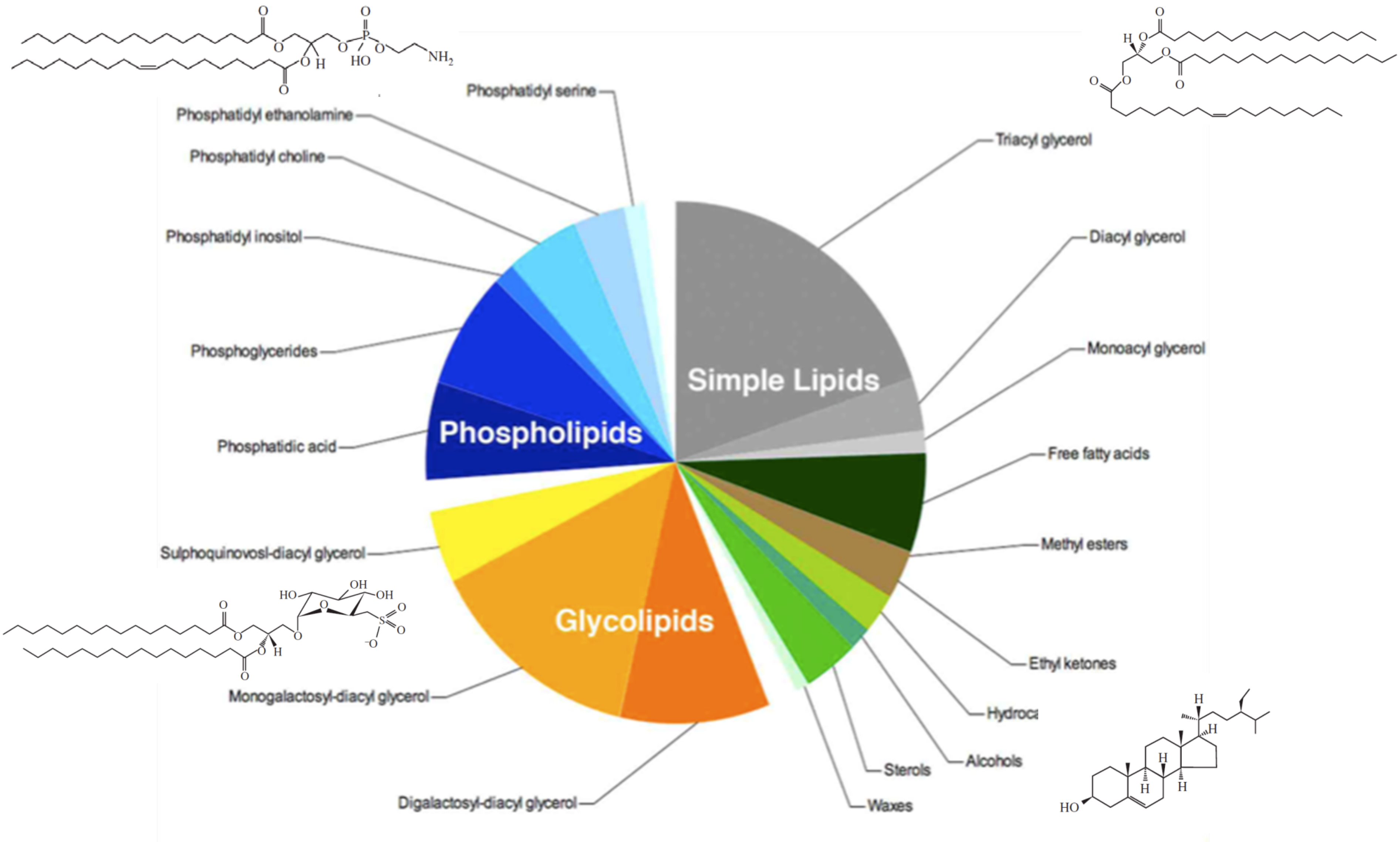
"Biodiesel from *Cyanobacteria*"

"Regulated Enzymatic Disruption of Algal Cell Walls as an Oil Extraction Technology"

"Identification of Novel Promoters in Green Algal Species"

"Development of Novel Cyanobacterial Biofuels"

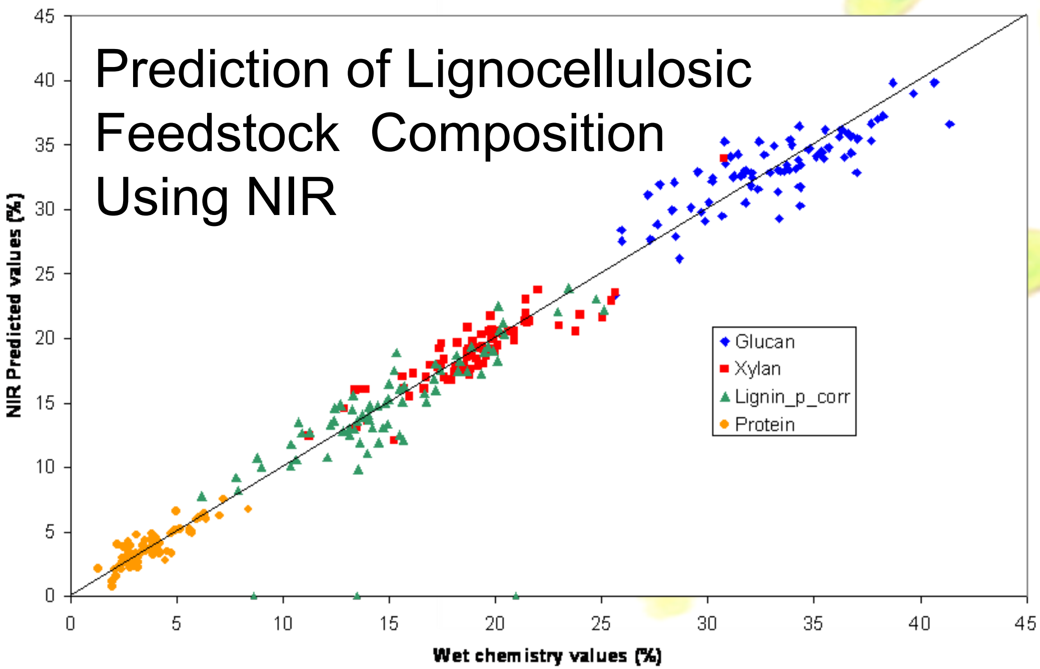
Algal Lipids



Courtesy of Peter Williams, Bangor University, UK

Characterization of microalgal biomass

1. Development of a high-throughput microalgae analytical platform
2. Chemometric correlation of IR spectra with microalgal lipids



Error varies with constituent, but for NREL models, well-predicted samples have typical uncertainties in glucan and xylan of ~2%

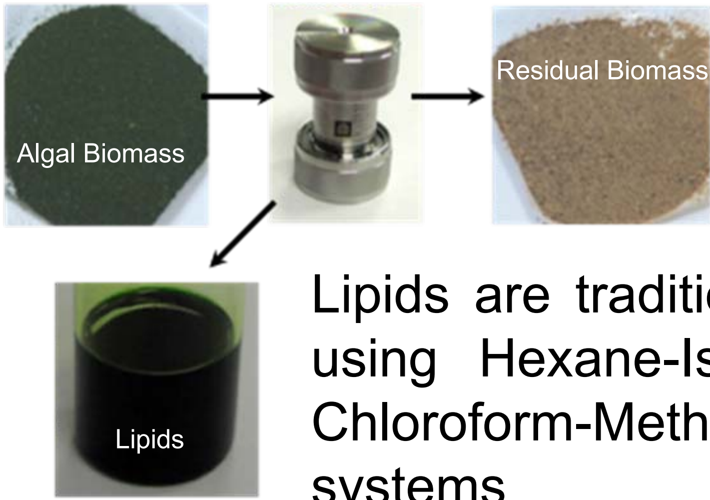
1. High-throughput analytical platform

- Lipid analysis is needed to assess the suitability of algal biomass as feedstock for biodiesel production
- Not all lipids are equal; e.g. phospholipids are less desirable due to a lower conversion efficiency of lipid to fuel
- High-throughput techniques would allow the screening of a large number of potential candidates for large-scale culturing

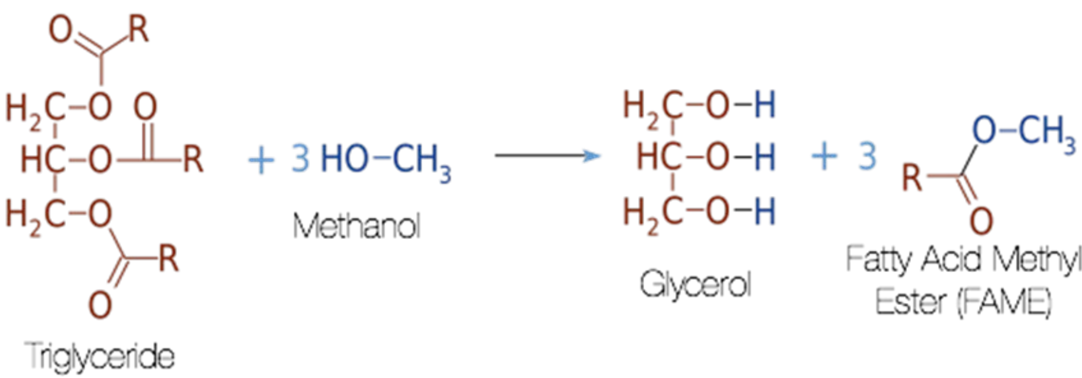
→

Courtesy of Ami Ben-Amotz, Seambiotic, Israel

Lipid extraction and *trans*-esterification



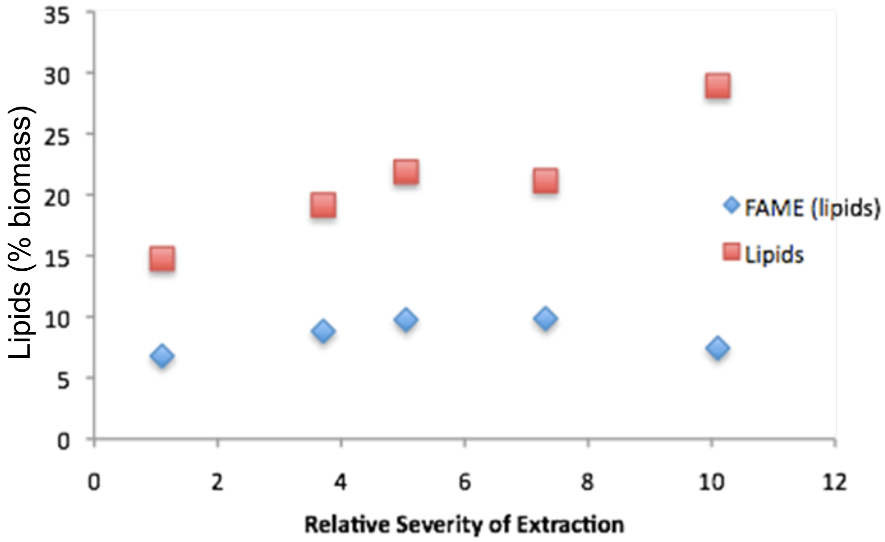
Lipids are traditionally extracted using Hexane-Isopropanol and Chloroform-Methanol as solvent systems

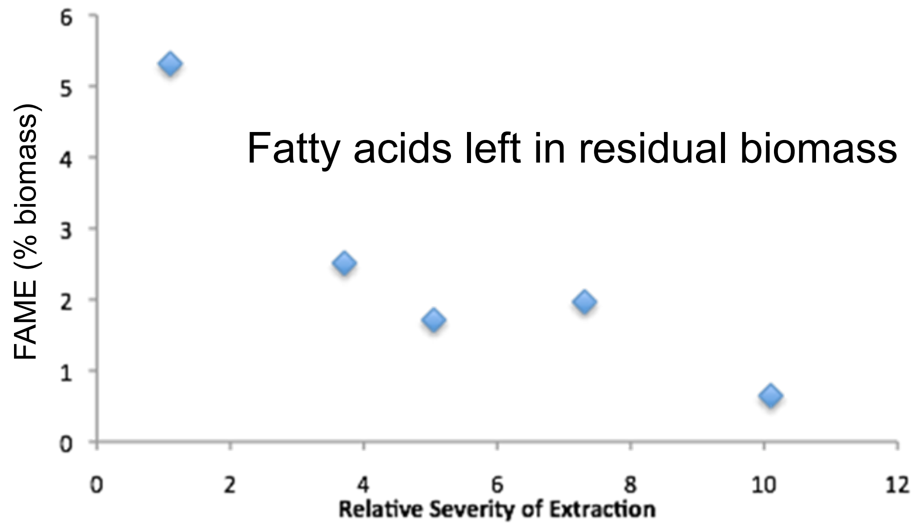


Fatty acid content in the lipid fraction are determined by acid catalyzed *trans*-esterification

Automated lipid extraction using the Accelerated Solvent Extractor (ASE 200, Dionex) can analyze 24 samples per run, using only 200 mg biomass per sample

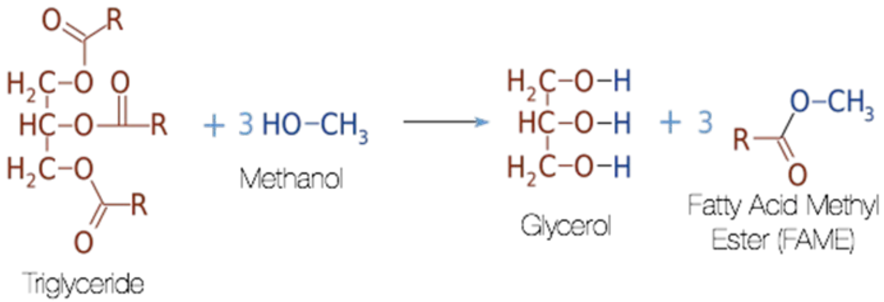
Solvent-based extraction inaccuracies



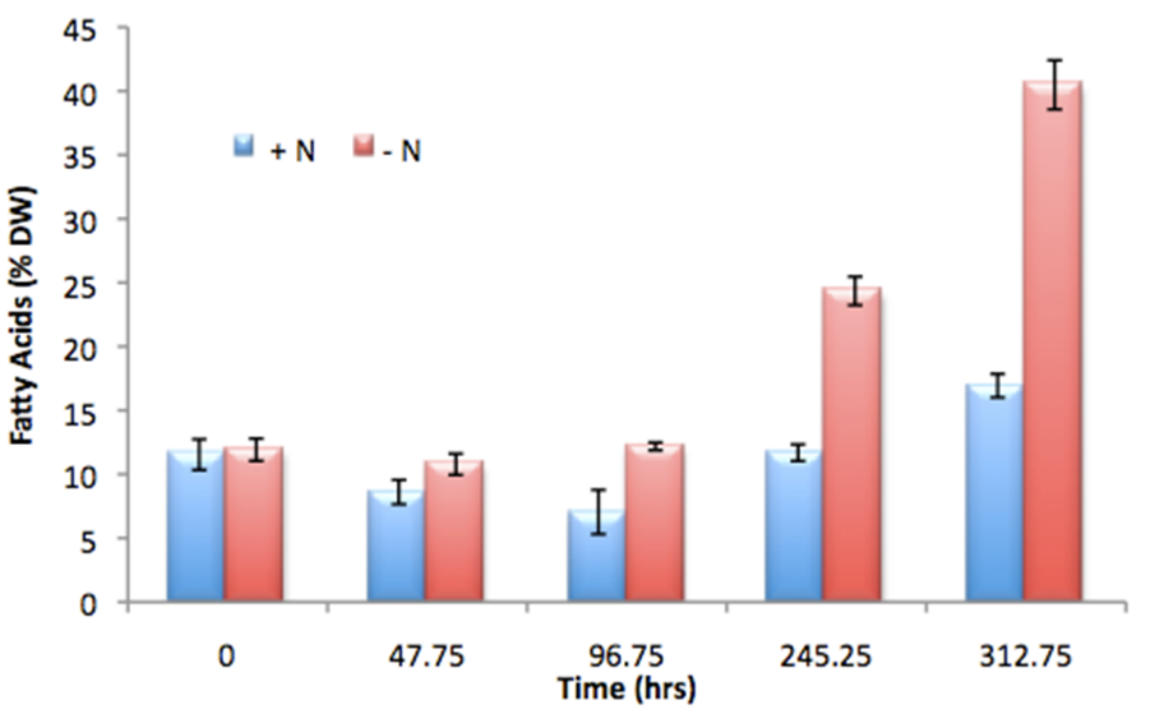


Variability in total extracted lipids and completeness of the extraction (based on severity of extraction conditions) using the solvent-based ASE system prompts the question for an alternative lipid quantification protocol for microalgae

Direct Biomass *Trans*-esterification

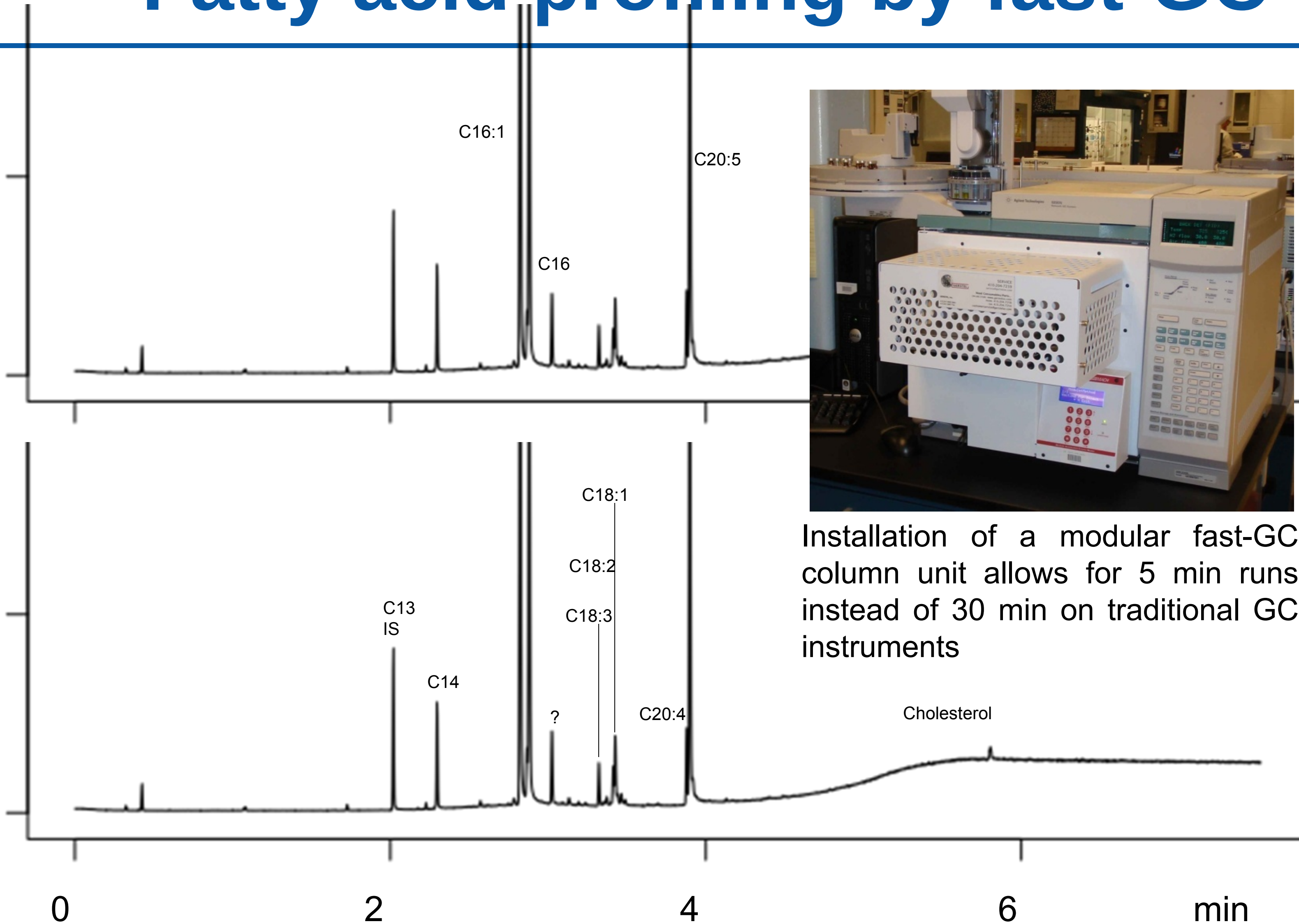


Fatty acid content in the biomass fraction are determined by acid catalyzed *trans*-esterification



Increase in total fatty acid content of *Chlorella vulgaris* strain under nitrogen starvation

Fatty acid profiling by fast-GC



Installation of a modular fast-GC column unit allows for 5 min runs instead of 30 min on traditional GC instruments

GC-FID FAME fingerprint of *Nannochloropsis* sp. lipids (HCl:MeOH)

2. IR spectroscopy for lipid quantification

- Spectroscopic techniques are being used routinely as an alternative for long laborious analytical chemical methods

- Chemical bonds of a molecule absorb energy in the IR region of the spectrum

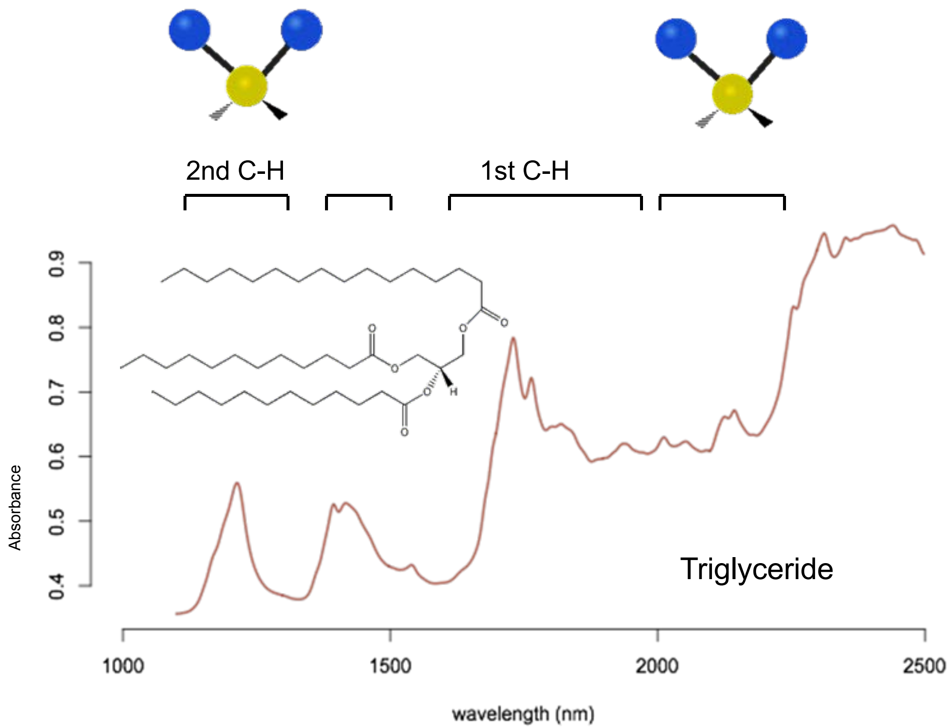
- Lipids have characteristic NIR spectra. Spectra contains overtones and combinations from stretching and bending of bonds in molecules.

- IR spectroscopy can distinguish between polar and neutral lipids

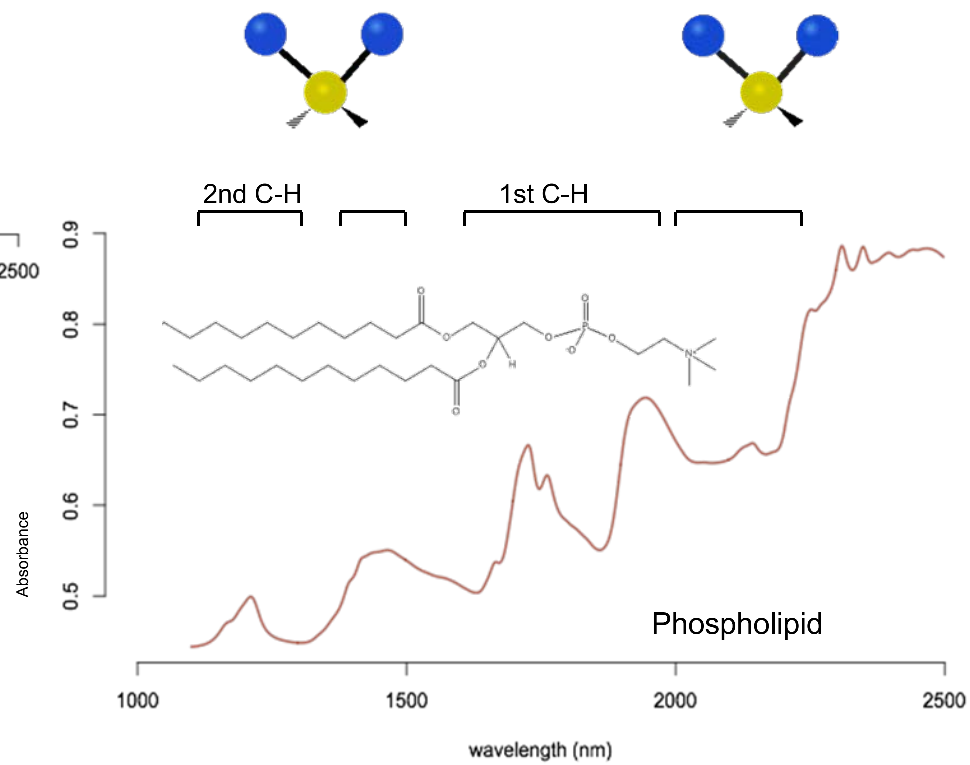
Time per sample:

Wet Chemical methods (ASE/HPLC/GC)	> 1 day
IR fingerprinting	< 1 min

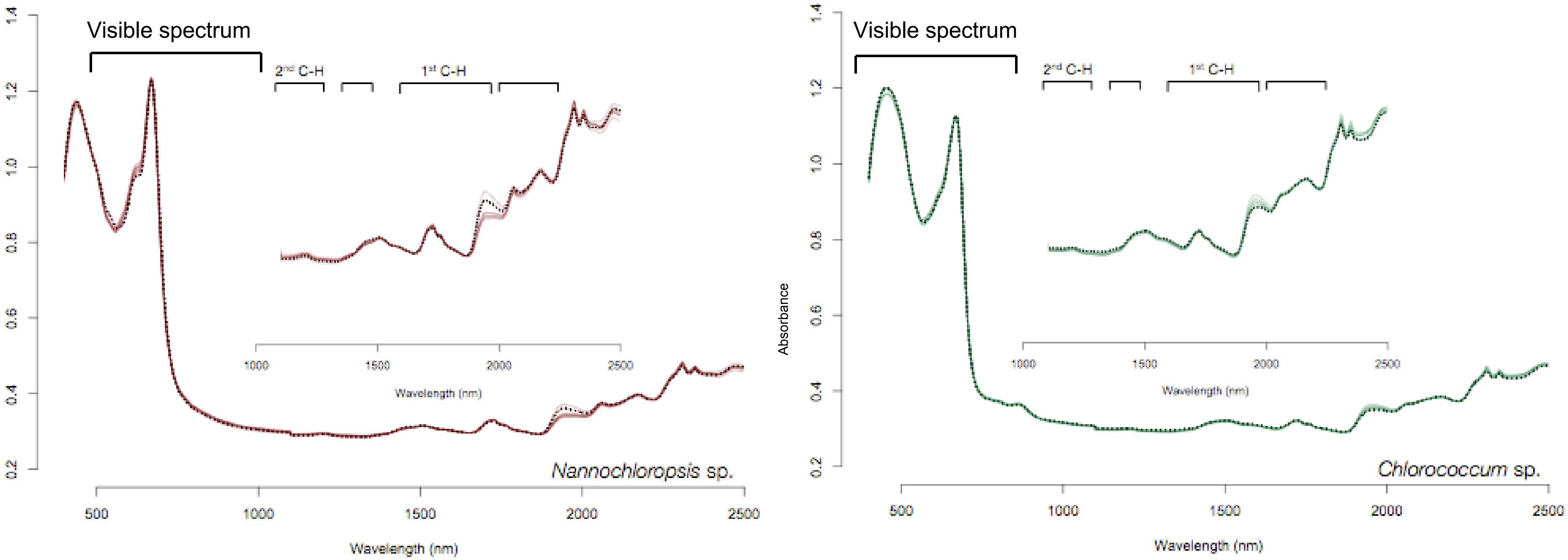
NIR fingerprinting of lipids



Both triglycerides (trilaurin) and phospholipids (phosphotidylcholine) have characteristic and distinct fingerprints in the NIR spectrum

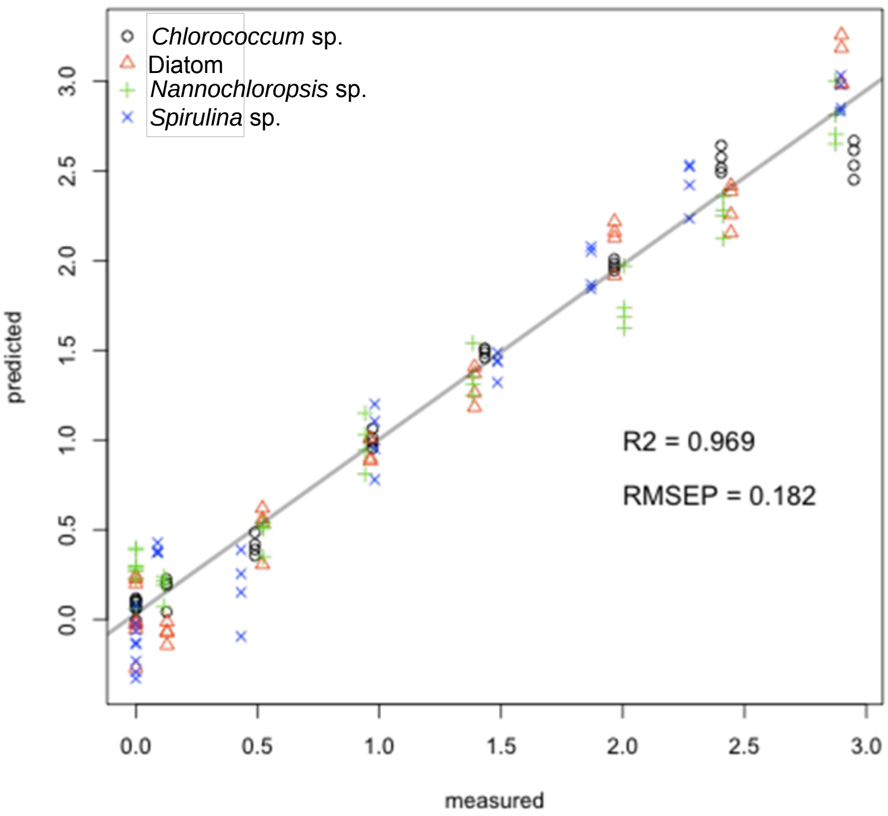


NIR fingerprinting of algal biomass

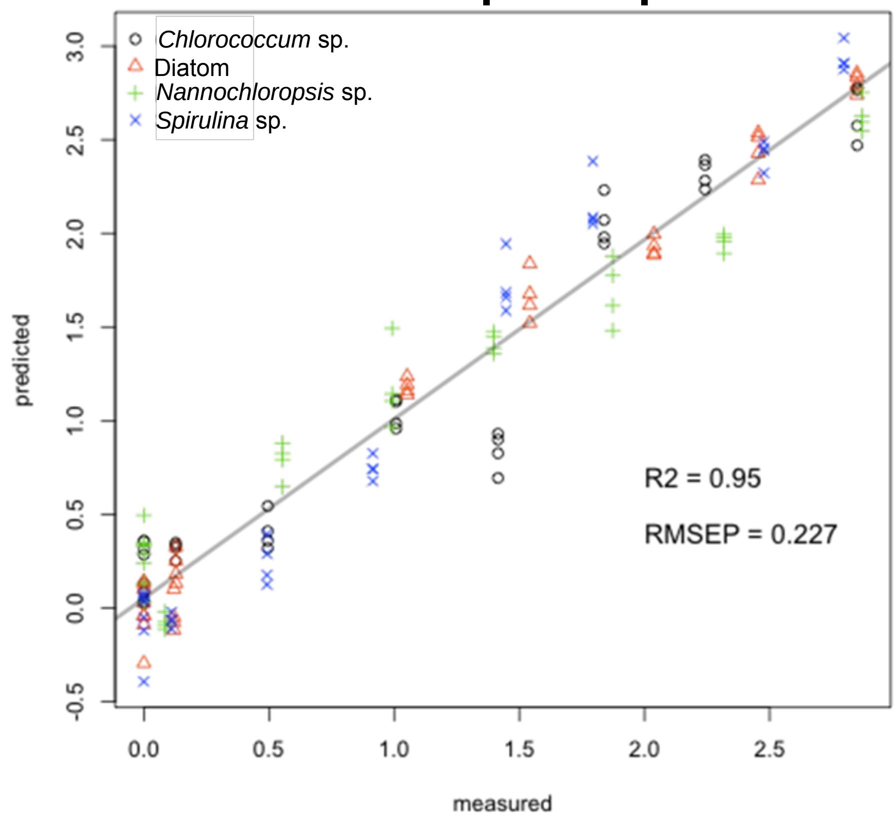


NIR Multivariate PLS Regression

Triglyceride



Phospholipid



Exogenous lipid spike content (measured) versus the predicted values by NIR spectra show a highly significant correlation (R2 > 0.94)

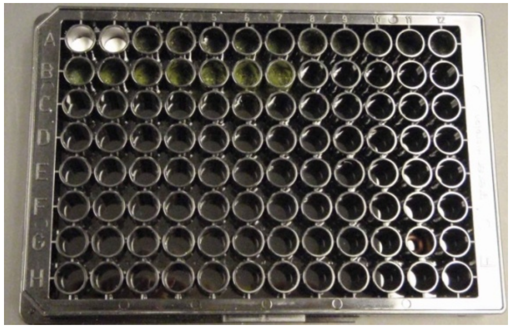
High-Throughput Algal Strain Screening

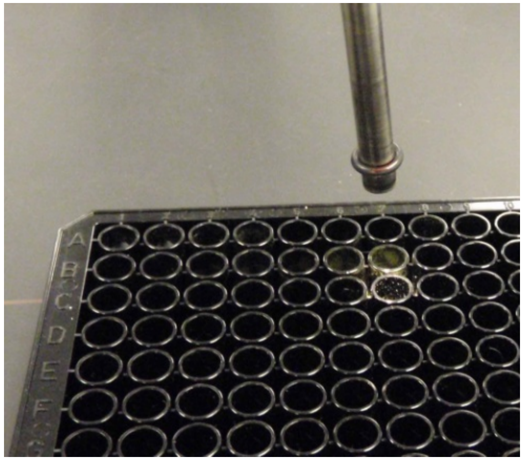
✓ Triglycerides and phospholipids have characteristic IR fingerprints

✓ Successful linear multivariate calibration models for single species and for multiple species of algae, based on the measured spike concentrations

✓ A combined multiple species model (NIR and FTIR) is robust in predicting the lipid content across species

✓ NIR models appear to perform better compared with FTIR models





Conclusions

- The potential of algal biofuels is significant
- Production of fuels from algae have been demonstrated; microalgae can be grown and harvested; lipids extracted and converted to transportation fuels
- Algal biofuels are not, however, currently economical
- Infrastructure does not exist for an algal biofuels industry
- The unanswered questions remaining at the end of the ASP remain the focus of intense R&D efforts.
- Many of the conclusions of the ASP have been reconsidered

Conclusions

- This time, the combined drivers of peak petroleum, energy security, sustainability, and climate change provide significant incentive to move beyond R&D into commercialization.
- A greater understanding of the underlying biological and engineering principles is necessary before a commercial scale-up is feasible.
- NREL is focusing its research efforts on all parts of the algal biofuels process value chain.

Algal Biology → Cultivation → Harvesting → Extraction → Fuel Production

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Milt Sommerfeld (ASU)
Joyce Yang (DOE)
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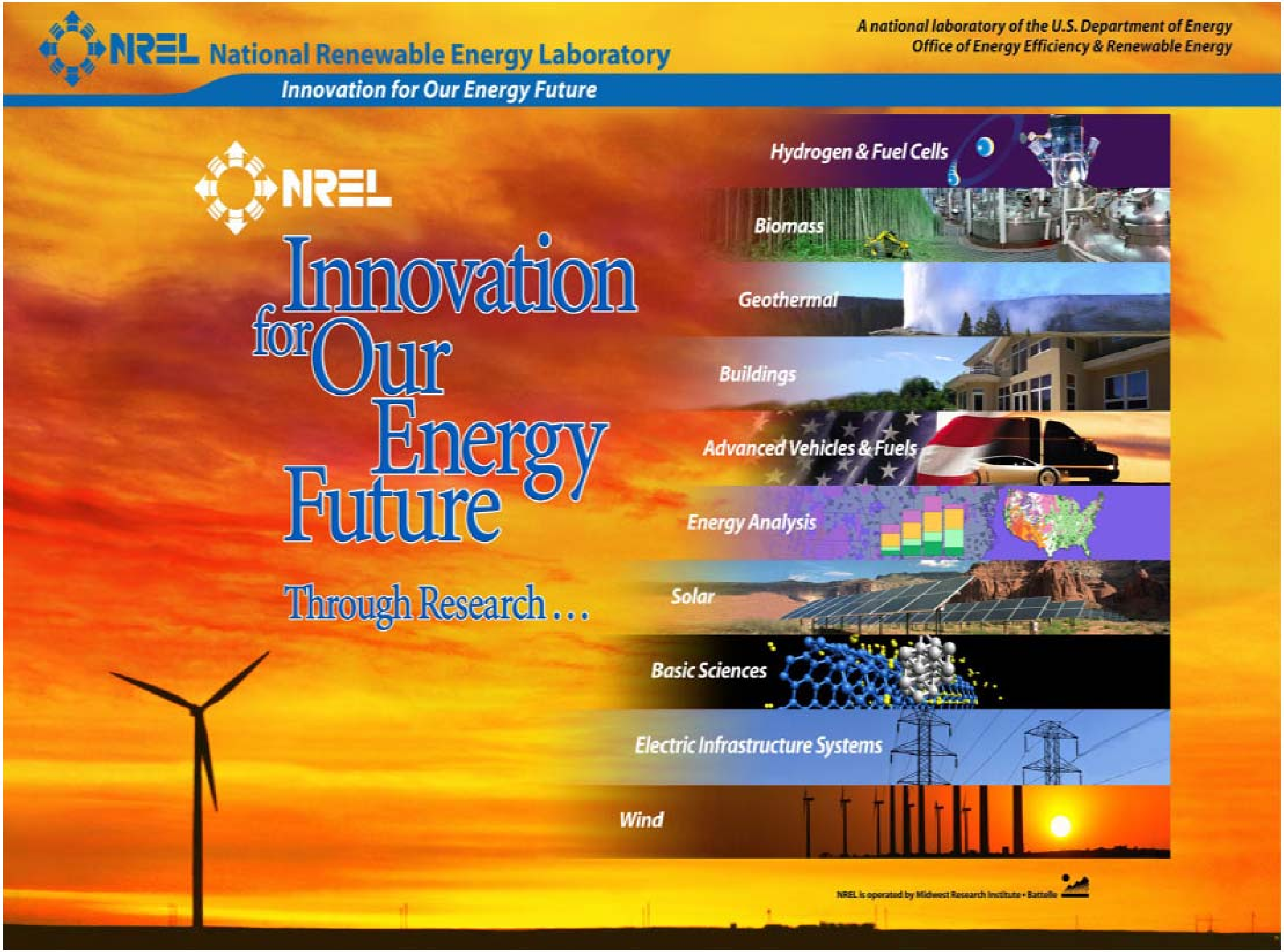
- C2B2
- IEA-Bioenergy
- EPA

NREL Algal biofuels research:
http://www.nrel.gov/biomass/proj_microalgae.html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