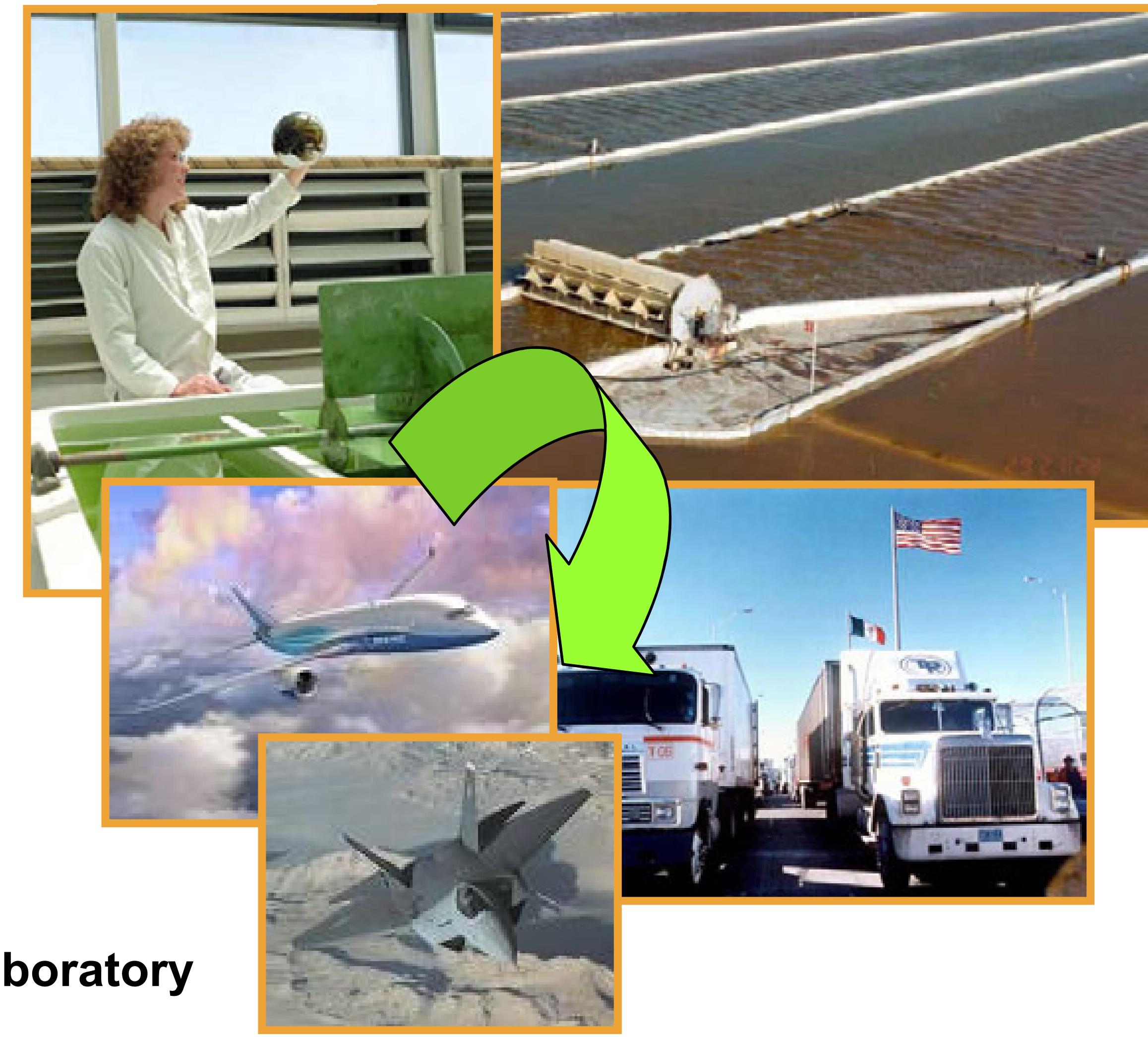
# The Potential for Biofuels from Algae



**Algae Biomass Summit**
**San Francisco, CA**
**November 15, 2007**

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**National Renewable Energy Laboratory**
**National Bioenergy Center**

NREL/PR-510-42414

# The Biodiesel Dilemma

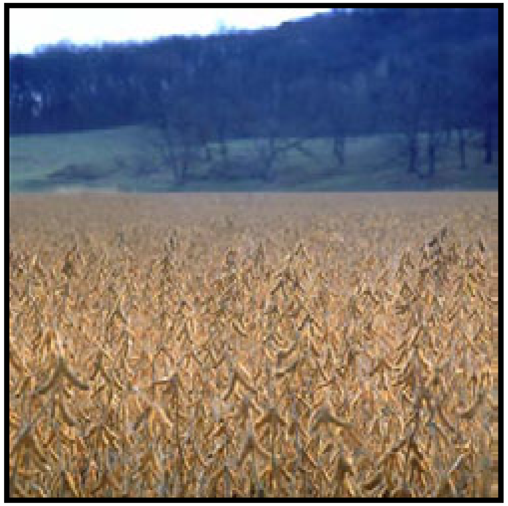
Triglycerides (TAGs) from current oilseed crops and waste oils cannot come close to meeting U.S. diesel demand (60+ billion gal/yr)

- The entire U.S. soybean crop could provide approximately 2.5 billion gallons per year.
- Estimated world-wide production of biodiesel would only yield 13 billion gallons per year.
- This much agricultural productivity cannot possibly be diverted from the food supply.
- TAGs also represent an attractive feedstock for biopetrochemicals meaning less would be available for transportation fuel.

→ ***Alternative sources of TAGs are needed!***

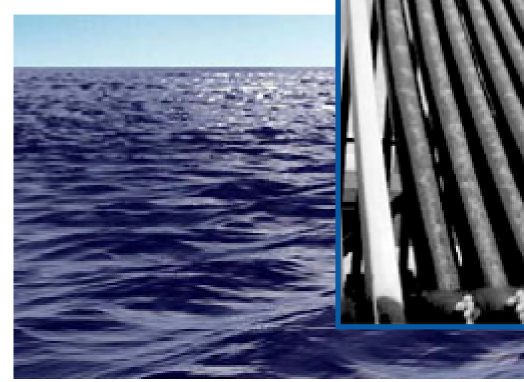
# Why Algae?

- Much greater productivity than their terrestrial cousins
- Non-food resource
- Use otherwise non-productive land
- Can utilize saline water
- Can utilize waste $CO_2$ streams
- Can be used in conjunction with waste water treatment
- An algal biorefinery could produce oils, protein, and carbohydrates



# Microalgal Cultivation

- Inexpensive culture systems using shallow (10 cm deep) ponds stirred with paddle wheels in areas of high solar insolation
- More intensive cultivation systems becoming available
- Algal cultivation can be 50x more productive than traditional crops
- Potential for culture in areas not used for crop production
    - Desert land
    - Ocean



# …Using Waste $CO_2$ from Coal-fired Power Plants

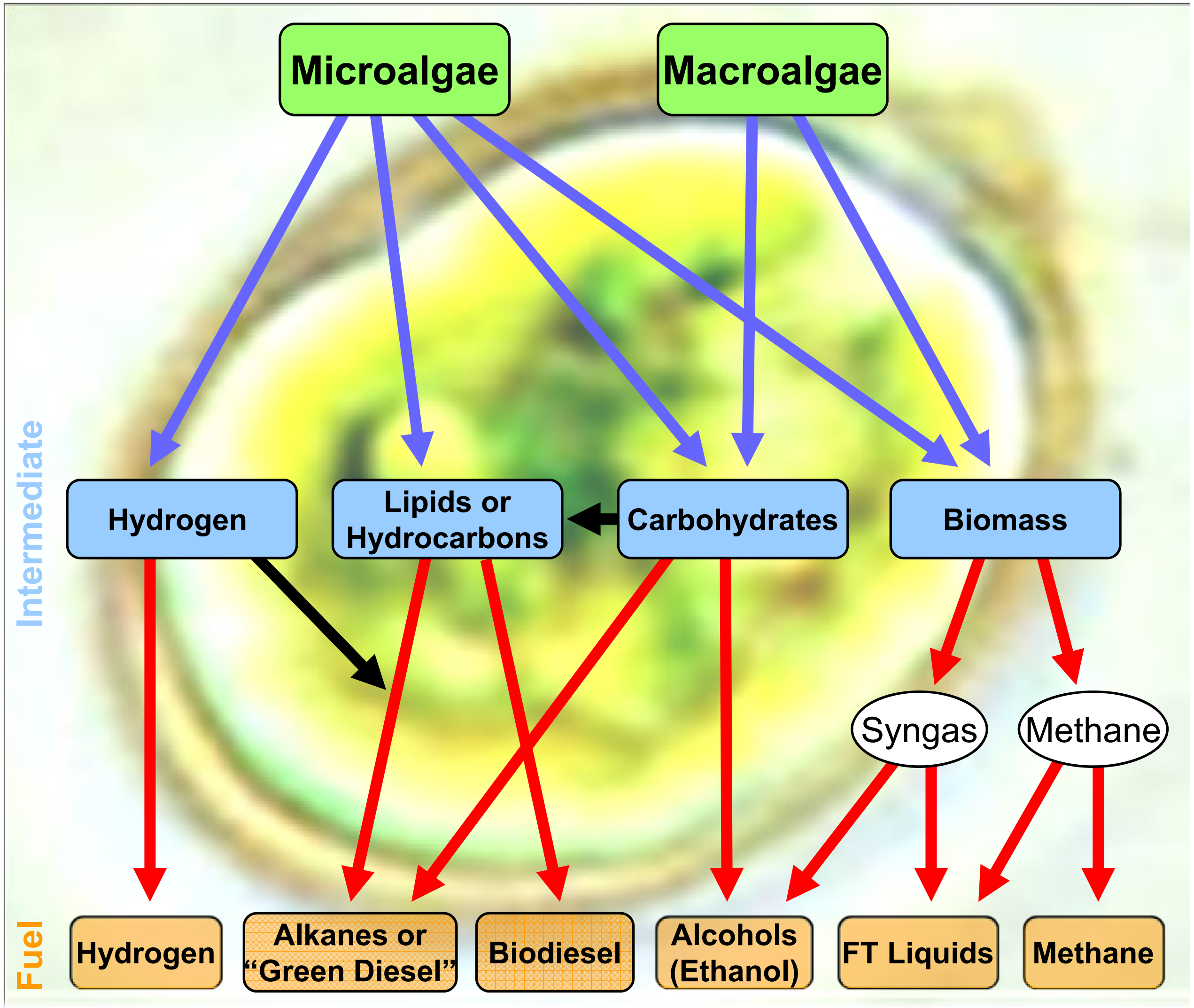
- Carbon dioxide rich streams from combustion of fossil fuels or other industrial processes ideal for algae production
- Double benefit:  provide food for algae, and remediate waste stream (recycling of fossil $CO_2$)
- Carbon credits may become economic driver

# Comparing Potential Oil Yields

| Crop | Oil Yield Gallons/acre |
|---|---|
| Corn | 18 |
| Cotton | 35 |
| Soybean | 48 |
| Mustard seed | 61 |
| Sunflower | 102 |
| Rapeseed/Canola | 127 |
| Jatropha | 202 |
| Oil palm | 635 |
| Algae (10 $g/m^2/day$ at 15% TAG) | 1,200 |
| Algae (50 $g/m^2/day$ at 50% TAG) | 10,000 |

Fatty acid composition of algal oils suitable for preparation of biodiesel

# Algae: Route to Numerous BioEnergy Sources



# What Are the Requirements?

Production of algal oil requires:

- Land
- Sunlight
- Water
- $CO_2$
- Macro- and micronutrients

# Resource Requirement: Land
## (Basis: algal oil needed for 60 billion gal/yr biodiesel)

<u>10@15 Productivity</u>
(~1,200 gal/acre-yr)

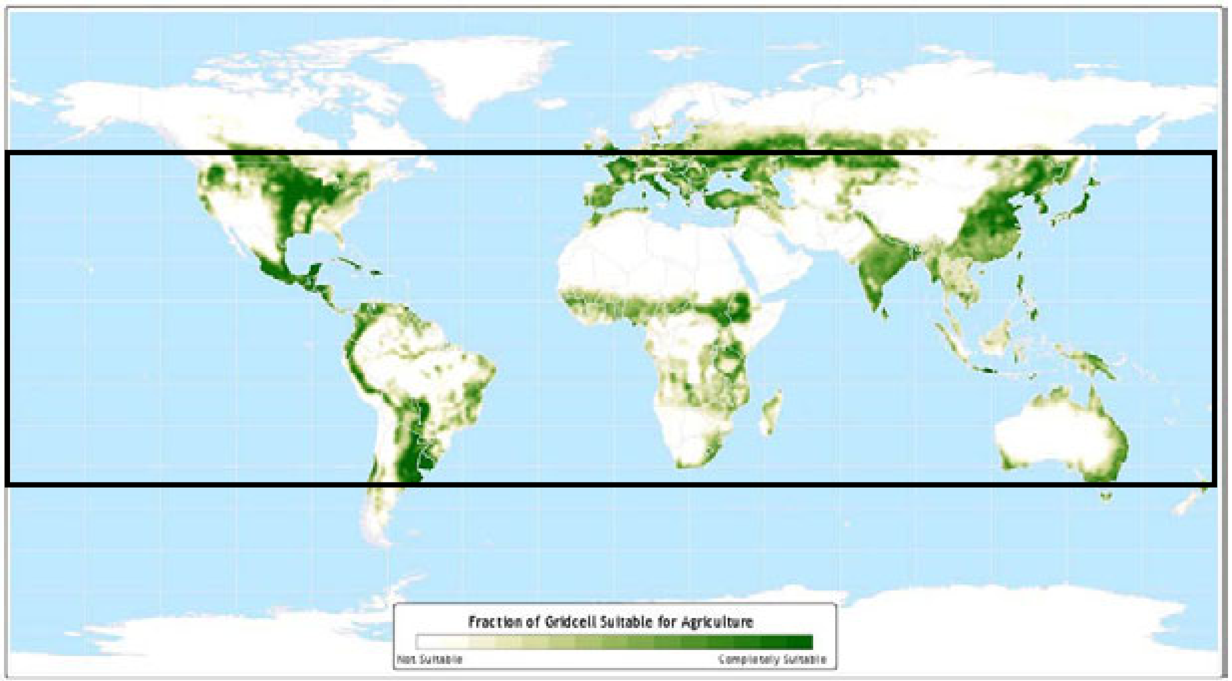
48,000,000 acres


- Compare to 74 million acres used for 2005 U.S. soybean crop
- Using land not currently used for crops

<u>50@50 Productivity</u>
(~10,000 gal/acre-yr)

6,000,000 acres

# Vast Areas of the Globe Are Not Suitable for High Levels of Terrestrial Agriculture




Data taken from: Ramankutty, N., et al. The global distribution of cultivable lands. Submitted to Global Ecology and Biogeography, March 2001.

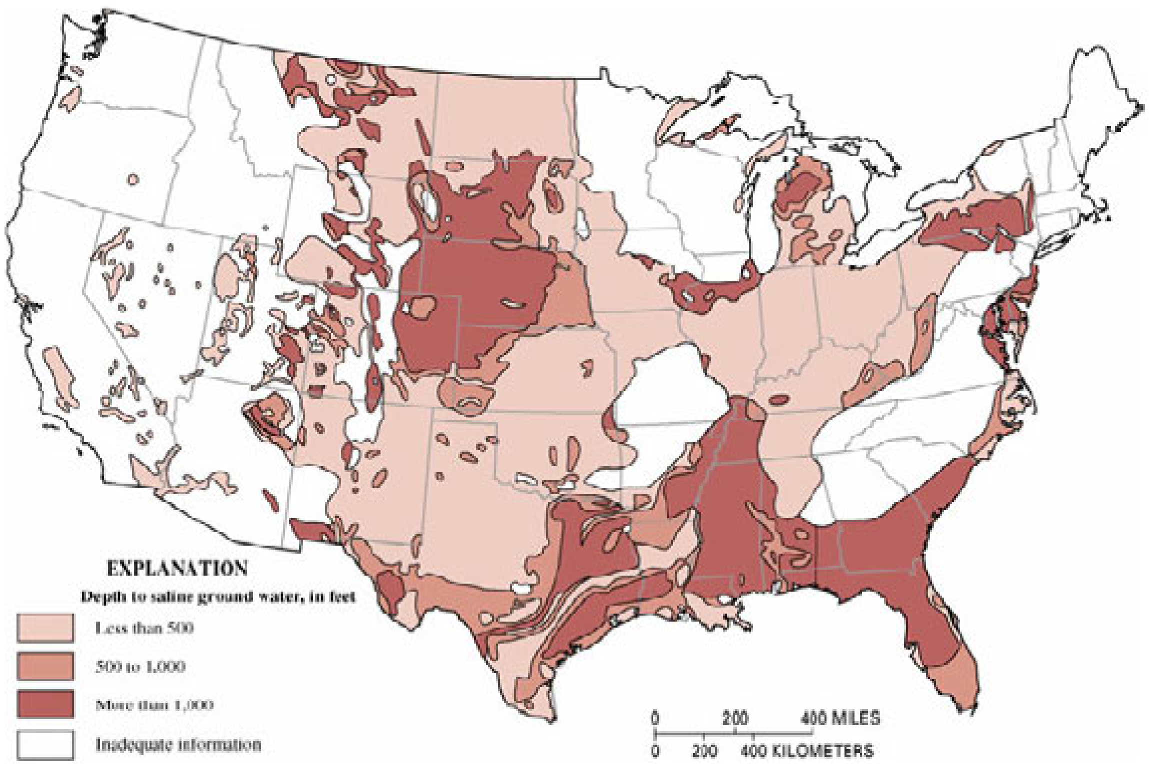
CRU 0.5 Degree Dataset (New, et al.)

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

But could be used for algal culture.

# Resource Requirement: Water

Saline aquifers in the U.S.




USGS

Feth and others, 1965

- Water with few competing uses
- Water resources show many areas of intersection with cheap land and $CO_2$ sources
- "Produced water" from oil wells potential source
- Seawater available in many parts of the world
- Identify ideal sites with more recent information

# Resource Requirement: $CO_2$ and Water
## (Basis: algal oil needed for 60 billion gal/yr biodiesel)

| | 10@15 Productivity | 50@50 Productivity |
|---|---|---|
| **$CO_2$** | | |
| ▪ Usage (ton/year) | 1.4 billion | 0.9 billion |
| ▪ % of US Power Plant Emissions | 56% | 36% |
| **Water** | | |
| ▪ Usage (trillion gallons/yr)* | 120 | 16 |

*Compare to ~22 trillion gal/yr saline water extracted in 2000 in U.S. (primarily for power plant cooling) (USGS), and to >4000 trillion gal/yr of water used to irrigate U.S. corn crop (USDA).

# What is the Potential?

- Overall potential is enormous
  - Scenarios for producing substantial amount of U.S. diesel from microalgae are not unrealistic
  - But would require a major dedicated effort
- Significant R&D is required to optimize yields in order to realize realistic scenarios of land and water use

# NREL's Aquatic Species Program

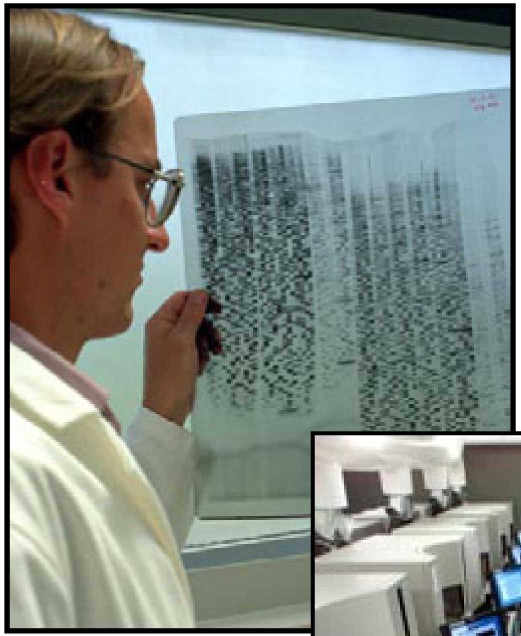
- Research project at NREL from 1978 to 1996
- Project cut to focus on ethanol
- 3000 strains of micro-algae collected and screened
- 1,000 $m^2$ outdoor test facility (Roswell, NM) – 10g/$m^2$/day biomass overall, 50g/$m^2$/day peak
- Process for lipid extraction and conversion to biodiesel
- Genetic manipulation of algae in last few years of project
- Analysis provides stalking horse for all efforts to commercialize technology

See the close-out report at:

http://govdocs.aquake.org/cgi/reprint/2004/915/9150010.pdf

# Technology Future – What's Changed Since 1996?

- Oil prices at record highs
- Wholesale diesel $0.60 -> $3+
- Increased interest in $CO_2$ capture, carbon trading, etc.
- Greater emphasis on energy security
- New photobioreactor designs, advances in material science
- Explosion in biotechnology
  - Advances in metabolic engineering
  - Genomics, proteomics, metabolomics, bioinformatics, etc.



DOE Joint Genome Institute

# Where are the hurdles?

**Algal Cultivation**

Photobioreactor design
Capital and operating costs
Temperature control
Saline water chemistries
Makeup water (evaporation)
$CO_2$ availability and transport
Nutrient requirements
Starting species
Growth rate
Oil content & FA profile
Robustness
Resistance to invasion
Biofouling in closed systems
Nutrient induction requirement
Environmental impact, containment

**Oil (Lipid) Recovery**

De-watering methods
Lipid extraction
Purification
Costs, energy input
Environmental issues
Value from residual biomass

**Fuel Production**

Process optimization
Fatty acid profiles
Costs and LCA
Fuel characteristics
- Energy density
- Carbon numbers
- Cloud point
- Stability
- Consistency

Additives required
Engine testing
ASTM standard

# Critical R&D Elements

## 1. Algal strains for continuous high-level oil production

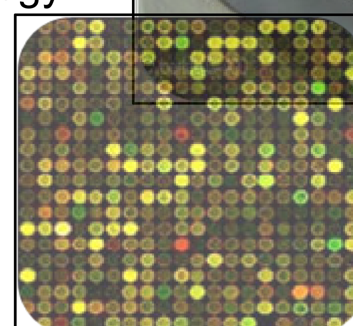
- Selecting the right starting species
- Mutation and selection/screening
- Genomics approaches to understand and control lipid induction

## 2. Cultivation facility design and operation

- Strain characteristics required for cultivation facility
- Harvesting and extraction technology
- Use of remaining algae components

## 3. Fuel production

- Selection of preferred triglycerides and conversion technology
- Optimize catalyst and operating conditions
- Develop any required pre/post processing



**<u>Goal:</u> Produce premium quality fuel from algae at a cost competitive with petrodiesel.**

# The Right Hand Giveth But the Left Hand Taketh Away

- Highly engineered systems can provide better yields but at higher cost
- Saline aquifers will provide cheap source of water but how will evaporated water be replaced and how will changing water chemistry affect yields?
- $CO_2$ from coal plants provide economic credits and necessary nutrient but also $NO_x$ and Hg
- Engineered organism offers promise of higher yields but may have difficulty competing and must face containment issues and regulation
- Underutilized lands can be developed but the development will only be suitable for algal farming
- Inexpensive resources and byproduct credit can look good on paper but flawed economic analysis will lead to failure

# NREL Commitment to Developing Algae Biofuels Technology

- Chevron CRADA
  - Chevron and National Renewable Energy Laboratory to Collaborate on Research to Produce Transportation Fuels using Algae
- NREL Programs
  - NREL Strategic Initiative
  - Infrastructure Development
  - Internally Funded Research Project: Development of a Comprehensive High-Throughput Technique for Assessing Lipid Production in Algae
- DOD
  - Support of AFOSR Algal Biofuels Program
- Colorado Center for Biorefining and Biofuels (C2B2) Research Consortium
  - Establishment of a Bioenergy-Focused Microalgae Strain Collection Using Rapid, High-Throughput Methodologies

# Government Agencies Supporting Algae Biofuel Research

- Department of Defense
  - DARPA*
  - AFOSR
- Department of Energy
  - NREL*
  - Sandia*
  - Los Alamos
  - PNNL*

# Algae Biofuel Companies

| | |
|---|---|
| A2BE Carbon Capture* | IGV |
| Algae Biofuels | Imperium Renewables* |
| Algae Link | Infinuel Biodiesel |
| Aquaflow Bionomic | Inventure Chemical* |
| Aurora BioFuels Inc.* | Kent SeaTech Corp.* |
| Bodega Algae* | Kwikpower |
| Community Fuels* | LiveFuels Inc.* |
| Diversified Energy* | OriginOil |
| Energy Farms | PetroAlgae (XL Tech Group) |
| Enhanced Biofuels & Technologies | SeaAg Inc* |
| General Atomics | Solazyme, Inc.* |
| Global Green Solutions* | Solix Biofuels Inc.* |
| Green Star | Texas Clean Fuels |
| Greenfuel | Trident Exploration/Menova |
| GreenShift | Valcent Products |
| GS Cleantech | XL Renewables* |
| HR Biofuel* | |

National Renewable Energy Laboratory

# Summary

- Microalgae are unicellular biofactories that can make oil (TAGs) from sunlight and $CO_2$
- Algal TAGs can be used to make biodiesel or other refinery feedstocks
- Algae represent new feedstock for biofuels – one that doesn't compete with food/feed/ethanol
- Potential to supply significant percentage of U.S. fuel demand
- The NREL Aquatic Species Program provides a unique knowledge and tool base
- There are many important issues to be addressed and fundamental research is needed
- Rapid growth in interest in algal oils technologies including renewed efforts at NREL