National Renewable Energy Laboratory

The Potential for Biofuels from Algae

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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

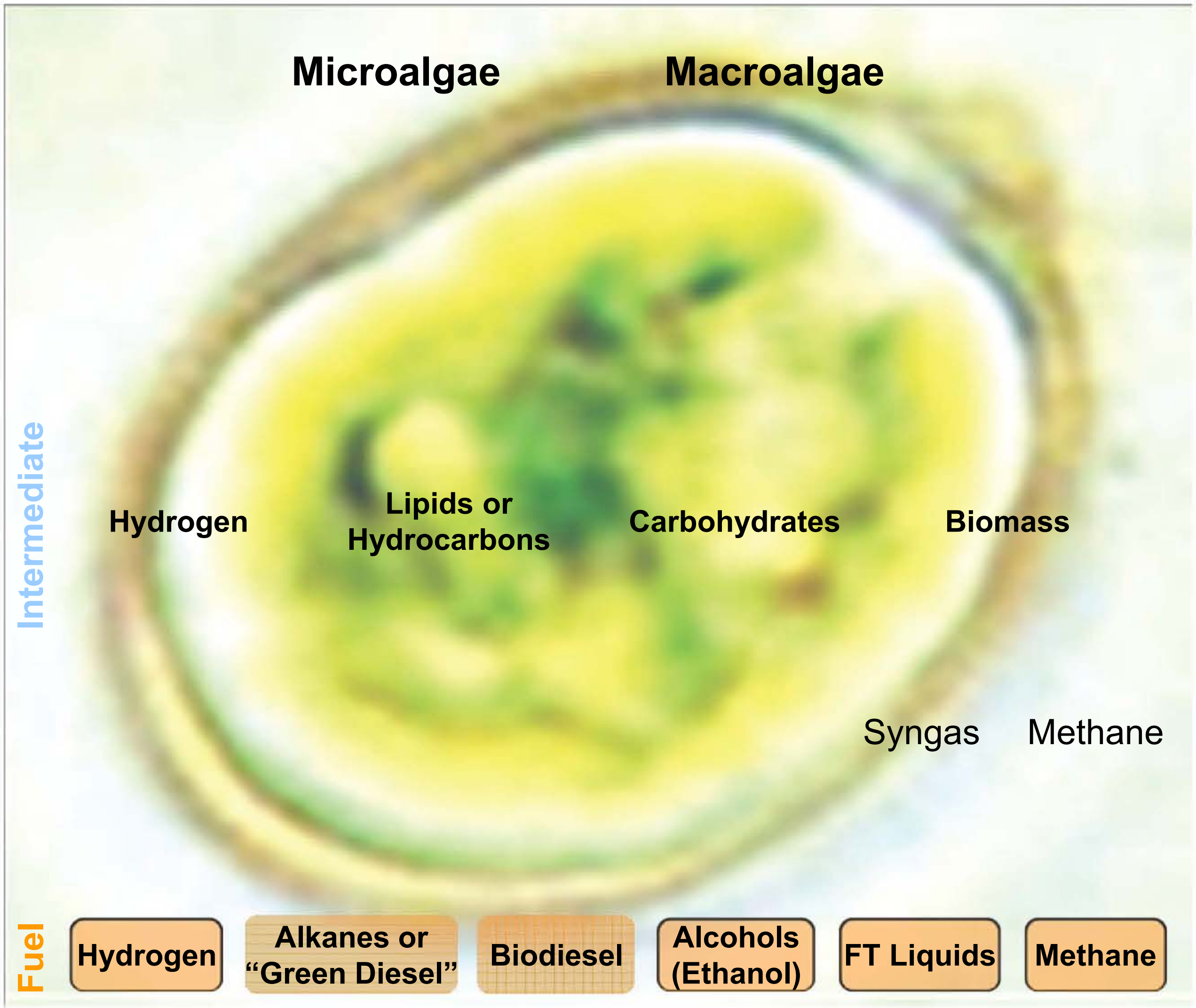
- Carbon dioxide rich streams from combustion of fossil fuels or other industrial processes ideal for algae production
- Double benefit: provide food for algae, and remediate waste stream (recycling of fossil CO_2)
- Carbon credits may become economic driver

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)

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

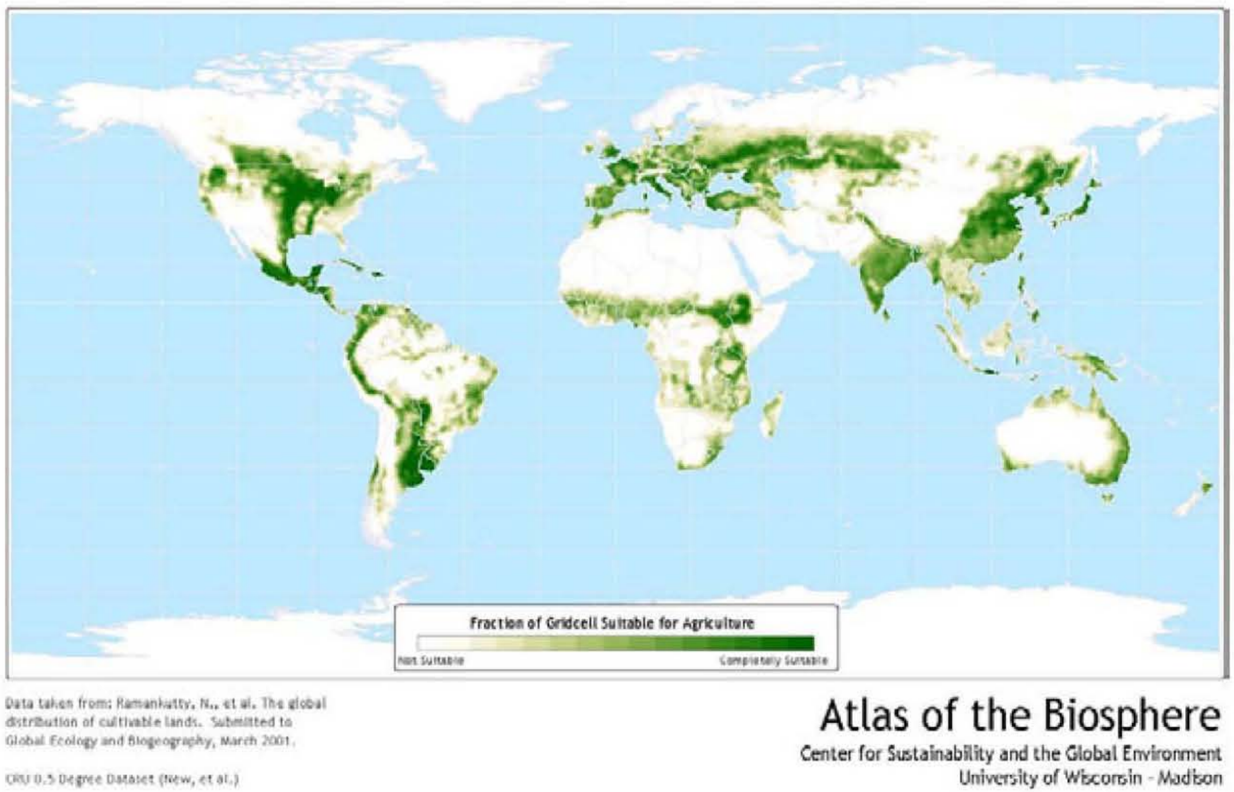
48,000,000 acres

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

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

6,000,000 acres

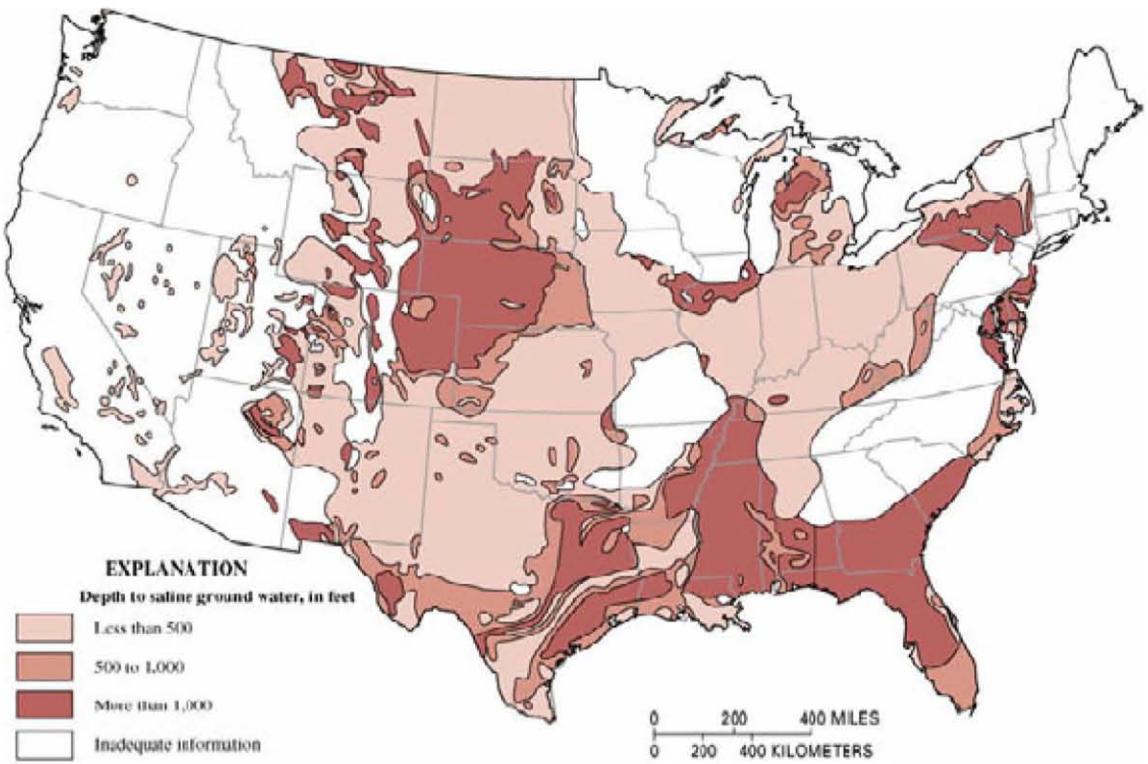
Vast Areas of the Globe Are Not Suitable for High Levels of Terrestrial Agriculture



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

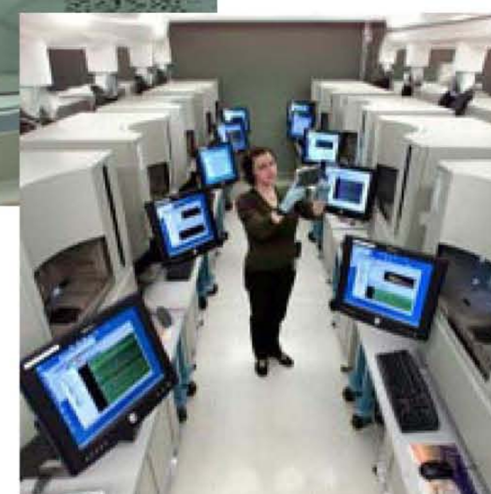
- Research project at NREL from 1978 to 1996
- Project cut to focus on ethanol
- 3000 strains of micro-algae collected and screened
- 1,000 m^2 outdoor test facility (Roswell, NM) – 10g/m^2/day biomass overall, 50g/m^2/day peak
- Process for lipid extraction and conversion to biodiesel
- Genetic manipulation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

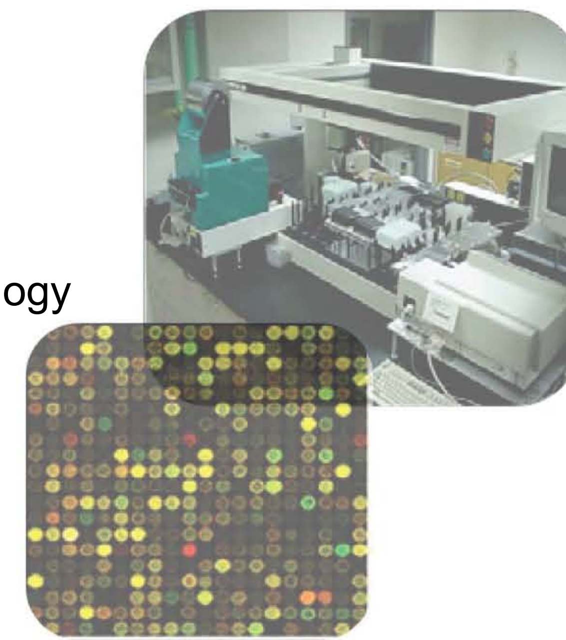
- Process optimization
- Fatty acid profiles
- Costs and LCA
- Fuel characteristics
  - Energy density
  - Carbon numbers
  - Cloud point
  - Stability
  - Consistency
- Additives required
- Engine testing
- ASTM standard

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



Goal: 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*
Algae Biofuels
Algae Link
Aquaflow Bionomic
Aurora BioFuels Inc.*
Bodega Algae*
Community Fuels*
Diversified Energy*
Energy Farms
Enhanced Biofuels & Technologies
General Atomics
Global Green Solutions*
Green Star
Greenfuel
GreenShift
GS Cleantech
HR Biofuel*

IGV
Imperium Renewables*
Infinuel Biodiesel
Inventure Chemical*
Kent SeaTech Corp.*
Kwikpower
LiveFuels Inc.*
OriginOil
PetroAlgae (XL Tech Group)
SeaAg Inc*
Solazyme, Inc.*
Solix Biofuels Inc.*
Texas Clean Fuels
Trident Exploration/Menova
Valcent Products
XL Renewables*

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