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Sustainable Development of Algal Biofuels

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http://www.ornl.gov/sci/ees/cbes/

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Acknowledgments

- Several slides taken or modified from those presented in briefings to DOE and in a public webinar by Jennie Hunter-Cevera and Mark Jones of the NRC Committee on Sustainable Development of Algal Biofuels
- Several slides taken or modified from sustainability presentations by Virginia Dale
- Funding for my participation on NRC committee provided by Oak Ridge National Laboratory

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Outline

- NRC Report--Sustainable Development for Algal Biofuels
- New Project: Sustainable Development of Algae for Biofuels
  - Sustainability Indicators (Efroymson and Dale)
  - Resource Analysis (Langholtz and Eaton)
- Other Activities at ORNL

NRC Committee Members

- **Jennie C. Hunter Cevera** (*Chair*)—Biotechnology
- **Sammy Boussiba**—Algae cultivation
- **Joel L Cuello**—Photobioreactors
- **Clifford S. Duke**—Ecology
- **Rebecca Efroymson**—Risk assessment
- **Susan Golden[1]**—Cyanobacteria genetics
- **Susan Holmgren**—Technology commercialization
- **Donald L. Johnson[2]**—Chemical engineering
- **Mark E. Jones**—Processing
- **Val H. Smith**—Algal ecophysiology
- **Cai Steger**—Natural resources
- **Gregory N. Stephanopoulos[2]**—Metabolic engineering
- **Larry P. Walker**—Bioengineering
- **Eric Williams**—Life-cycle assessments
- **Paul V. Zimba**—Marine biology

[1] Member of the National Academy of Sciences
[2] Member of the National Academy of Engineering

Statement of Task

- Identify and anticipate potential sustainability concerns associated with a selected number of pathways for large-scale deployment of algal biofuels
- Discuss potential mitigation strategies
- Suggest indicators and metrics of sustainability and data gaps related to impacts
- Identify indicators most critical to address or those that have greatest potential for improvement through DOE intervention
- Suggest preferred cost-benefit analyses

Goals for Sustainable Development

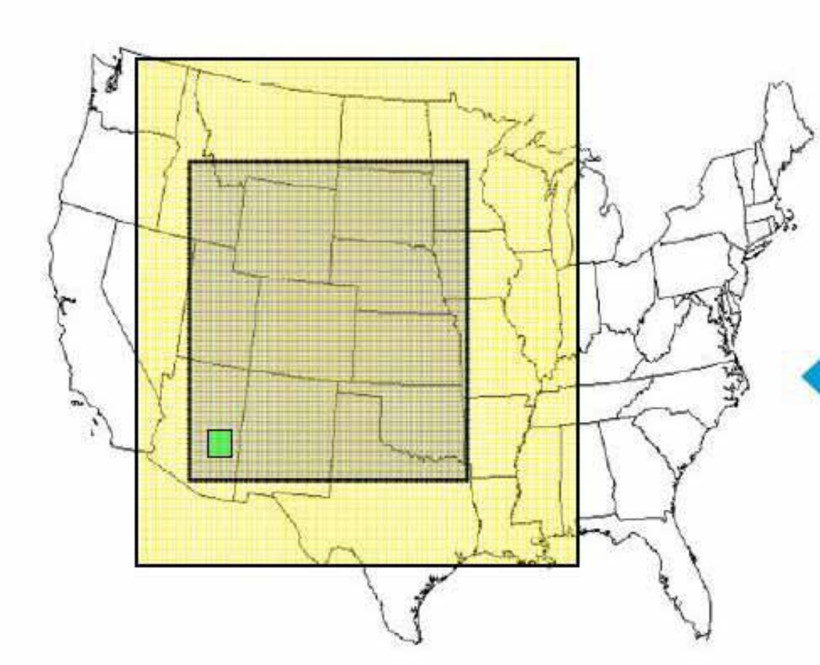
- Contribute to energy security by providing domestically sourced fuels
- Maintain and enhance the natural resource base and environmental quality
- Produce fuel that is economically viable[1]
- Enhance the quality of life for society as a whole

[1]This report does not assess the economics or costs of algal biofuels, as specified in the statement of task. "Public data on the economics of algal biofuel production are sparse. Therefore, it is premature for the committee to conduct generalized economic analyses of algal biofuels."

Advantages of algae as biofuel

- Can use sunlight more efficiently than terrestrial plants
- Can double biomass in less than a day
- Can accumulate lipids up to 50% of cell dry weight
- Can utilize a wide variety of water sources and nonarable lands
- Potential to recycle CO_2 and nutrients from waste streams

- Existing large-scale production for
  - Health food (*Chlorella* and *Spirulina*)
  - Beta-carotene (*Dunaliella salina*)
  - Astaxanthin (*Haematococcus pluvialis*)
  - Aquaculture feed (several species)



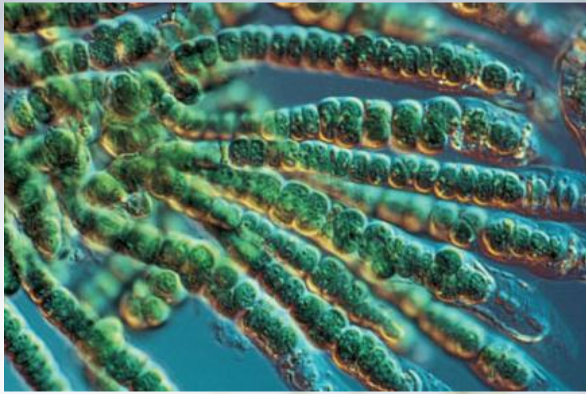
2010 "notional example" of land needed for biofuel to replace 50% of current petroleum diesel using oil from corn, soybean, algae (DOE/EERE, Ron Pate presentation)

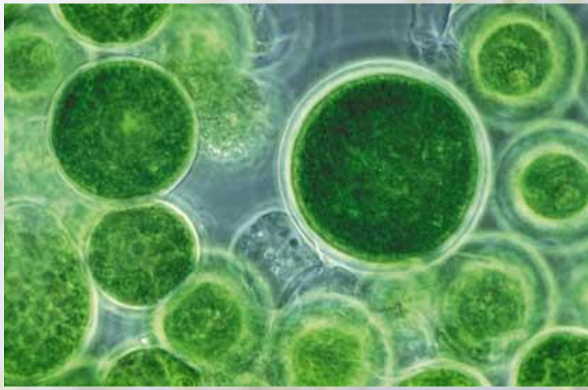
Characteristics of Photoautotrophic Algae

Division	Dominant Photosynthetic Pigment(s)	Accessory Pigments (Carotenoids)	Principal Energy Storage Compound	% Protein[2]	% Lipid[2]
Cyanoprokaryota (blue-green algae)	Phycobilins, Chlorophyll a	Zeaxanthin, beta-carotene myxoxanthin, echinenone, canthaxanthin	Glycogen, other polysaccharides, polyhydroxyalkanoates	10-70	1-20
Bacillariophyceae	Chlorophyll a, Chlorophyll c	Fucoxanthin, diatoxanthin beta-carotene, Diadinoxanthin	Lipid	5-35	5-55
Haptophyceae	Chlorophyll a, Chlorophyll c	Beta-carotene	Chrysolaminaran	5-30	5-55
Chlorophyceae	Chlorophyll a, Chlorophyll b	Lutein, beta-carotene, vioaxanthin, neoxanthin	Starch	5-30	5->50
Haptophyceae	Chlorophyll a, Chlorophyll c	Fucoxanthin	Starch	5-35	5-50
Raphidophyceae	Chlorophyll a	Diatoxanthin	Lipid	5-35	5-55
Rhodophyceae	Phycobilins, Chlorophyll a		Starch	5-15	5-15
Phaeophyceae	Chlorophyll a	Fucoxanthin	Starch	5-15	5-15
Chrysophyta	Chlorophyll a and c	Beta-carotene, fucoxanthin	Lipids (oil) Leucosin	20-30	30-40
Eustigmatophyta	Chlorophyll a	vialoxanthin, beta-carotene	Lipids (oil)	10-30	40-65

Strain selection

- High photo-conversion efficiency
- Rapid and stable growth
- High contents of lipids (for biodiesel)
- High contents of valuable coproducts
- High CO_2 absorbing capacity
- Limited nutrient requirements
- Genetic stability
- No toxins produced
- Ability to flourish in brackish or wastewater
- Robustness toward shear stresses in photobioreactors
- Competitiveness against wild native strains in open ponds
- Resistance to predators, viruses, and fungi in open ponds
- Tolerance to temperature variations, pH, salinity
- Harvestability (e.g., sedimentation rate, self-flocculation ability)
- Capability for live extraction (milking)
- Extractability (influenced by cell volume, cell wall thickness, toughness)


Cyanobacteria


Microalgae

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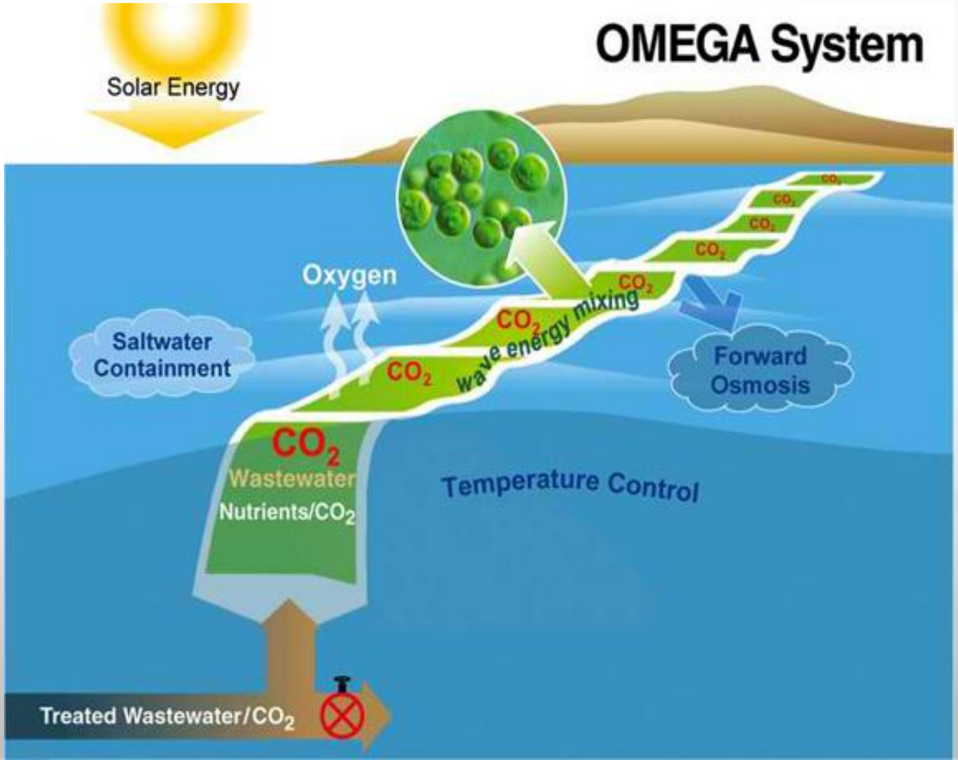
Open pond designs and photobioreactors

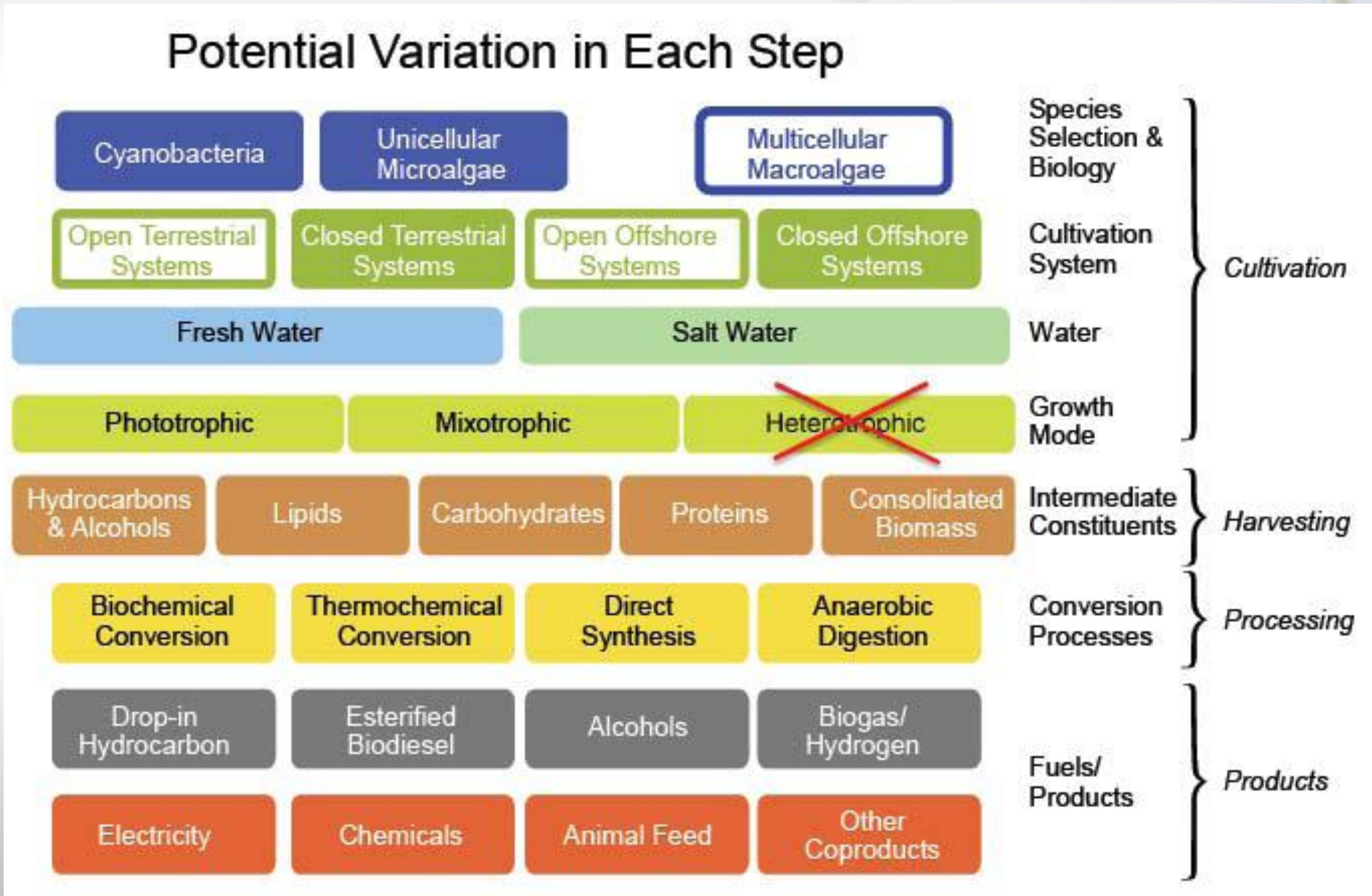
[photos belonging to others removed for posting to web]

NASA's OMEGA system

- Offshore Membrane Enclosure for Growing Algae
- Designed for surface of saline bodies of water
- Uses waves to mix cultures and regulate temperature



Supply chains for algal biofuels



Pathways used for illustration

- Reference Pathway–Raceway pond producing drop-in hydrocarbon
- Alternative Pathway #1–Raceway pond producing drop-in hydrocarbon and coproducts
- Alternative Pathway #2–Raceway pond producing FAME
- Alternative Pathway #3–Photobioreactor with direct synthesis of ethanol
- Alternative Pathway #4–Whole-cell processing (pyrolysis and hydrotreating)

Open pond vs. closed system most important for evaluating environmental effects

Comparison of open and closed cultivation systems

Parameter	Open ponds	Photobioreactor
Capital and operation costs	Lower	Higher
Energy requirement	Lower	Higher
Land footprint	Higher	Lower
Water requirement	Higher	Lower
Sparged CO2 loss	Higher	Lower
Productivity	Lower	Higher
Temperature control	Not needed	Required
Cleaning	Not needed	Required
Contamination risk	Higher	Lower
Product quality	Variable	Reproducible
Microbiology safety	No	Yes
Ease of scale up	Greater	Lower

Not all information from NRC report

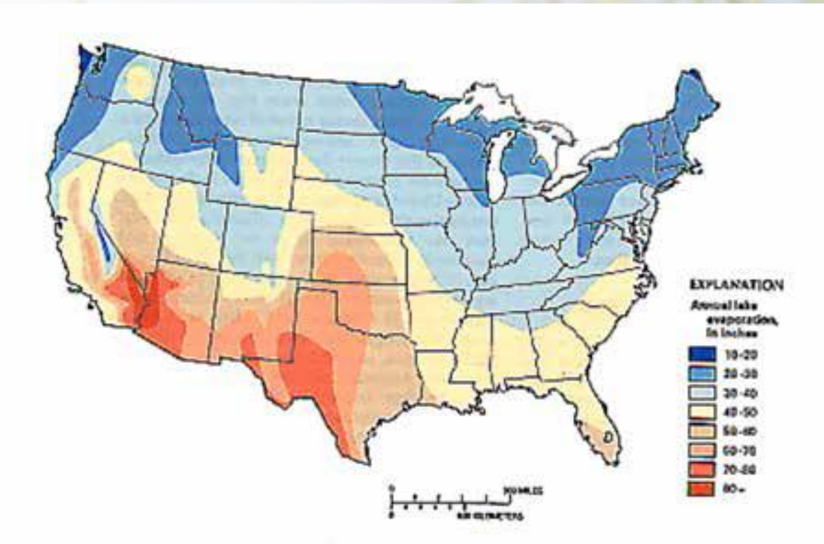
Key finding

Based on a review of literature published until the authoring of this report, the committee concluded that the scale-up of algal biofuel production sufficient to meet at least 5 percent of U.S. demand for transportation fuels would place unsustainable demands on energy, water, and nutrients with current technologies and knowledge. However, the potential to shift this dynamic through improvements in biological and engineering variables exists.

Sustainability concerns of high importance

- **Water use** (whether freshwater or saline water is used as culture media)
  - Published estimates for life-cycle water use in freshwater open-pond systems—32-3,650 L/L algal biofuel
  - Published estimates for life-cycle water use in closed photobioreactor systems—30-63 L/L algal biofuel
  - Published estimates for life-cycle water use in closed photobioreactor with direct synthesis (Algenol)—3.15 L/L gasoline equivalent fuel[1]

[1]Estimate does not include upstream water use for inputs to their facilities.



Mean annual lake evaporation in US

USGS paper. Hanson (1991)

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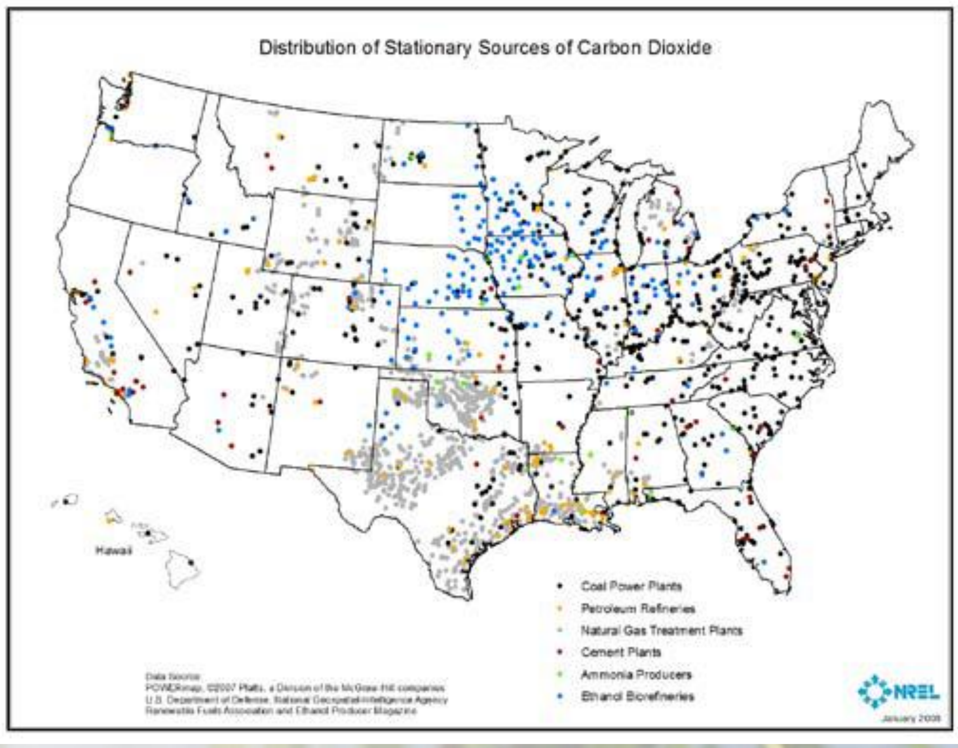
Sustainability concerns of high importance

- **Supply of key nutrients** (nitrogen, phosphorus, and CO_2)
  - Estimated N requirement to produce 5% of US demand for fuels—6 million-15 million tonnes[1]
  - Estimated P requirement to produce 5% of US demand for fuels—1 million-2 million tonnes[1]
  - CO_2—Proximity to this nutrient could limit the number of sites for algae cultivation. Transporting this resource could increase cost of production



Pienkos and Darzins 2009

[1]Assumed no recycling of nutrients. No published study on proportion of nutrients that could be recycled.

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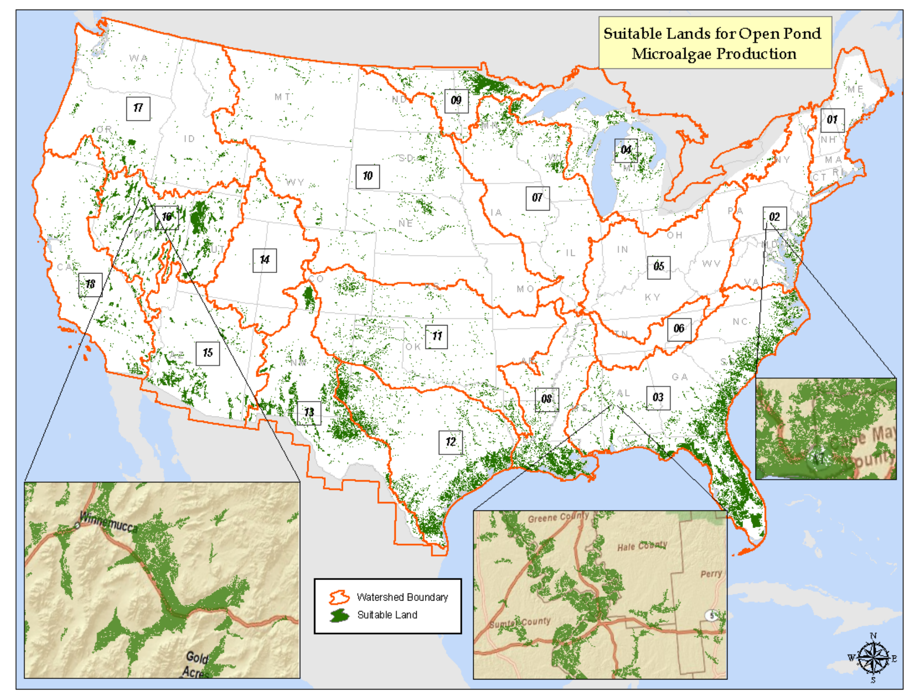
Sustainability concerns of high importance

- **Appropriate land area for cultivation**
  - ○ Suitable topography and climate
  - ○ Proximity to sustainable water supplies (whether freshwater, inland saline water, marine water, or wastewater)
  - ○ Proximity to sustainable and economic nutrient supplies
  - ○ Current use of the land
  - ○ Price of the land



Analysis and photo from M Wigmosta, PNNL

•Potential 90,000 areas >= 1200 acres suitable for open ponds (total 431,000 km^2, 5.5% of conterminus US)

•Excluded croplands, urban, open water, wetlands, riparian zones, parks and protected areas, areas with slope >1%

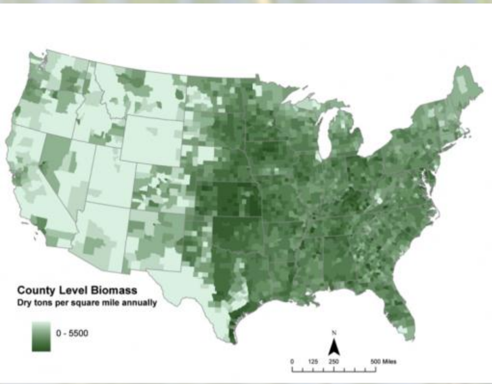
Key finding

A national assessment of land requirements for algae cultivation that takes into account climatic conditions; freshwater, inland and coastal saline water, and wastewater resources; sources of CO_2; and land prices is needed to inform the potential amount of algal biofuels that could be produced economically in the United States.

City of Boulder wastewater treatment

Kingston, TN, TVA coal-fired power plant

A new Billion Ton study?



Sustainability concerns of high importance

- **GHG emissions over the life cycle of algal biofuels**
  - -Drivers of GHG emissions
    - Nutrient source
    - Productivity
    - Process performance
    - Credit associated with coproducts

Examples of Life-Cycle CO2 Emissions of Algal Biodiesel Production

Source	Life-Cycle CO_2 Emissions (kg CO_2 equivalent per liter of biodiesel)
Clarens et al. (2010)	8.7
Lardon et al. (2009)	4.0
Stephenson et al. (2010)	0.6
Sander and Murthy (2010)	-0.8
Campbell et al. (2010)	-1.1

Sustainability concerns of high importance

- **Energy return on investment**
  - Values for open-pond systems range from 0.13 to 3.33
  - Values for closed photobioreactor systems not estimated over the life cycle
  - Drivers of energy consumptions:
    - Virgin fertilizers versus recycled nutrients
    - Energy use for mixing water
    - Energy credits for coproducts

Sustainability concerns of medium importance

- Waterborne **toxicants** in cultivation systems
- Effects of **land-use changes** (e.g., potential displacement of rangeland or pasture)
- **Air-quality** emissions over the life-cycle of biofuels
- Potential effects on **local climate**
- **Releases of cultivated algae** to natural environments
- **Biodiversity** effects from changing landscape pattern
- Potential adverse effects of introduction of **genetically engineered organisms**
- **Waste products** from processing algae to fuels
- Potential presence of **pathogens** if wastewater is used in cultivation systems
- Potential unknown, unidentified, or unexpected algal **toxins**


USFWS photo

Industrial impoundment

or

Oasis


Fish Spring NWR, UT, Wikimedia Commons

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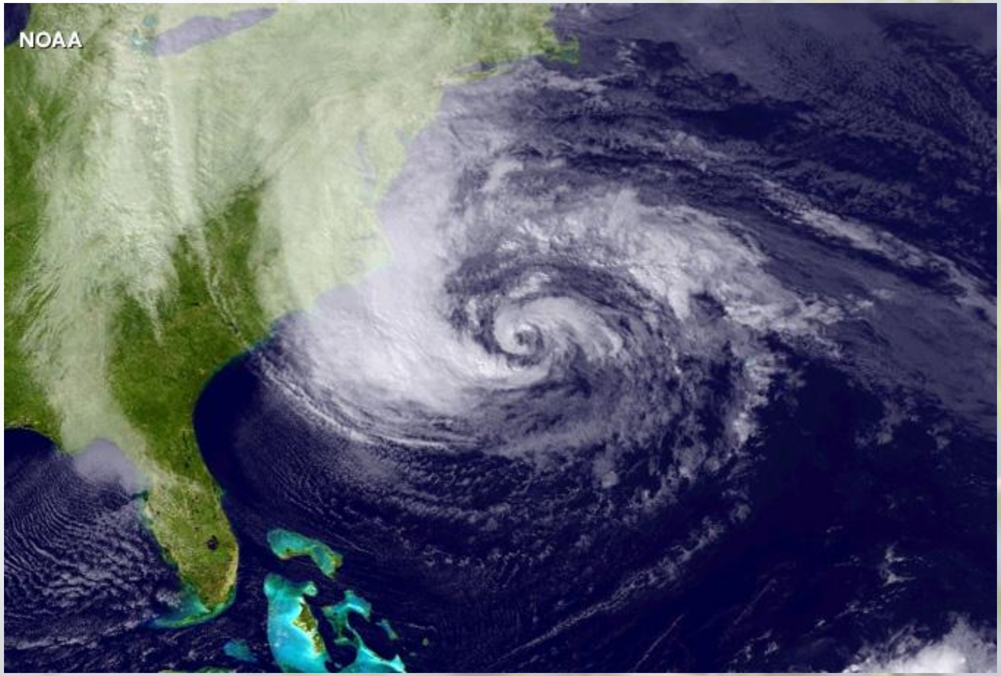
Sustainability concerns of low importance

- Accidental releases of culture water
- Seepage of culture water into groundwater system
- Potential presence of mosquitoes (and mosquito-borne diseases) around poorly managed ponds

But what would Superstorm Sandy do?



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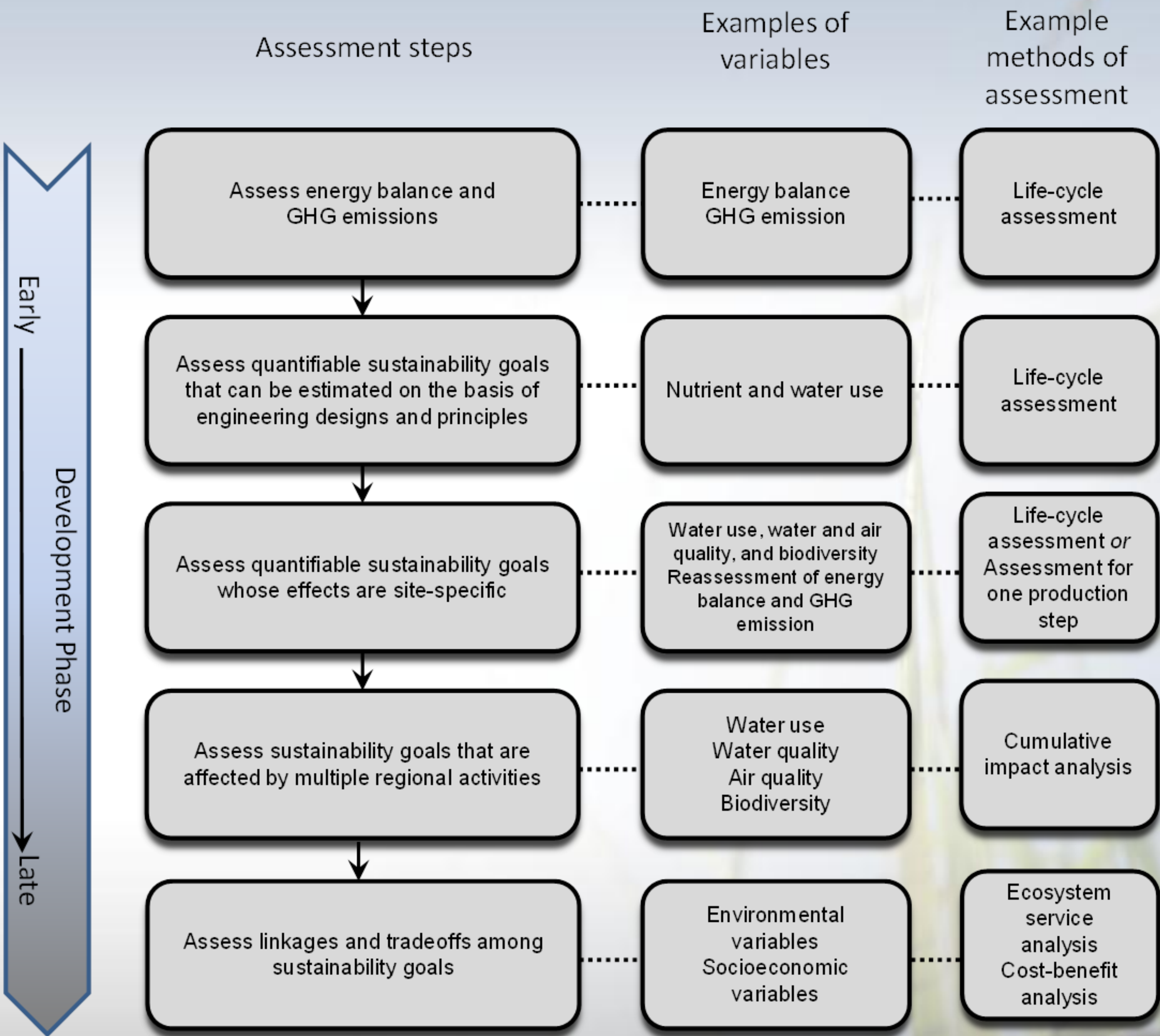
A framework for assessment



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Comparative context important

- **Caution:** The sustainability of algal biofuels cannot be viewed in isolation and needs to be put into the broader context of transportation fuels.
- The environmental, economic, and social effects of algal biofuel production and use have to be compared with those of petroleum-based fuels and other fuel alternatives to determine whether algal biofuels contribute to improving sustainability. Such comparison will be possible only if thorough assessments of each step in the various pathways for algal biofuel production are conducted.

Reactions to NRC Report

- Algae Biomass Organization applauds NRC Report that finds algal fuels can increase energy security and decrease GHG emissions
- National Algae Association
  - Disagreement about need for more research
  - Closed systems are superior to open ones
  - Study based on out-dated, inaccurate information
  - Existing strains are sufficient

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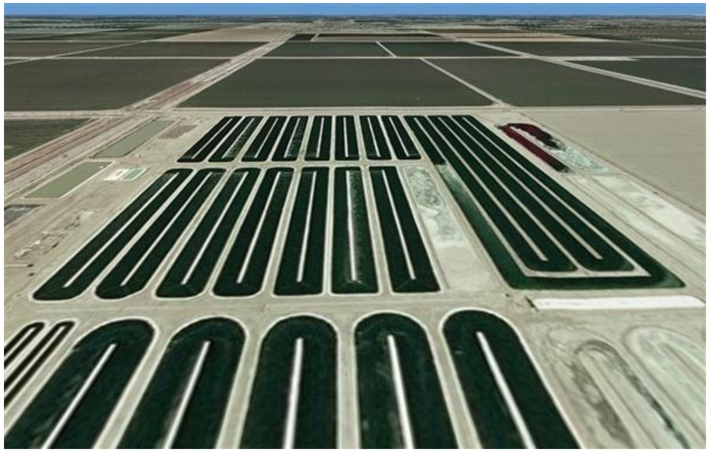
New project: Sustainable Development of Algae for Biofuels

Rebecca Efroymson, Virginia Dale, Matt Langholtz (ORNL) and PNNL

Objective: conduct research that defines and addresses potential environmental, socioeconomic, and production hurdles

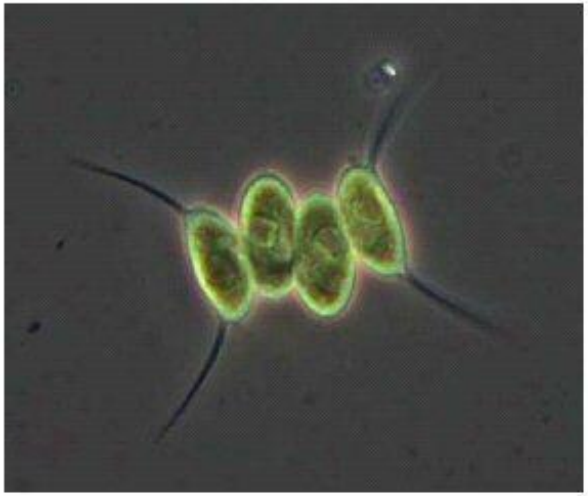
- Evaluate applicability of 19 proposed environmental sustainability indicators to algal biofuels
- Begin to evaluate applicability of 16 proposed (and 10 *de minimus*) socioeconomic sustainability indicators to algal biofuels



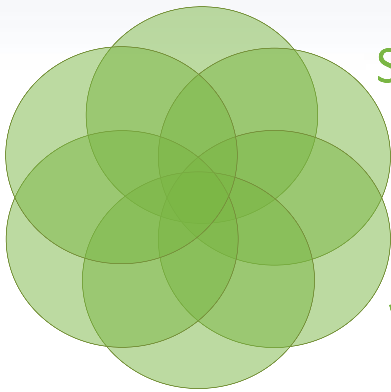
PNNL photo

- Add open-pond algae model to POLYSYS modeling framework (report intermediate results of algae competing with terrestrial feedstocks)
- Refine land categories in POLYSYS used for algae
- Begin to incorporate sustainability constraints in algae module of POLYSYS

Scenedesmus for biodiesel, Nielson et al.



Categories for indicators of environmental and socioeconomic sustainability



McBride et al. (2011) *Ecological Indicators* 11:1277-1289

Dale et al. (In press) *Ecological Indicators*

Recognize that measures and interpretations are context specific

Efroymson et al. (In press) *Environmental Management*

Categories of environmental sustainability indicators

Environment	Indicator	Units
Soil quality	1. Total organic carbon (TOC)	Mg/ha
	2. Total nitrogen (N)	Mg/ha
	3. Extractable phosphorus (P)	Mg/ha
	4. Bulk density	g/cm^3
Water quality and quantity	5. Nitrate concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	6. Total phosphorus (P) concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	7. Suspended sediment concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	8. Herbicide concentration in streams (and export)	concentration: mg/L; export: kg/ha/yr
	9. Storm flow	L/s
	10. Minimum base flow	L/s
	11. Consumptive water use (incorporates base flow)	feedstock production: m^3/ha/day; biorefinery: m^3/day

Environment	Indicator	Units
Greenhouse gases	12. CO_2 equivalent emissions (CO_2 and N_2O)	kgC_{eq}/GJ
Biodiversity	13. Presence of taxa of special concern	Presence
	14. Habitat area of taxa of special concern	ha
Air quality	15. Tropospheric ozone	ppb
	16. Carbon monoxide	ppm
	17. Total particulate matter less than 2.5μm diameter ($PM_{2.5}$)	$\mu g/m^3$
	18. Total particulate matter less than 10μm diameter (PM_{10})	$\mu g/m^3$
Productivity	19. Aboveground net primary productivity (ANPP) / Yield	gC/m^2/year

McBride et al. (2011)
Ecological Indicators
11:1277-1289

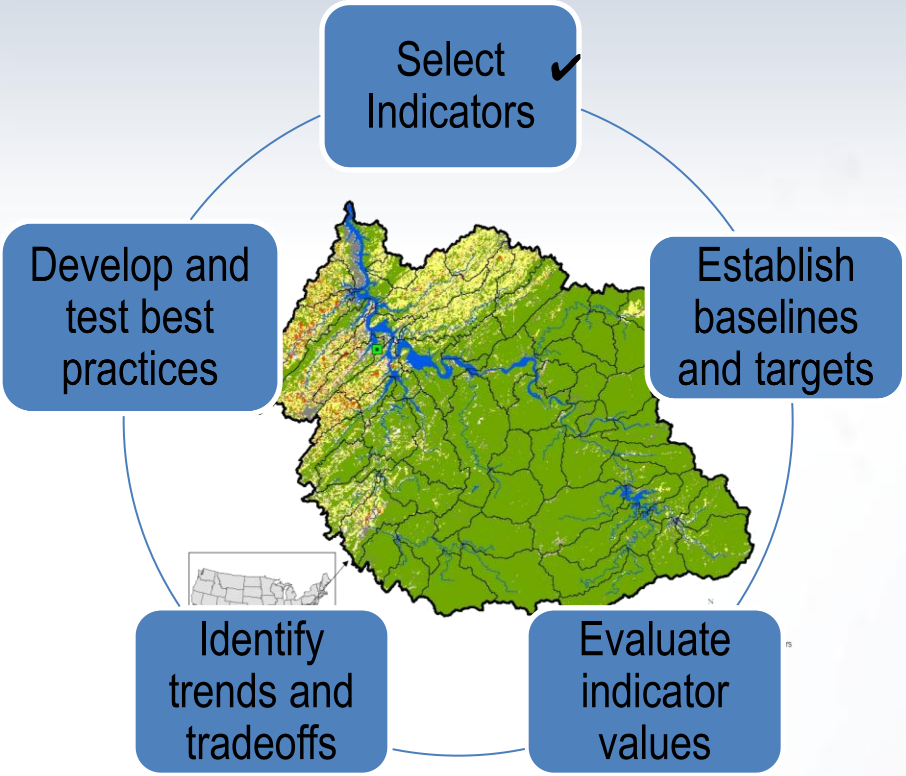
Set of Indicators Should Apply to

- Entire supply chain
- Diverse feedstocks
- All conversion pathways

Feedstock production → Feedstock Logistics → Conversion → Biofuel Distribution → End use

- **Feedstock production**
  - Land and resource conditions
  - Strain biology
  - Cultivation system
- **Feedstock Logistics**
  - Harvesting and dewatering
  - Fractionation, extraction, separation
  - Storage
  - Transport
- **Conversion**
  - Conversion process
  - Fuel type
  - Co-products
- **Biofuel Distribution**
  - Transport
  - Storage
- **End use**
  - Engine type and efficiency
  - Blend conditions

Defining and Quantifying Bioenergy Sustainability

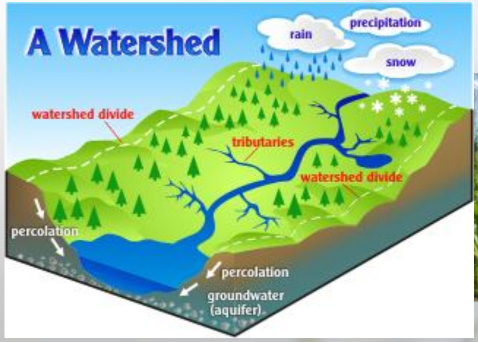


Facilitating establishment of sustainable industry

- Establish indicators of sustainability
  - Defining indicators – what are critical few?
  - Determining baseline conditions and targets
  - Testing indicators of sustainability in specific contexts
- Evaluate trends and effects of tradeoffs
- Develop tools for multi-criterion spatial decision support to define optimal management
- Conduct multi-variant assessment of "sustainability"

Collaborators include:

- Other DOE Labs (5)
- Other federal agencies
- Bioenergy teams (3)
- Certification efforts (4)
- Universities (7)
- Industry (7)



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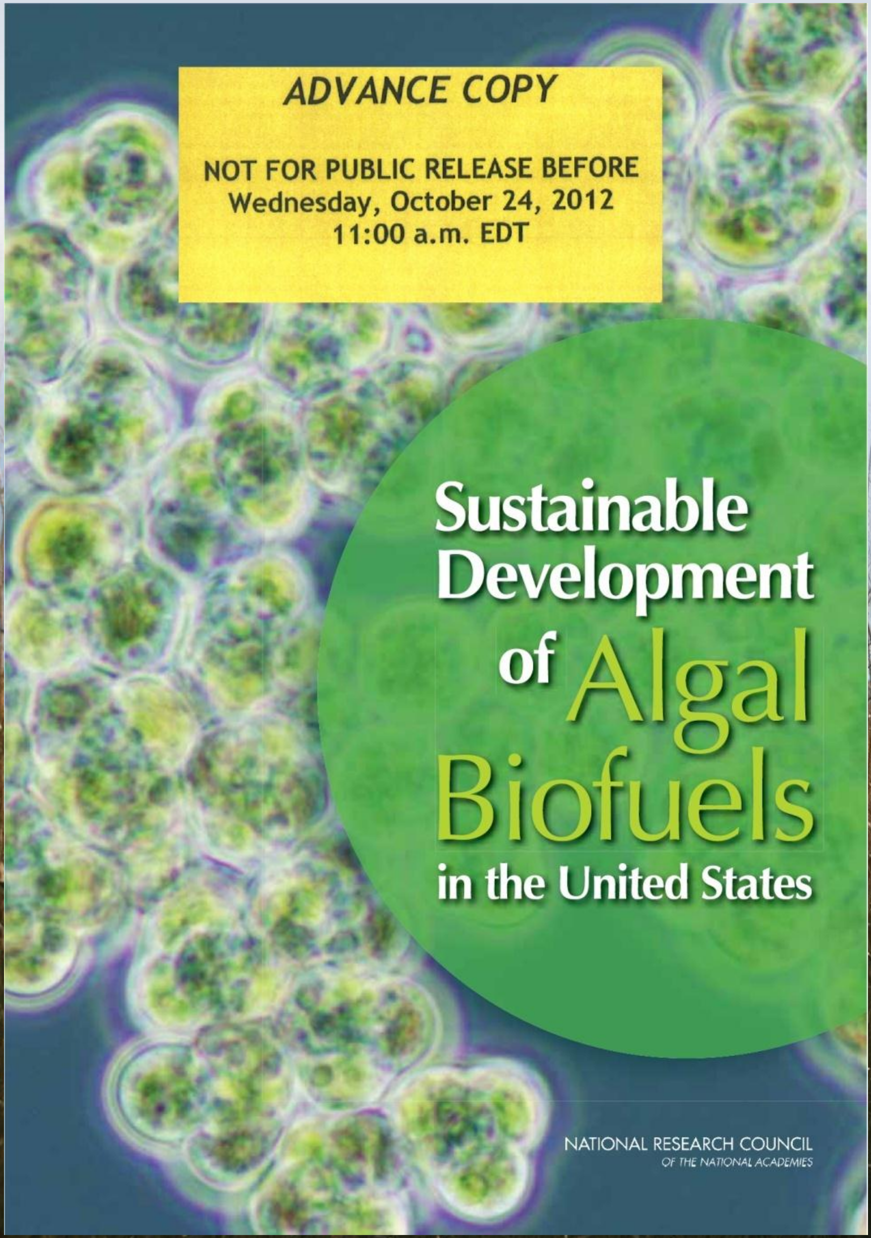
Thank you!



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