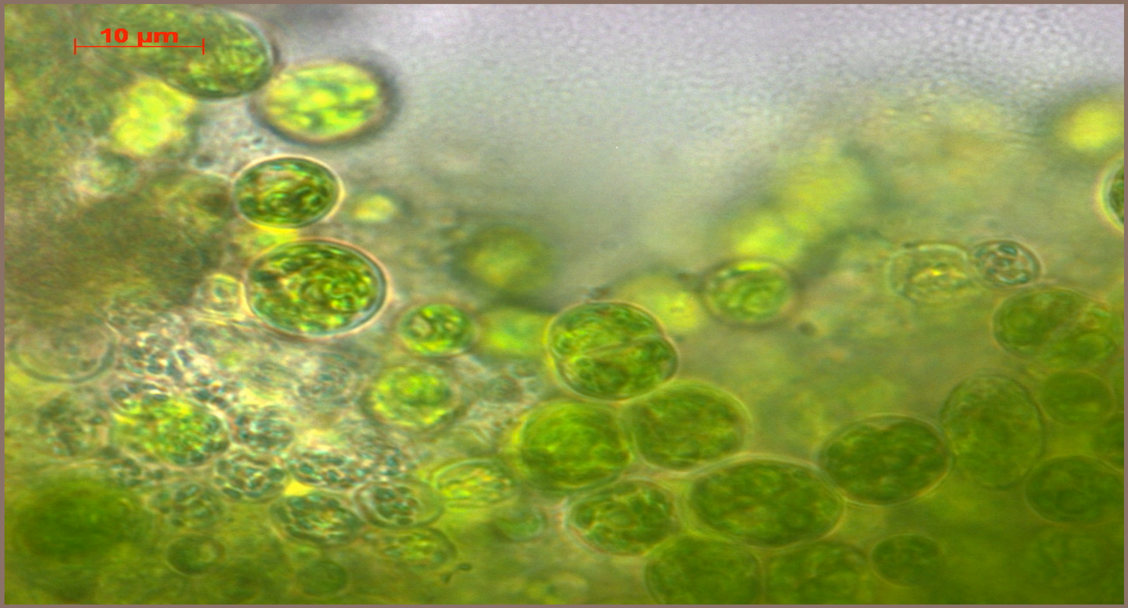
IDENTIFYING OPPORTUNITIES IN ALGAE BIODIESEL: A VALUE CHAIN AND LIFE CYCLE ASSESSMENT APPROACH



Robert Levine

Amy Oberlin

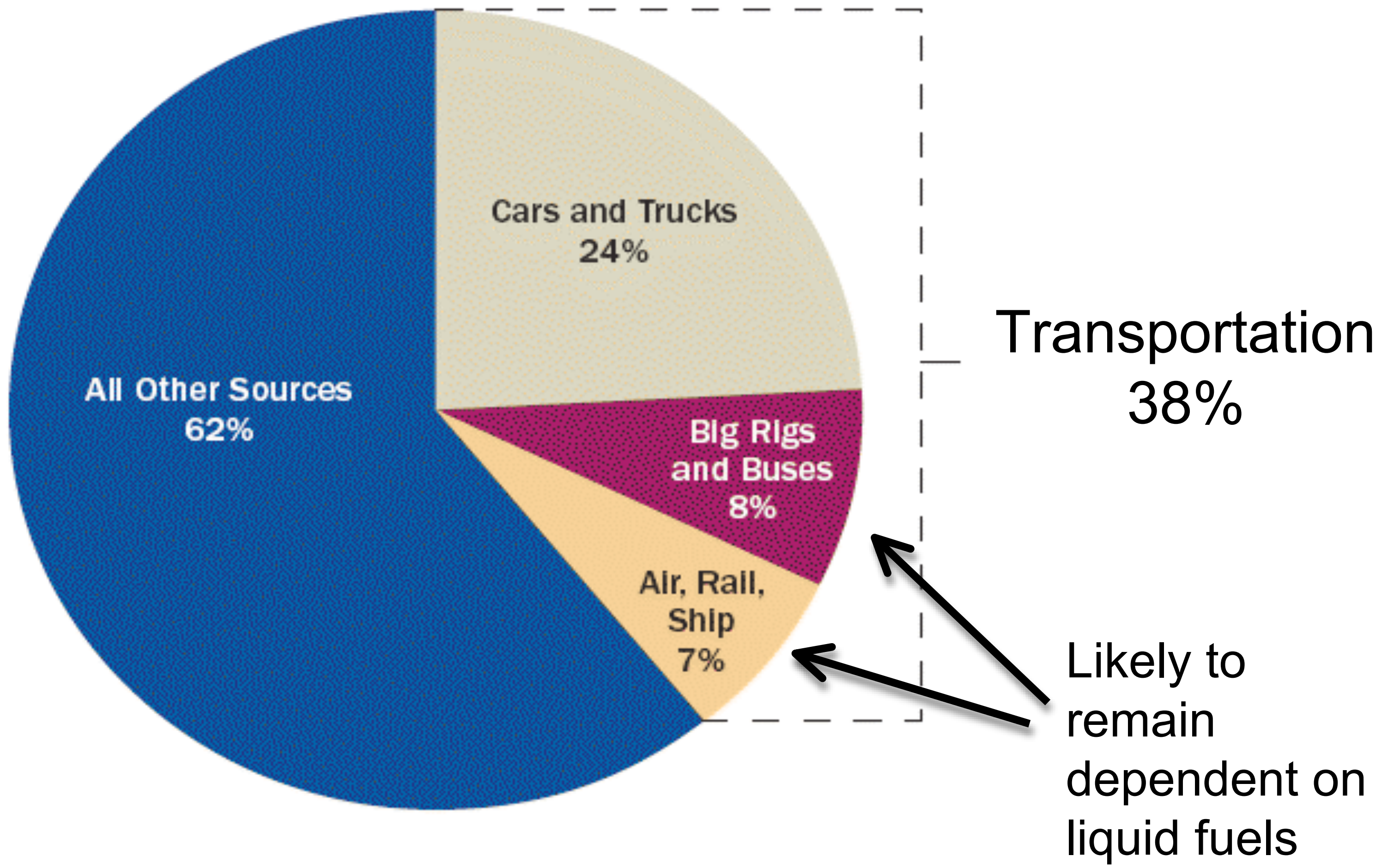
Dr. Peter Adriaens

Clean Technology Conference, Houston, May 5th, 2009

Outline

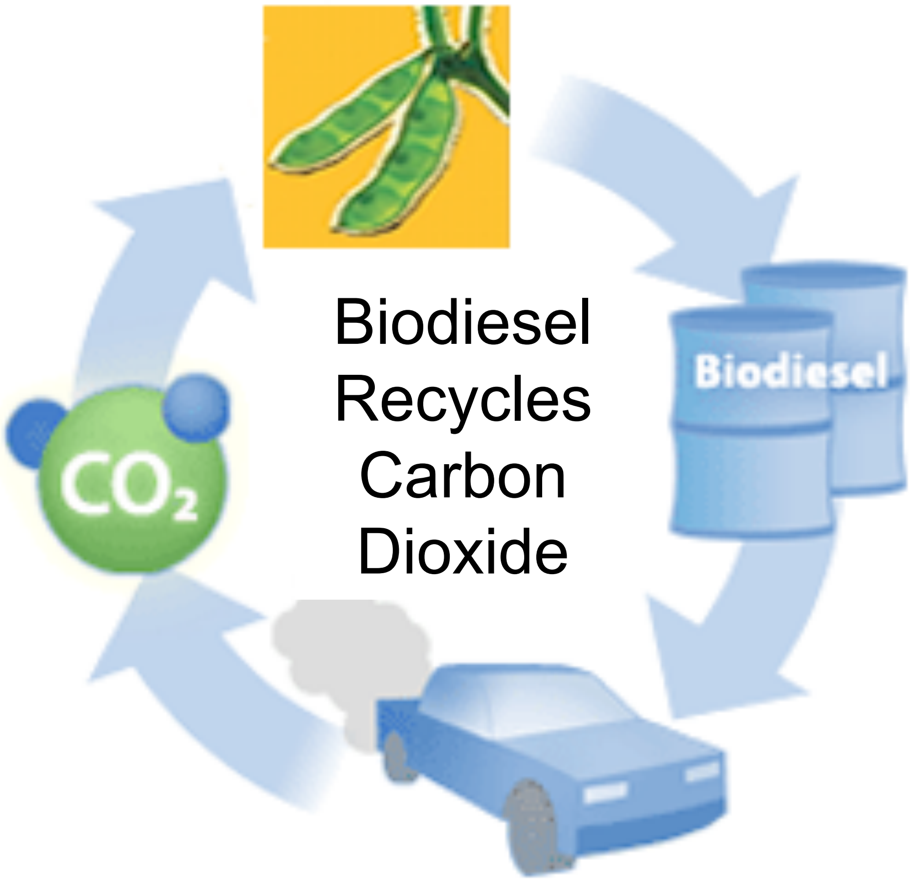
- Introduction
  - Why now? Why algae?
  - Overview of the space
- The Algae Biodiesel Value Chain
- Life-Cycle Assessment

Transportation's share of US GHG emissions



Source: UCS Report "Biofuels: An Important Part of a Low-Carbon Diet"

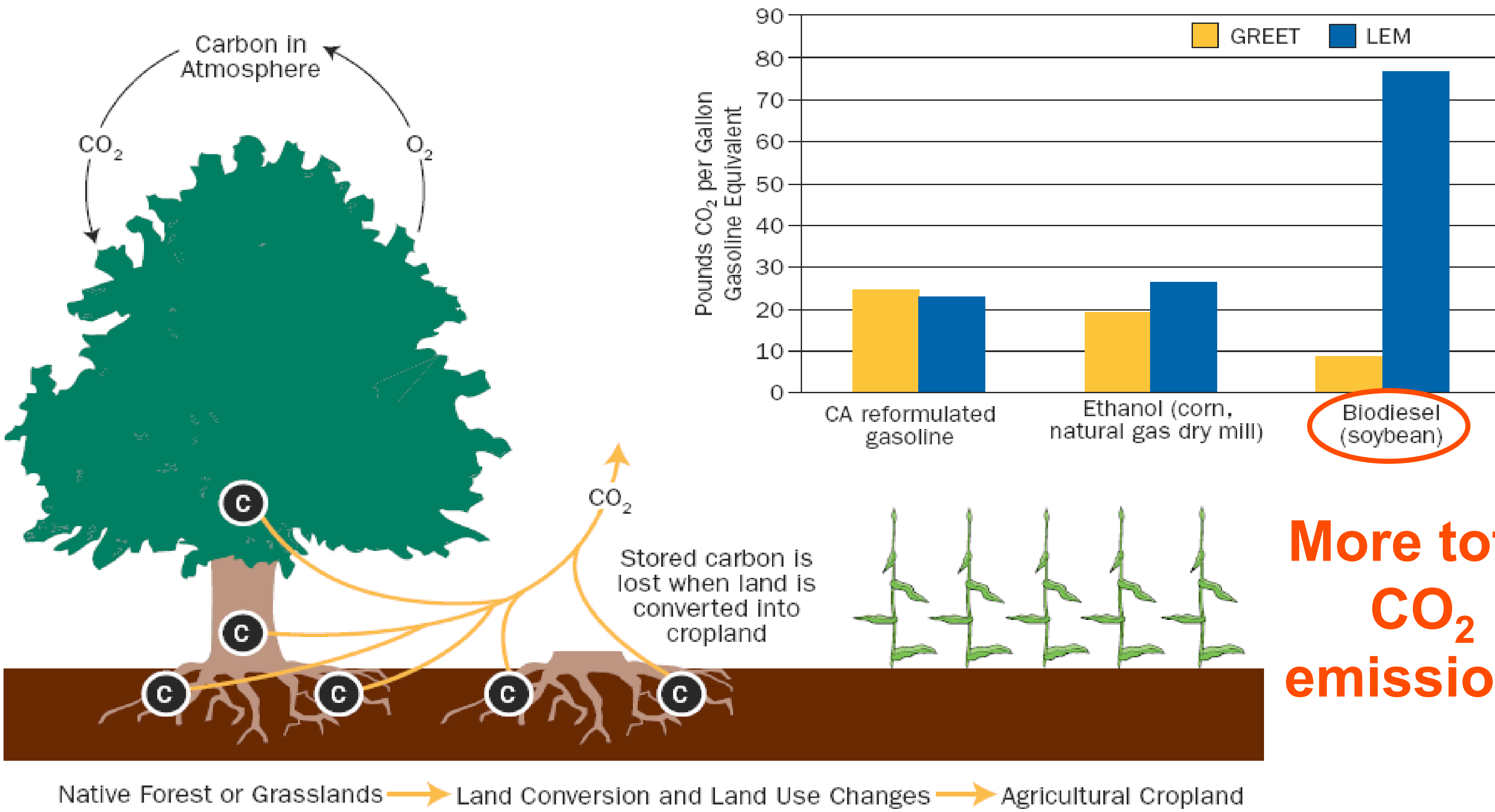
The current biofuels paradigm



General conclusion:
Seed-to-wheel beats well-to-wheel

NOT
the whole truth…

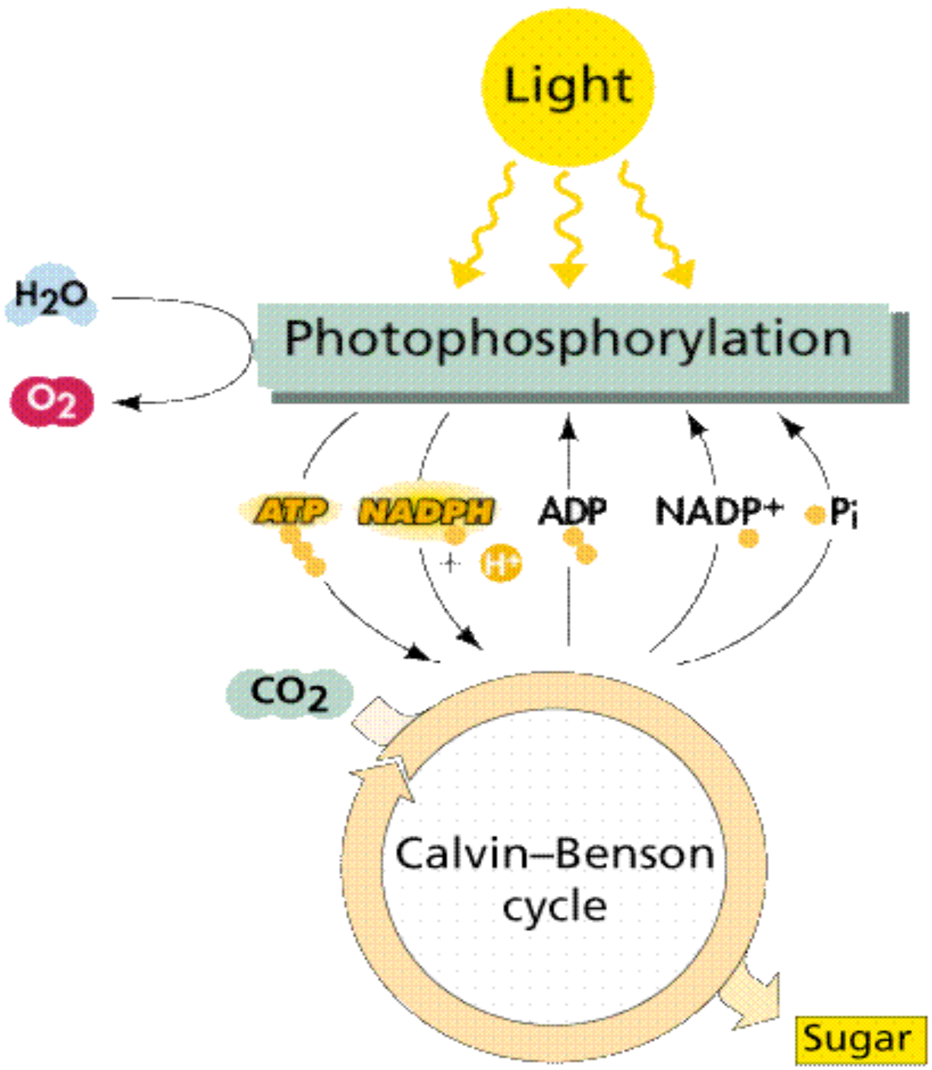
Indirect land use changes: converting forests and grasslands into croplands



More total CO_2 emissions

Source: UCS Report “Biofuels: An Important Part of a Low-Carbon Diet”

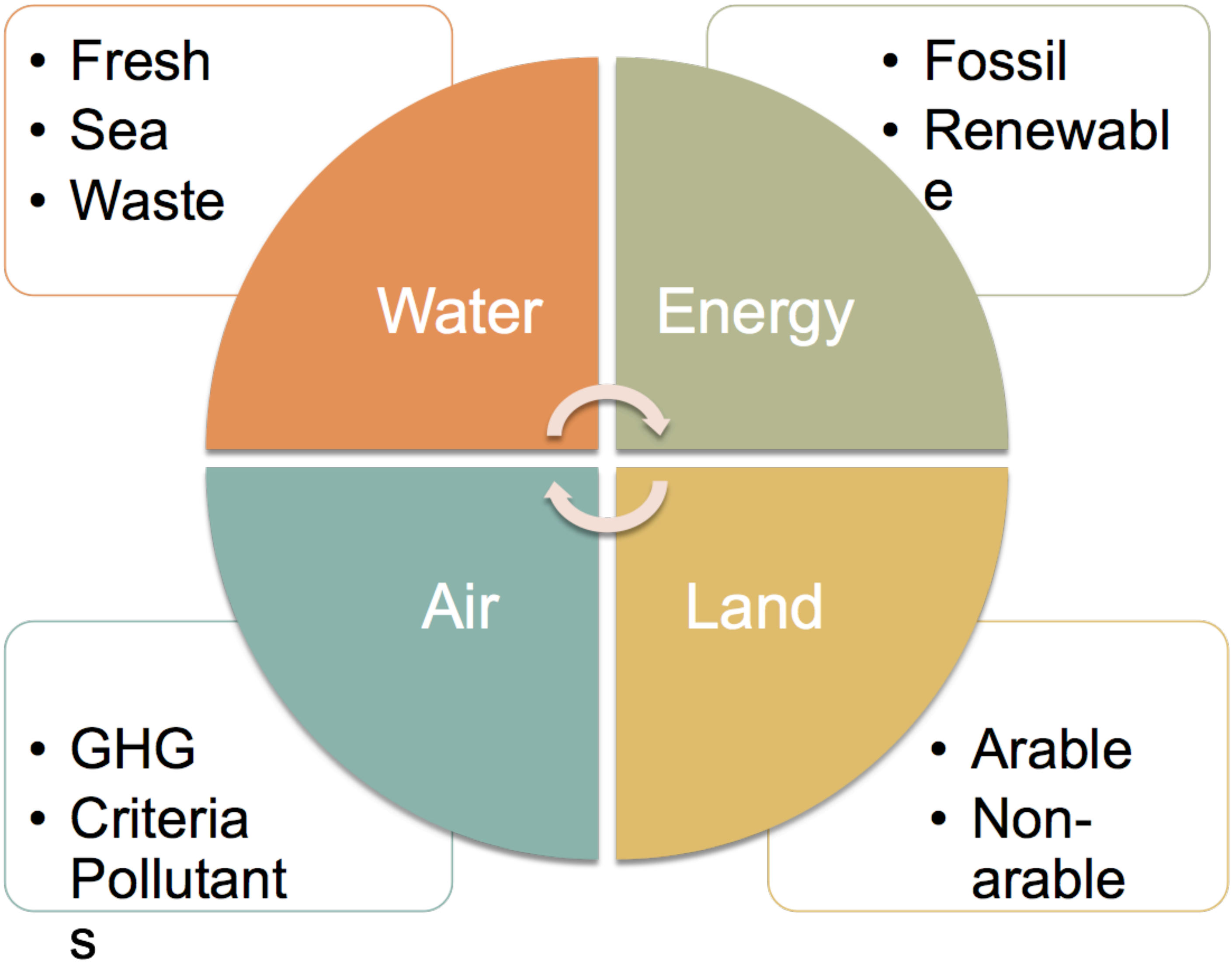
Photobiological fuel production



More than just sugar

LIPID:	9 kcal/g
CARBO:	4 kcal/g
PROTEIN:	4 kcal/g

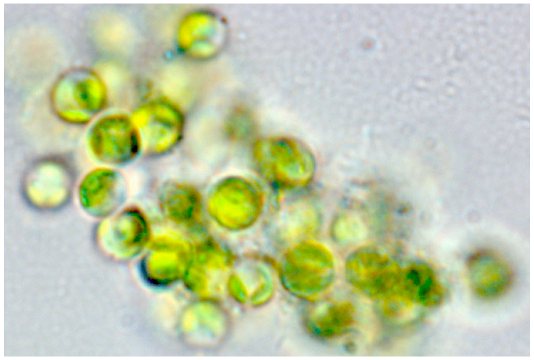
Life-Cycle Perspective



hotosynthetic Efficiency = Land Use Efficiency

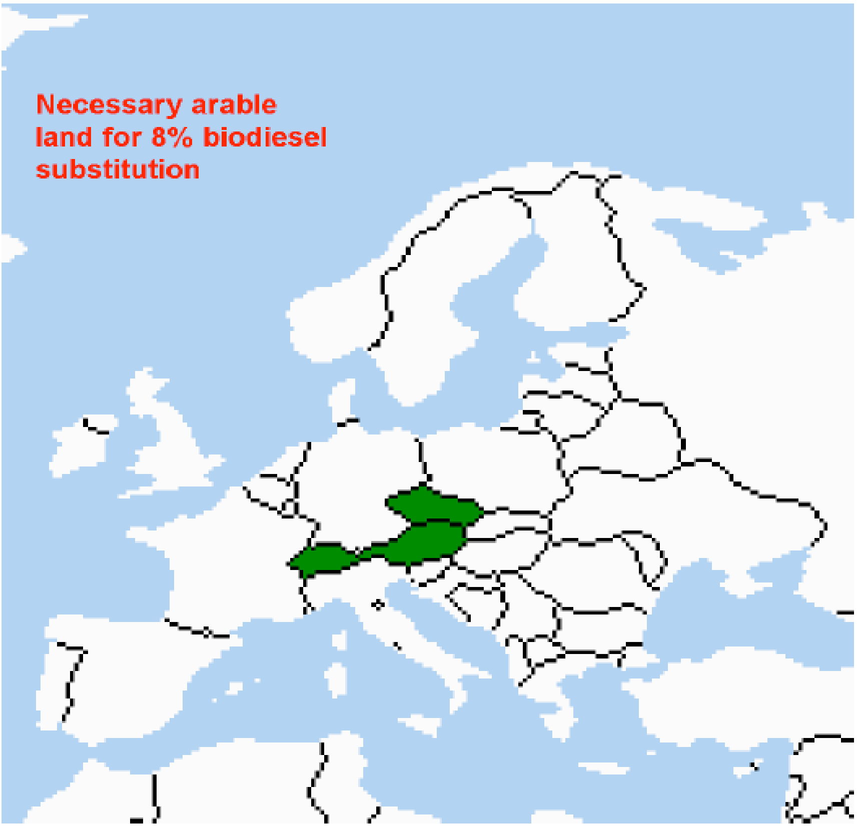
105 - 140 gallons biodiesel/acre/year

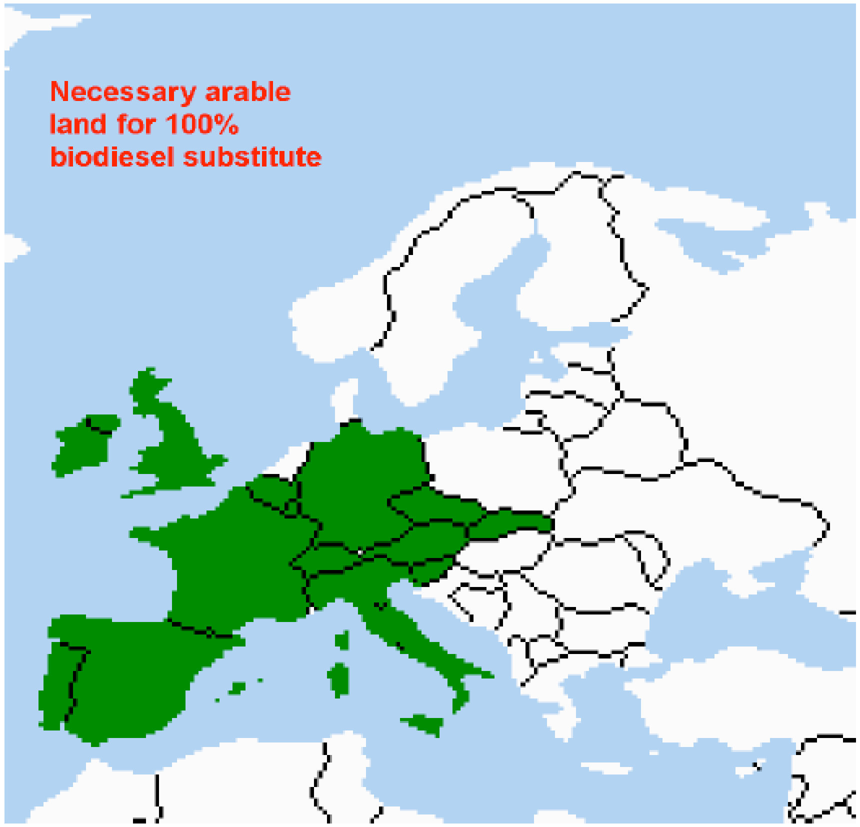
37- 48 gallons biodiesel/acre/year



1,000-10,000 gallons biodiesel/acre/year

Using rapeseed to grow Europe's fuel





Water Use

- Evaporation
- Wastewater treatment
  - Replacing conventional treatment (credits)
  - Nutrient source
- Salt water
- Regional issues
  - Great Lakes: lots of water
  - Arizona: brackish aquifers
  - Areas where rainfall > evaporation

Water Use

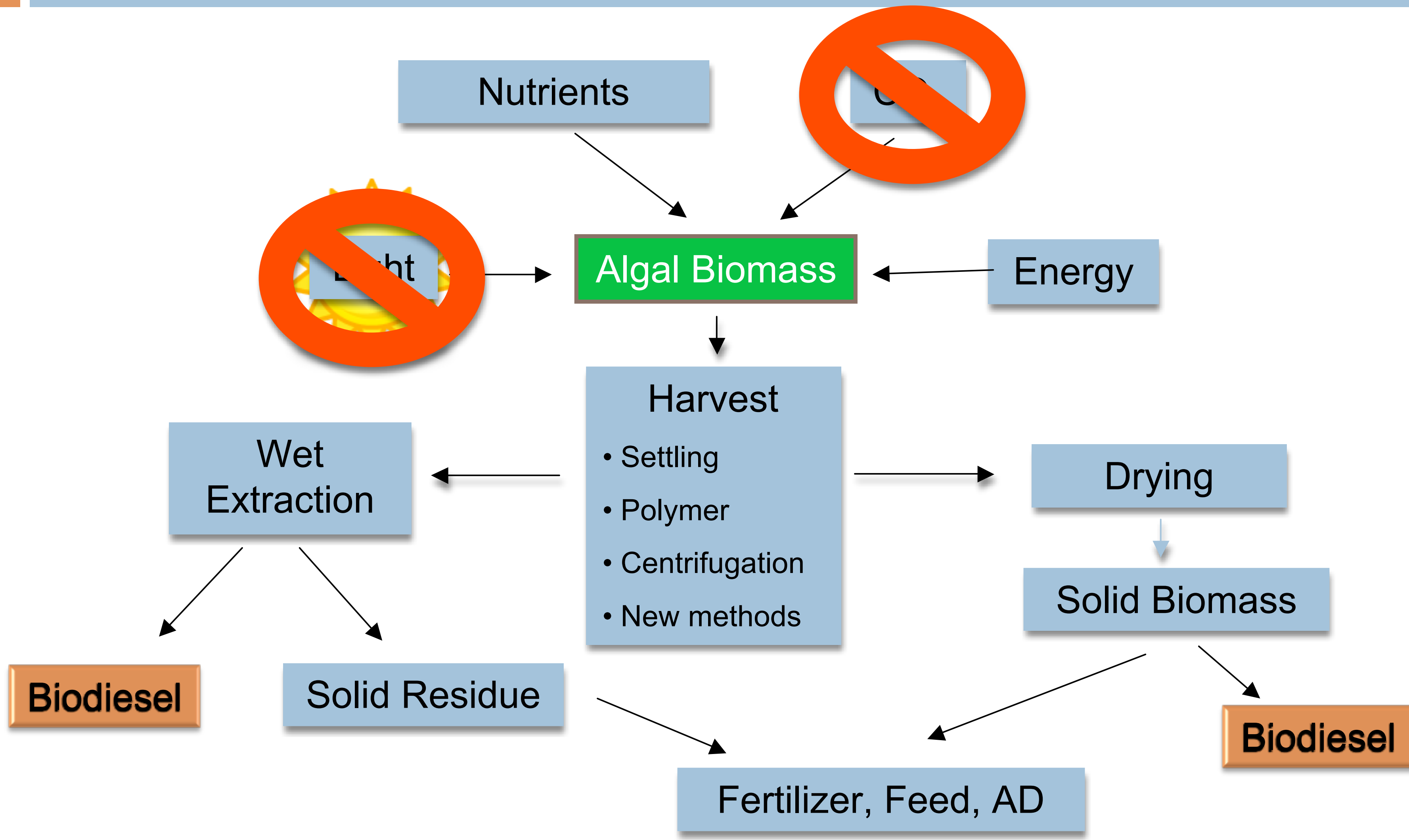
Water Intensity of Transportation
Carey W. King, and Michael E. Webber
Environ. Sci. Technol., **2008**, 42 (21), 7866-7872 • DOI: 10.1021/es800367m • Publication Date (Web): 24 September 2008

Transportation Fuel	gal H_2O/mile driven		gal H20/gal product	
	Low	High	Low	High
Petroleum gasoline	0.07	0.14	1.4	2.8
Petroleum diesel	0.05	0.11	1	2.2
Oil Shale	0.15	0.37	3	7.4
Tar Sands	0.2	0.46	4	9.2
Coal to FT to Liquids	0.19	0.58	3.8	11.6
NG to FT to Liquids	0.12	0.43	2.4	8.6
Electric Vehicle	0.24	n/a	4.8	n/a
CNG	0.06	0.07	1.2	1.4
E85 (irrigated corn)	1.3	62	26	1240
E85 (non-irrigated corn)	0.15	0.35	3	7
E85 (irrigated corn stover)	2.6	46	52	920
Biodiesel (irrigated soy)	0.6	24	12	480
Biodiesel (non-irrigated soy)	0.01	0.02	0.2	0.4
Algae with WWT	?	?	?	?

Commercial algae production: can these be a model for biofuels?

Species	**Products**
Chlorella sp.	Protein
Spirulina platensis	Protein
Dunaliella sp.	β-carotene
Haematococcus pluvialis	Astaxanthin

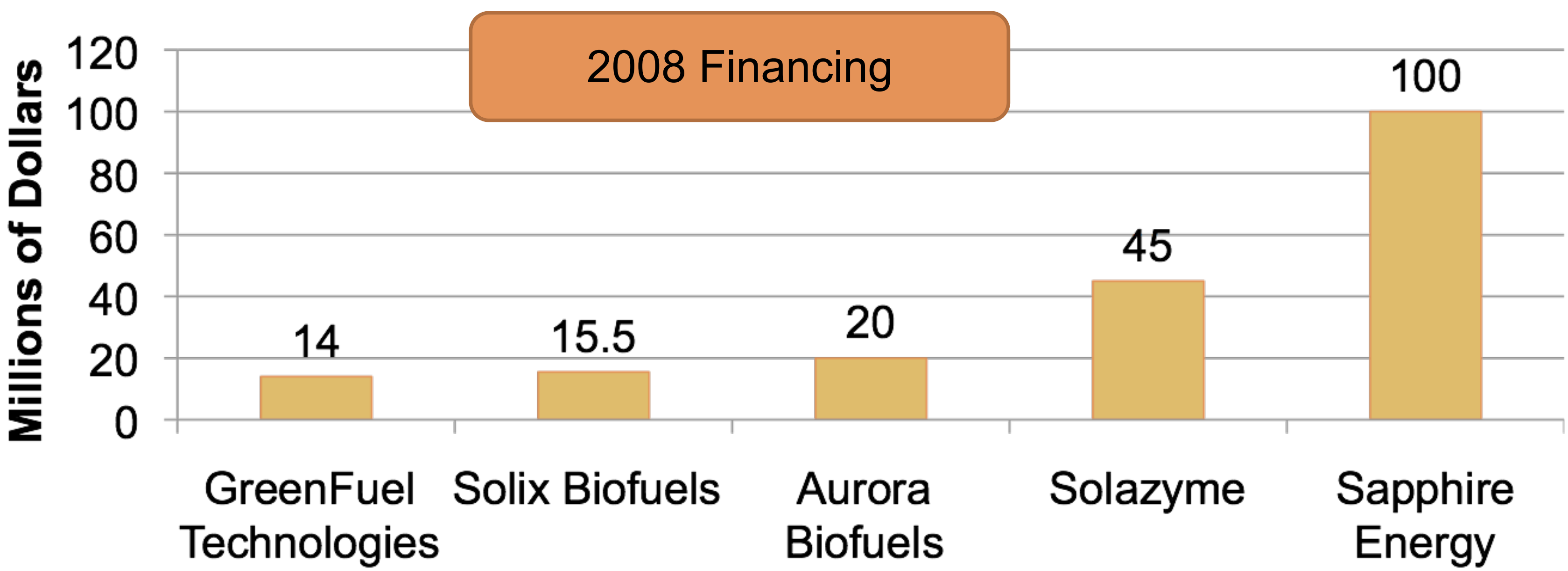
Algae to Biodiesel



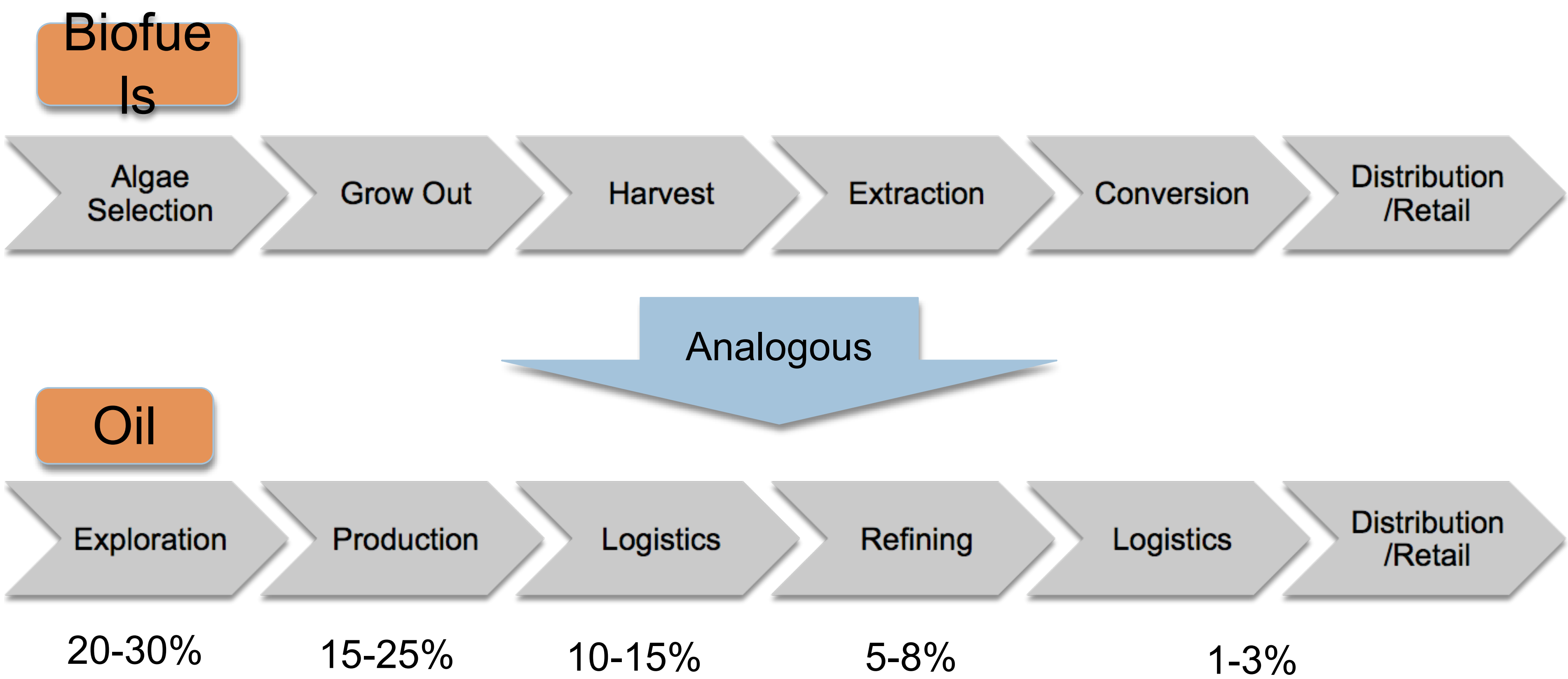
VC financing for algae start-ups

Totals:

- 2007: $34 MM
- 2008: $195 MM



Value Chain



Where is value captured?

Value chain: Algae selection

- Heterotrophic (sugar + no light) vs. Photosynthetic (with light)
- Composition
  - High lipid
  - High hydrocarbon (i.e. alkanes)
  - High starch (i.e. ethanol production)
- Genetically modified

Value chain: Grow out

Algae Selection → **Grow Out** → Harvest → Extraction → Conversion → Distribution /Retail

- Reactor/Pond Design
  - Paddlewheel raceways
  - Closed PBRs
- Site Management
- Construction
- Sensors and Monitoring

Growing energy requirements (mixing)

	Raceway	Tubular Reactor	Vertical Flat Panel
GJ/ha-yr	6.6	180	670
Percent of energy in biomass (%)	0.5	14	42
Total energy produced (implied)	1320	1285	1600

Source: Adapted from: Tredici, 2008. Raceway data from Oswald 1988 (5 kWh/ha-d). Tubular reactor data from Burgess and Fernandez Velasco (2007).

Energy of materials

	Raceway	Tubular Reactor	Vertical Flat Panel	
Energy input (GJ/ha-yr)	120	?	1214	550
Percent of energy in biomass (%)	10	?	75	35
Total energy produced (implied) (GJ/ha-yr)	1200	?	1620	1570

Value chain: Harvesting

- Well-known:
  - Centrifugation
    - Seambiotic
- Flocculation
  - Bio-
  - Co-
  - Chemical
- Novel
  - Fish system (Brune)
  - AlgaeVenture Systems
  - Ames Lab/Iowa State/Catilin
    - Nanofarming
  - OriginOil
    - combines electromagnetism and pH modification

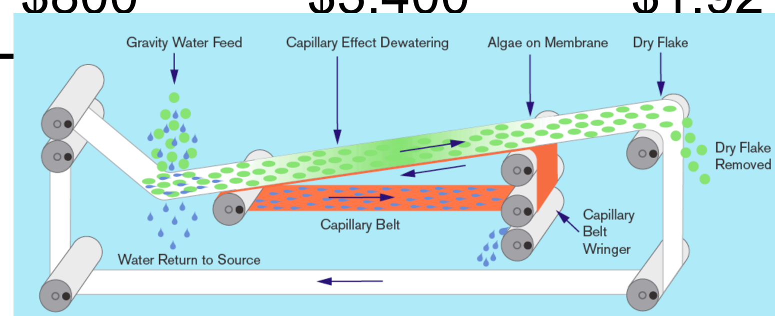
Seambiotic

- *Dunaliella*
- Health food supplement
- Bowl separator (Westphalia)
  - Then spray dryer
- Selling for ~$4,000/kg algal dw
- For Bio-Fuel cost should be below $0.5/kg algal dw

Harvesting—can you afford it?

	Centrifuge	Centrifuge	Centrifuge (AlgaeVS)	AlgaeVS New Tech
Density (m^3 solution/MT dw algae)	333	1000	333	333
kWh/MT algae	2664	8000	47,200	26.7
kWh/m^3	8	8	142	0.08
$/MT	$270	$800	$3,400	$1.92

Avg. 0.66 kWh/m3 for WWT
~1.5-2.5 bbl oil/MT algae
At $50/bbl→ $75-125/MT algae



AlgaeVenture Systems

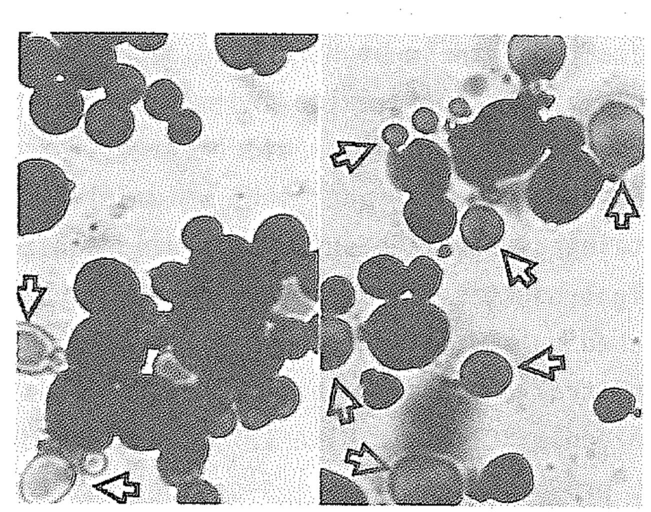
Sources: Grima et al. (2003); www.algaevs.com

Brine shrimp harvesting (D. E. Brune)

Harvest Technique	Energy Input Compared to Output
Direct Centrifugation	520% of energy content
Sedimentation to 5% solids, then centrifugation	2%
Chemical Flocculation	10-30% cost of product value
Brine Shrimp Harvest	1.8%

Value chain: Extraction

- Dry Algae
  - Model is soybean oil extractior
    - Hexane
- Wet Algae
  - Hard to use solvents
  - Need something new here?
- Excretion



Value chain: Conversion

- Transesterification: pure oil → biodiesel
- Cracking, decarboxylation → “green diesel”
- Catalysts, reactor design, process controls

Example: Inventure

Value chain: Distribution/Retail

Algae Selection | Grow Out | Harvest | Extraction | Conversion | Distribution /Retail

- Drop-in fuels fit right into the current infrastructure

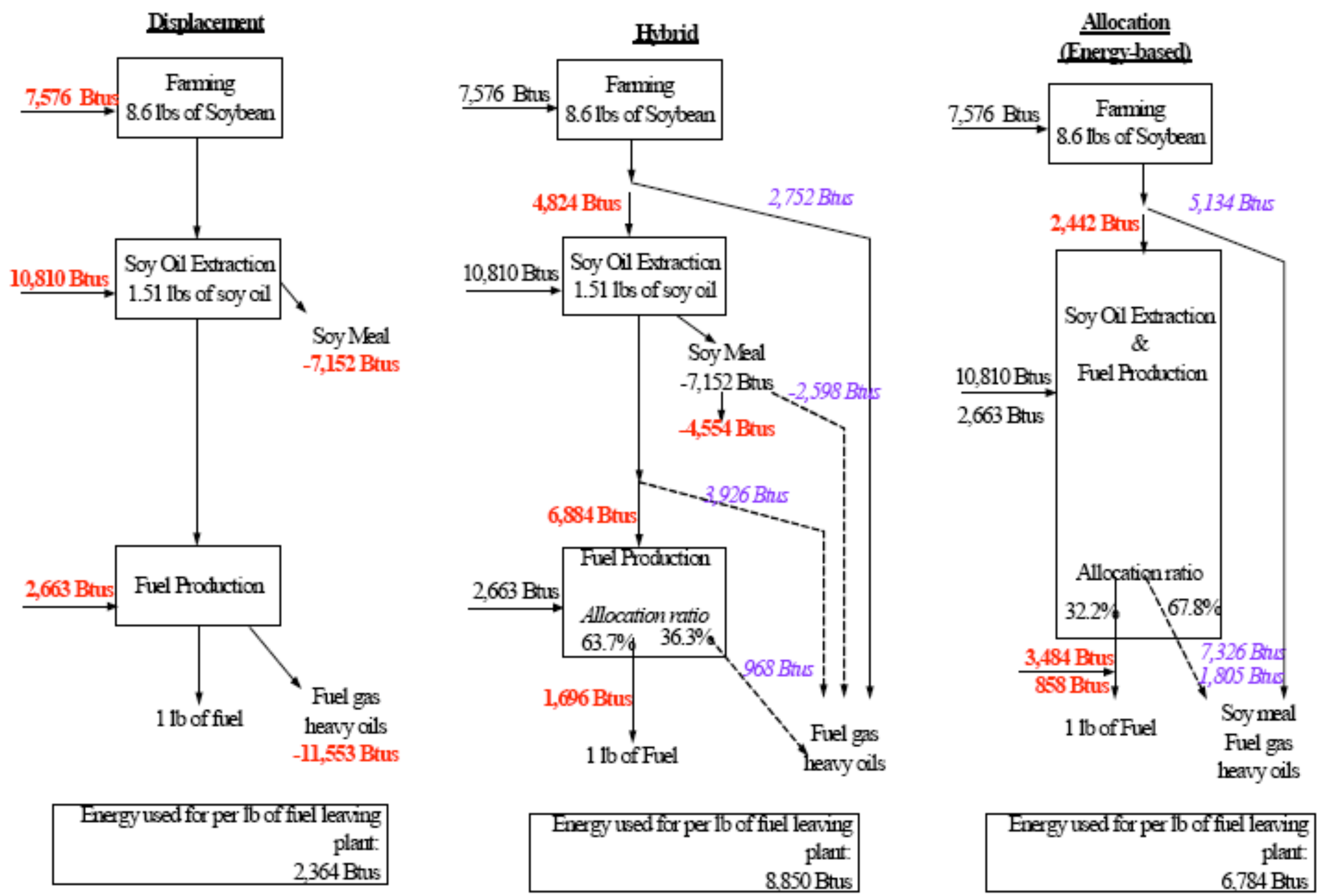
Goals of the LCA

- Stay ahead of the environmental impacts
- Algae fuel pathways are whole systems: we need to assess the integrated system
- Many pathways → no consensus on LCA methods → no comprehensive data
  - Need LCA database for each pathway/process
  - Need standards → breeds competition on level playing field
- Always keep the triple bottom line in view (environmental, social, economic)
  - Make tradeoffs carefully
- Protect industry from outside criticism

Life-cycle assessment methodology

- Allocation
  - Mass
  - Energy
    - Improve biofuel performance by making more waste
    - Neglect quality of energy produced
  - Market value
    - Prices drive production
    - Price not constant
    - Market value + subsidy
- Substitution
  - Credit for avoided processes

Many different ways to do LCAs



Literature is sparse (and real world experience is more sparse)

- Wijffels et al. (2008)

	Major Energy Input	Pro/Con	Net Benefit
Raceway	Harvesting	Inexpensive/Low density	?
Bioreactor	Mixing	High density/High cost	Negative

- Sawayama et al. (1998)
  - Thermochemical liquefaction of *Dunaliella*
  - Fossil energy inputs exceeded outputs by 56% with 15 Mg/ha-yr production

LCA in the news

- (4/21/09) Soladiesel's full life-cycle greenhouse gas (GHG) emissions are 85 to 93 % lower than standard petroleum based ultra-low sulfur diesel (ULSD).

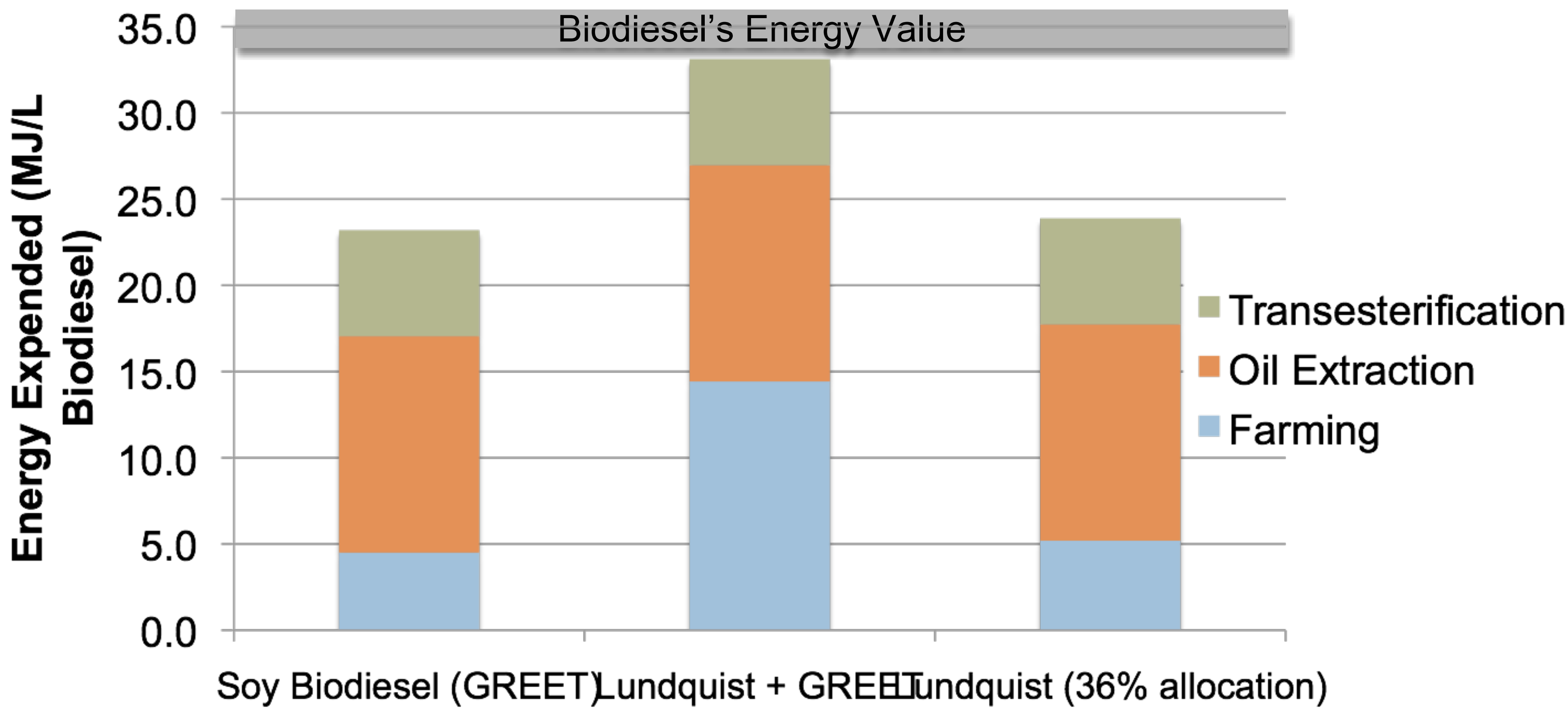
solazyme

LCA's are process specific

- Large differences between experimental yields and average commercial yields

- Huntley and Redalje (2007)
  - *Haematococcus p.* in hybrid bioreactor-pond system.
  - Personal communication: they're working on an LCA

Net Energy Benefit of Biodiesel



NET	1.6	1.1	1.7

Wastewater treatment

- Benemann (HROP)
- Craggs (New Zealand)

Credit for wastewater treatment

- 7300 MG/yr treated
  - 56.2 gal oil/MG treated
  - 850 kWh/MG treated
- National average ~2500 kWh/MG
  - ~1650 kWh/MG savings
- Savings: 28.5 MJ/L biodiesel

IN		CREDIT		SUM
23.9	-	28.5	=	-4.6 MJ/L

12 MTCDE/ha-yr

Concluding thoughts

- Integrated inputs
  - Waste nutrients and waste CO_2
- Integrated products
  - Oil, feed, bio-plastics, high-value chemicals, etc.
- Satisfy the triple bottom line: environmental, economic, and social well-being
  - Positive net energy balance with high photosynthetic efficiency
  - Use land appropriately
  - Reduce water requirements for biofuels

Q&A

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Thanks for your attention.

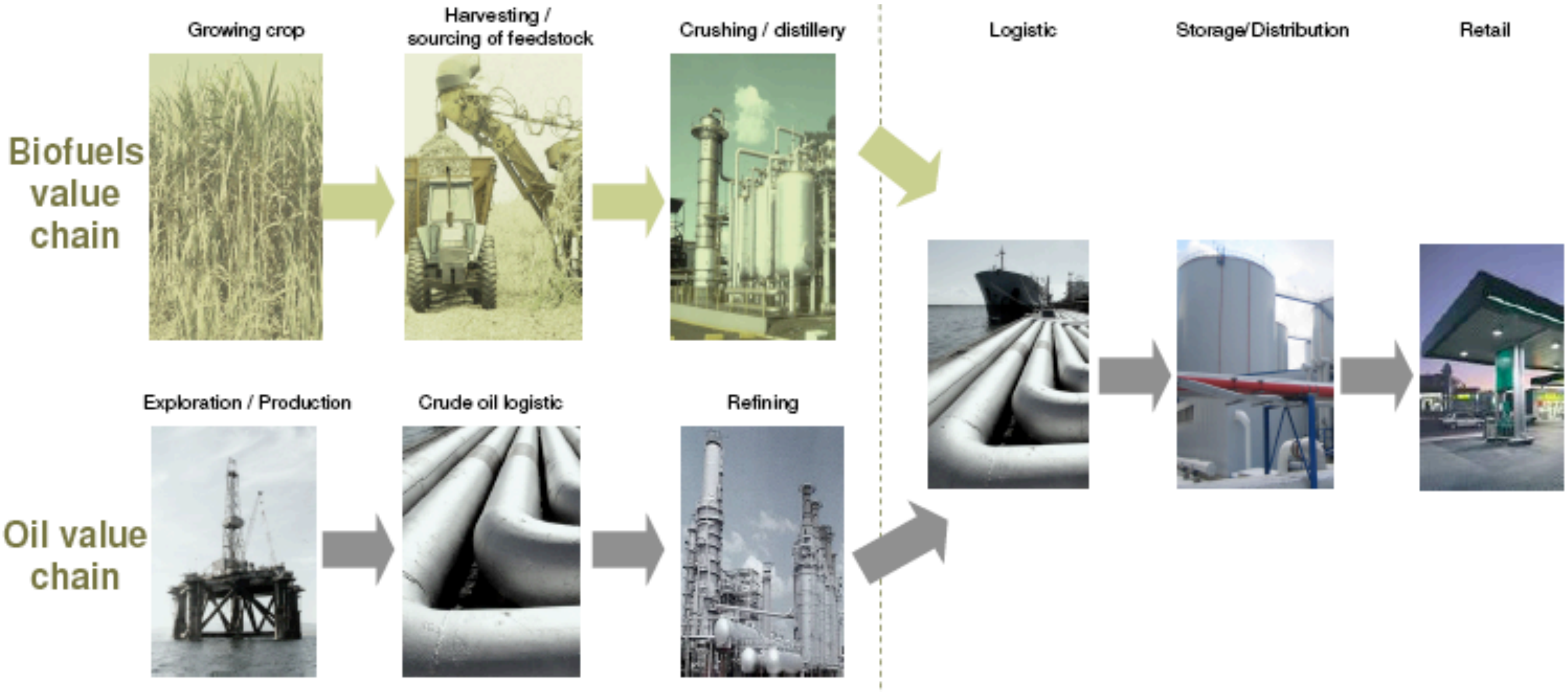
BACKUP SLIDES

Due Diligence (J. Long from Gabriel Partners who invested in Aurora)

The key due diligence for us at the time of 1st investment was:

1) Do we think biodiesel will be a strong economic market in a short enough timeframe?
2) Do we think algae has a likely chance to be a key feedstock for the biodiesel market?
3) Do we think the company can create value in the several related areas of the algae-biodiesel opportunity that the founders considered critical to their success? (and did they have an edge already?)
4) Do we think significant value could be created on a reasonable to small amount of capital? (and do we think the initial operating plan and milestones is the best algae bet to place?)

Aligning oil and biofuel value chains: Investment momentum



Main limitations and bottle-necks of large-scale algae farming

- **Low actual PE (photosynthetic efficiency) and productivities**
- A negative Net Energy Ratio *(due to high energy consumption for water pumping, CO_2 distribution, mixing and harvesting, etc.)*
- Instability of the culture (difficulty in maintaining the selected species) *(and we do need selected species)*
- No experience on large scale (thousands of hectares) cultures
- Large variability in perfomances among culture systems and difficulty to standardize techniques
- Limited data on large scale algae biomass processing (e.g. extraction)

Brune estimates

Parasitic Energy Estimates

PROCESS	% of algal energy @ 20% oil
Nitrogen input	
@ 55 BTU/gm-N	1-22%*
CO_2 supply	7%*
Culture mixing	3.5%
Harvest	2-500%
Oil extraction/conversion	2-30%
Pumping	1.5%
Total	10-40%

*Must utilize waste CO_2 and waste nutrients

The experiments showed that *Nannochloropsis* ha
20 tons of lipid per ha per year in the Mediterra
lipid per ha per year in sunny tropical areas (20

Algae do not make miracles.... they

1 - obey the laws of thermodynamics

2- convert solar energy into biomass by oxygenic photosynthesis

Lundquist et al. assumptions

- 140 ha total land required
- 100 ha of ponds (250 acres)
- 20 MGD wastewater flow (~200,000 persons)
- 4-day annual average residence time
- 20 g/m2/d annual average productivity
- 25% extractible oil

The analysis did not include the energy
necessary to extract the oil and convert it to biodiesel.

- Southern California insolation, temperature & evaporation
- $0.7/gallon oil extraction assumed
- No processing to fuel, oil only
- 100% financed by debt
- 10% interest rate
- 8 yr. commercial term loan (Principal plus interest)
- Straight line depreciation
- Income tax neglected
- Breakeven costs only shown

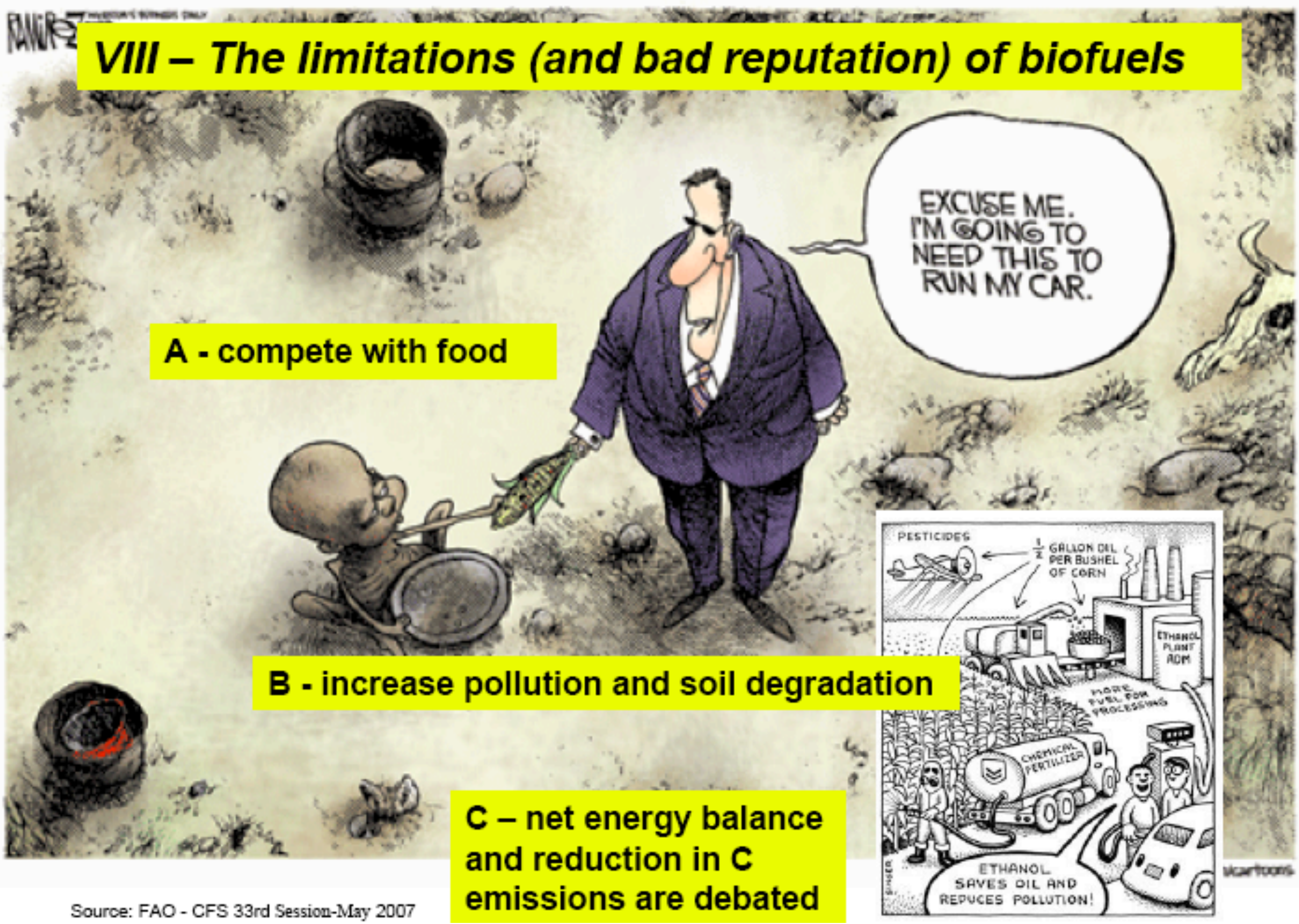
General Atomic

Cost Component	Conventional ($/gal)
Algae growth	$15.00 – $20.00
Water and nutrient supply	$0.40 – $0.70
Carbon dioxide supply	$1.20 – $2.40
Harvesting	$0.80 – $1.60
Oil extraction	$1.50 – $2.60
Inoculation	$1.10 – $5.50
Algae oil subtotal	**$20.00 – $32.80**

Biofuels from microalgae: advantages

1. No need of arable/fertile soils
2. No need of freshwater
3. Biomass production may be combined with wastewater treatment
4. Carbon from flue gases
5. No need of pesticides and herbicides
6. No production of toxic substances
7. No need of GMO
8. *Higher oil yields than traditional crops*
9. *Their cultivation can (and should) be coupled with food production*

VIII – The limitations (and bad reputation) of biofuels



A - compete with food

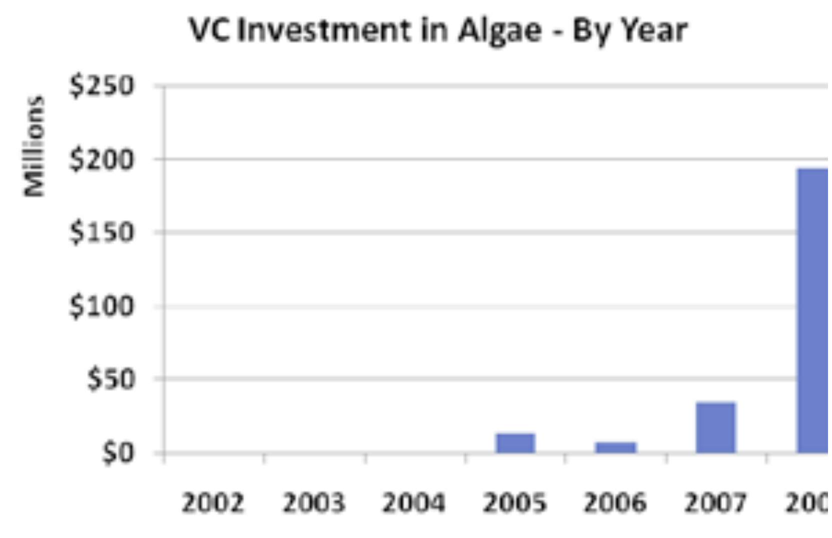
B - increase pollution and soil degradation

C – net energy balance and reduction in C emissions are debated

Source: FAO - CFS 33rd Session-May 2007

- Biofuels companies raised $904 million in venture capital in 2008, up 37% from 2007.
- Within the bi… ethanol companies r… % of the
- biofuels total… diesel companies w… biomass rais…
- $150M (17%), biodiesel ven… $125M (14%), grain ethanol $21M (2%),
- while biogas raised $18M (2…

- Cellulosic Ethanol: $396M
- Algae Biodiesel: $195M
- Biomass: $150M
- Biodiesel: $125M
- Grain Ethanol: $21M
- Biogas: $18M



Although oil is currently trading at $40/barrel, the long-term supply outlook is daunting. The IEA forecasts the need to *bring online 64 million barrels per day, or six Saudi Arabia's worth, of new production, by 2030 – just 20 years away – to meet increased demand and to offset declines* from existing fields.

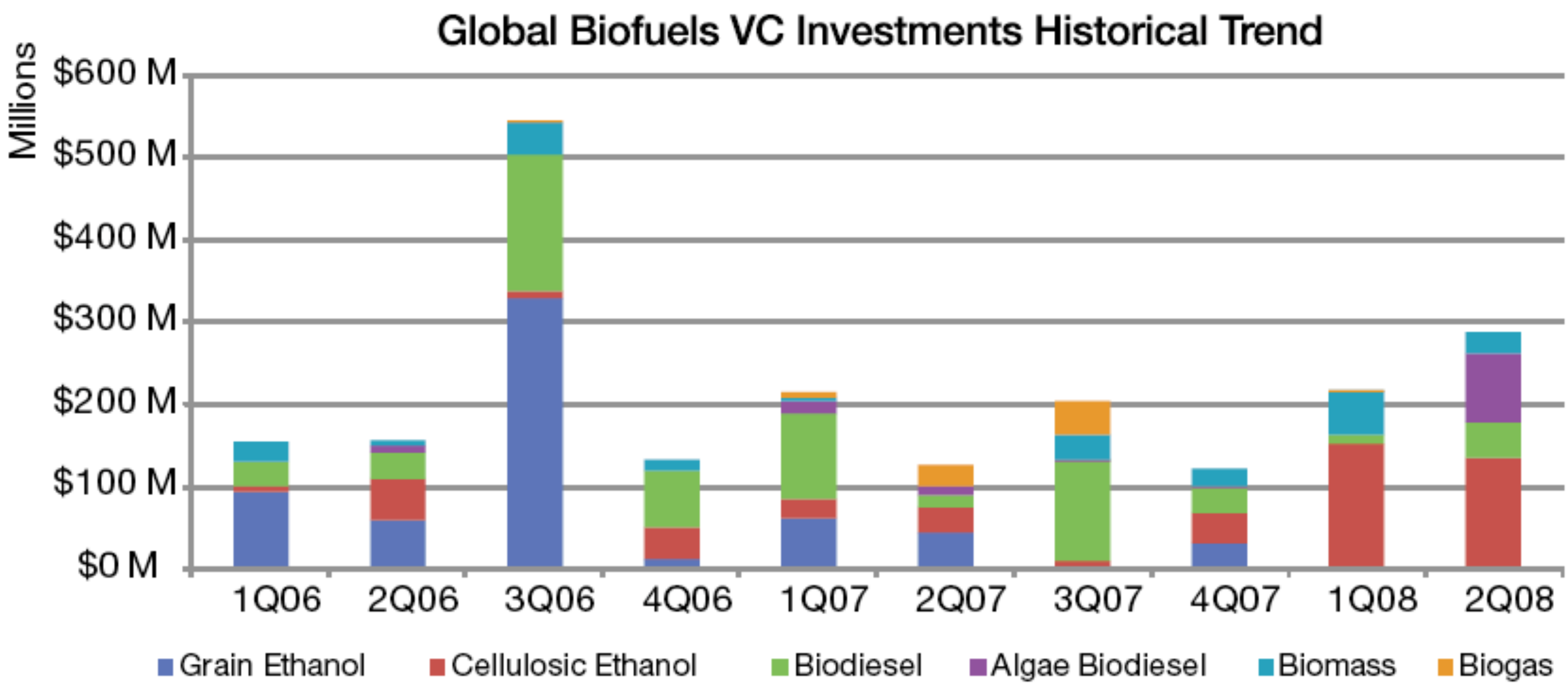
the need to reduce our dependence on petroleum, which provides 37% of total energy consumed worldwide and 90% of all transportation fuel,

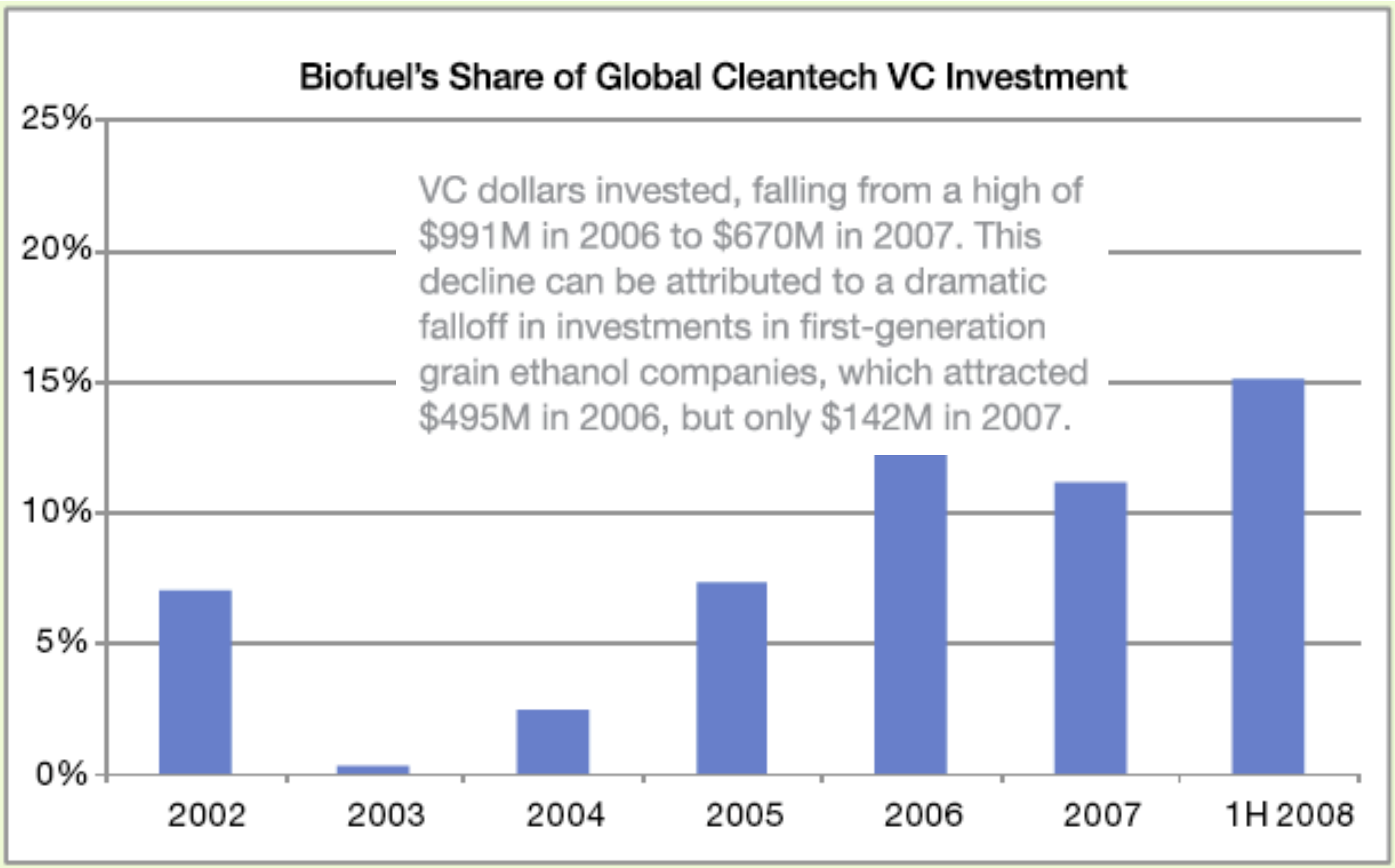
Oil
Climate Change
China and India

Totals:

- Meet growing demand for liquid fuels
  - Heavy movers
  - Airplanes
- Climate change
- China and India

Global VC Investment




Biofuel's Share of Global Cleantech VC Investment
25%
20%
15%
10%
5%
0%
VC dollars invested, falling from a high of $991M in 2006 to $670M in 2007. This decline can be attributed to a dramatic falloff in investments in first-generation grain ethanol companies, which attracted $495M in 2006, but only $142M in 2007.
2002
2003
2004
2005
2006
2007
1H 2008

Theoretical Case Practical Cases

	Theoretical Case	Practical Cases
Solar energy	→ Weather data	Weather data
% PAR	45.8%	45.8%
ght transmission efficiency	100%	90%
hoton absorption efficiency	100%	50%
Photosynthetic efficiency	26.7%	26.7%
Biomass accumulation efficiency	100%	60%
% Oil	70%	50%
Annual Oil Production (gal ·ac^{-1}·yr^{-1})	25,600 (Kuala Lumpur) 27,700 (Denver) 29,000 (Málaga) 30,800 (Tel Aviv) 32,600 (Honolulu) 35,500 (Phoenix)	**,900** (Kuala Lumpur) **,300** (Denver) **,600** (Málaga) **,900** (Tel Aviv) **,300** (Honolulu) **,500** (Phoenix)

Table 1 Comparison of some sources of biodiesel [7]

Crop	Oil yield ($L\ ha^{-1}$)
Corn	172
Soybean	446
Canola	1,190
Jatropha	1,892
Coconut	2,689
Palm	5,950
Microalgae[a]	136,900
Microalgae[b]	58,700

[a] 70% oil (by wt) in biomass

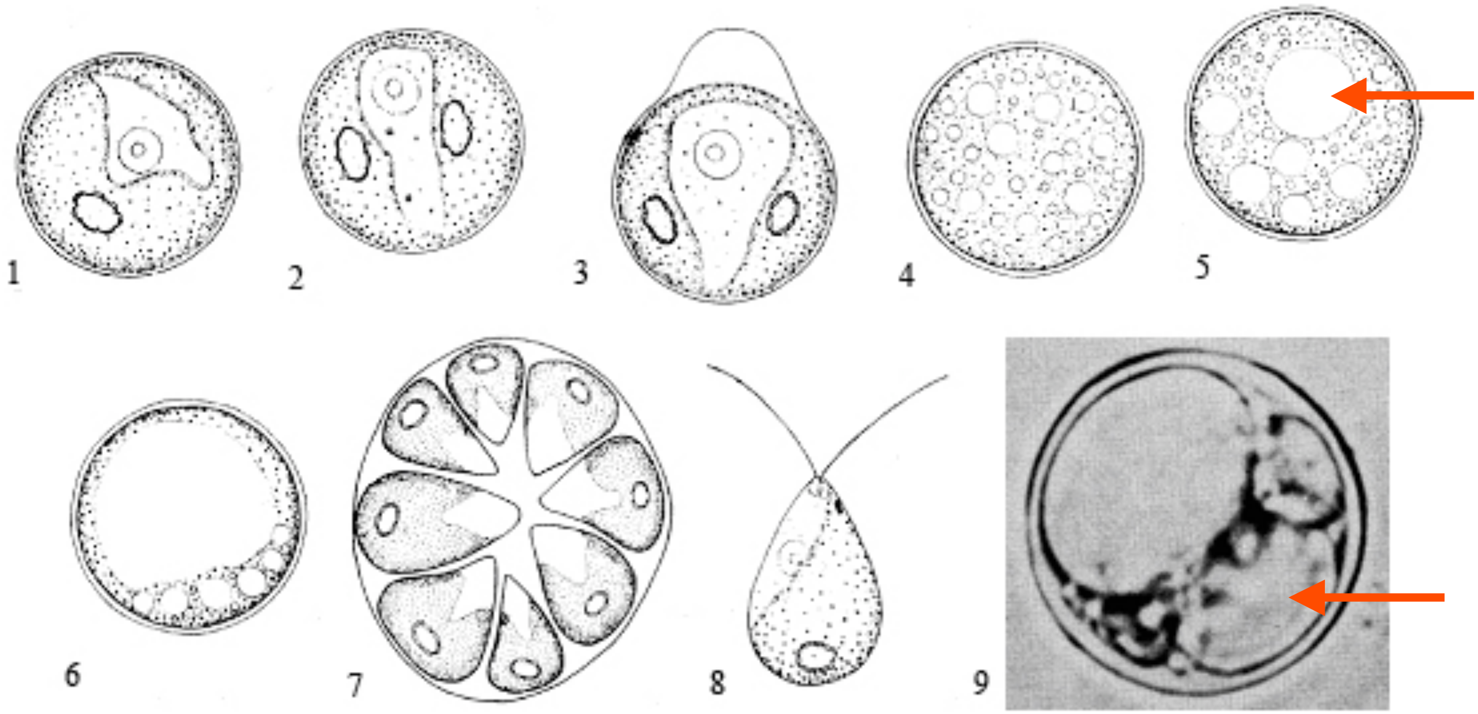
[b] 30% oil (by wt) in biomass

Produce renewable energy with

- less fossil energy
- less fresh water
- less land

Algae — WT — Extraction — Biodiesel

Neochloris oleoabundans



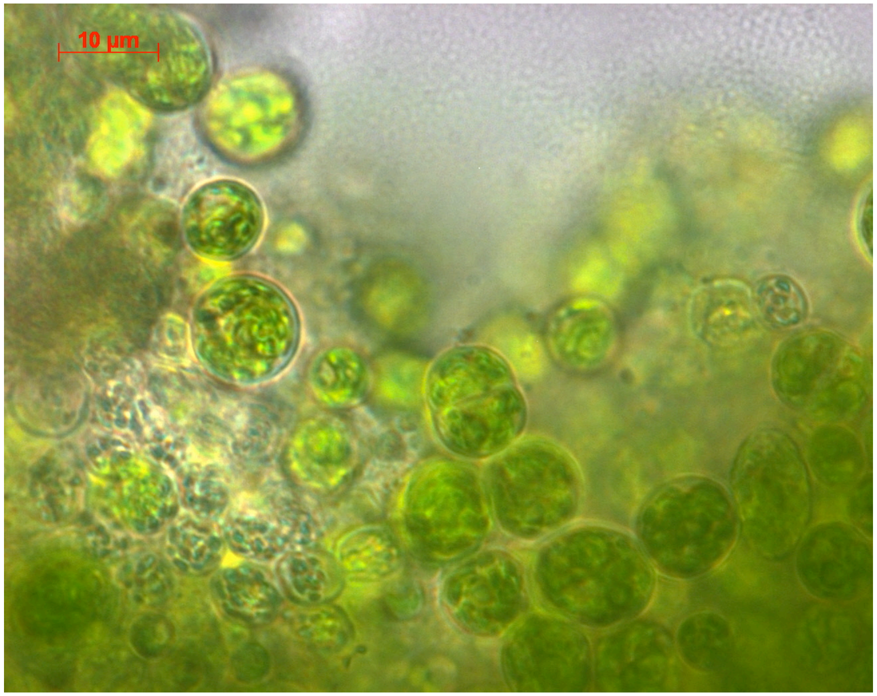
N-Stress and Lipid Accumulation

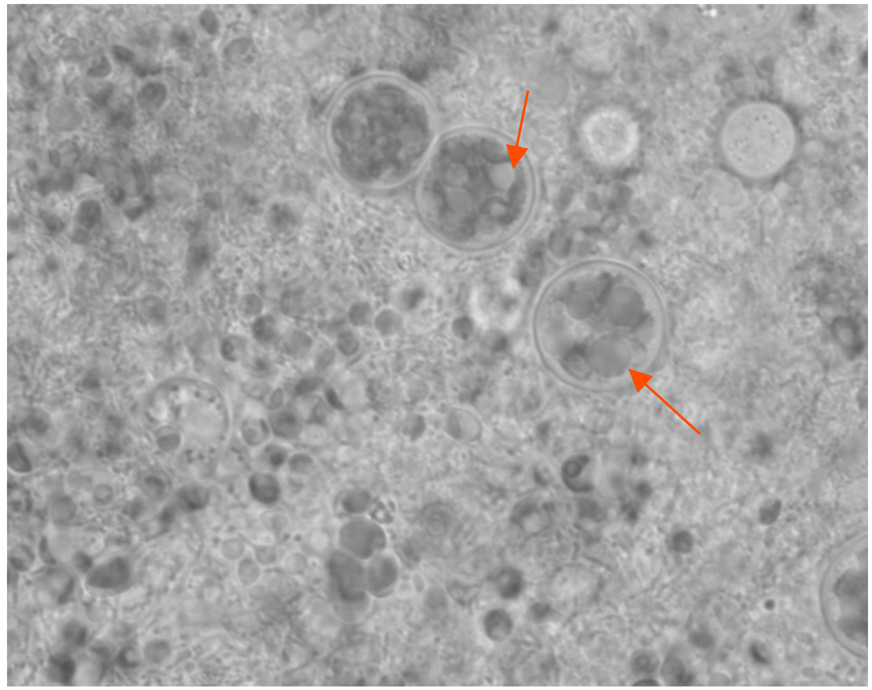
- ↓ amino acids → ↓ protein synthesis
- Cell division slows/stops
- Chlorophyll breaks down
- Shunting chemical energy to N-poor compounds

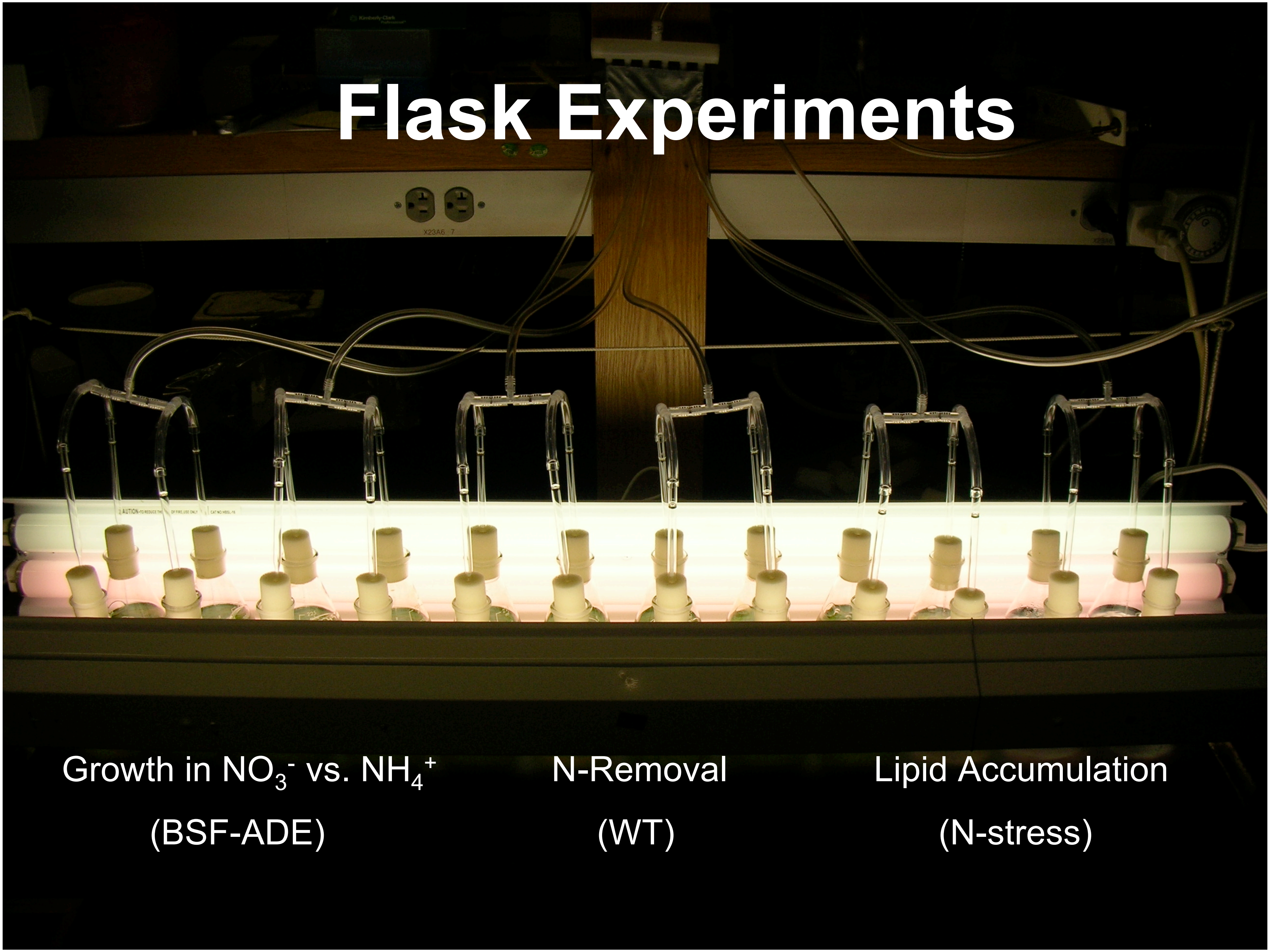
↓ N → ↑ Lipids → ↓ Productivity

Algae — WT — Extraction — Biodiesel

Neochloris oleoabundans






Flask Experiments
Growth in NO_3^- vs. NH_4^+
(BSF-ADE)
N-Removal
(WT)
Lipid Accumulation
(N-stress)

Funding

- May 2006: Aurora BioFuels Takes Top Prize ($25K) in the UC Berkeley Business Plan Competition
- March 2007: The company raised $3.21M in Series A (Oak Investment Partners and Noventi Sorgenia Ventures)
  - to validate proof of concept.
- June 2008: $20M in series B (Oak Investment Partners, along with Noventi and Gabriel Venture Partners) Use the funds
  - to expand its field operations and
  - to increase its efforts to optimize the production cycle of growing, harvesting and extracting microalgae to produce bio-oil

Comments from J. Long (Gabriel partners)

- 18 months ago Aurora had several legitimate biz models it could exploit or mix. so we were confident they could find a way to make money.
- The goal of the Series-A was to get smarter about the opportunity while building the biotech and engineering technology and answering some key unknowns then finalizing rev-1.0 of the biz model prior to raising the Series-B.
- In most VC cases the expected specific biz model is known prior to investing but in this case the options were known and positive and there was no need to put something 'in stone' ahead of time.

Exit Options

- Aurora has an exit rich ecosystem, (assuming algae becomes valuable) as there are dozens of large companies worldwide who would want to be in the biodiesel business (M&A)
- Besides it is one of the few areas where an IPO is very possible.
- When we made the investment we did an exit analysis which was quite positive since the exit options were many and varied.

Aurora: Position Statement

“ *Aurora’s proprietary technology (read: genetically modified), developed at The University of California, Berkeley, allows Aurora BioFuels to create bio-diesel with 125X higher yields and 50% lower costs than current production methods.”*

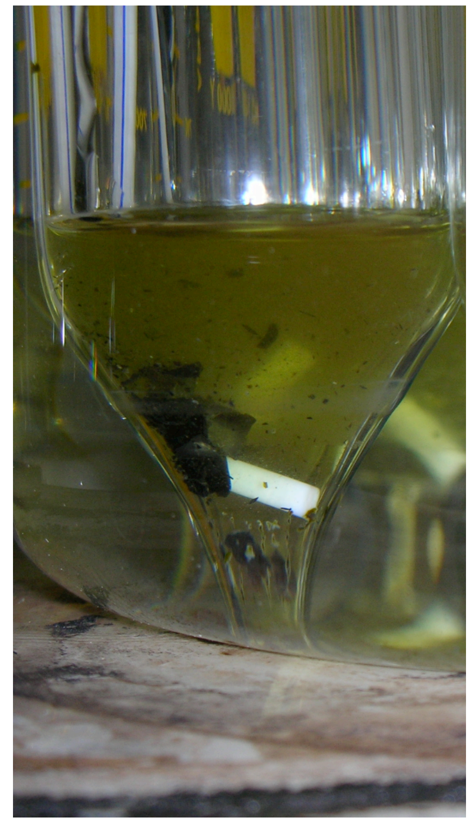
Life-Cycle Perspective

we propose a hypothetical
situation in which algae at a density of 1 g d.w./L is being harvested by centrifugation. We assume this algal biomass contains 25% oil on a dry weight basis and the extracted oil has a similar density (0.916 g/ml) and calorific value (39.6 MJ/kg) to soybean oil [13]. If we only consider the oil harvested from 1 m3 of suspended algae, the energy obtained is 2.75 kWh. As referenced above, harvesting could potentially require up to 8 kWh/m3, suggesting this is not a viable harvesting strategy when used as a primary method.

Algae — WT — Extraction — Biodiesel

Analytical Approach

→ Dry Biomass → Solvent Extraction → Crude Lipid Extract



- Modeled commercial-scale technology
  - Hexane
  - Iso-propanol

Algae — WT — **Extraction** — Biodiesel

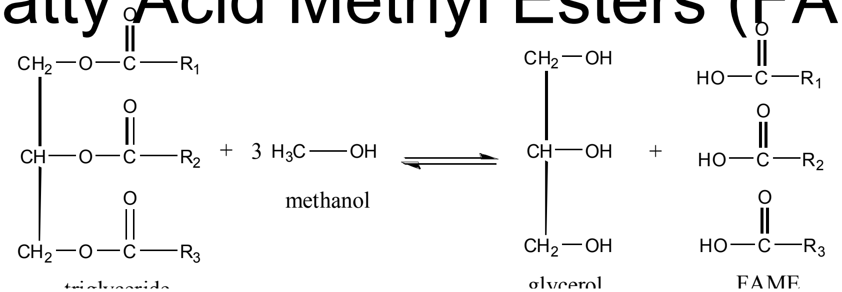
Analytical Approach

→ Dry Biomass → Solvent Extraction → Crude Lipid Extract

↓

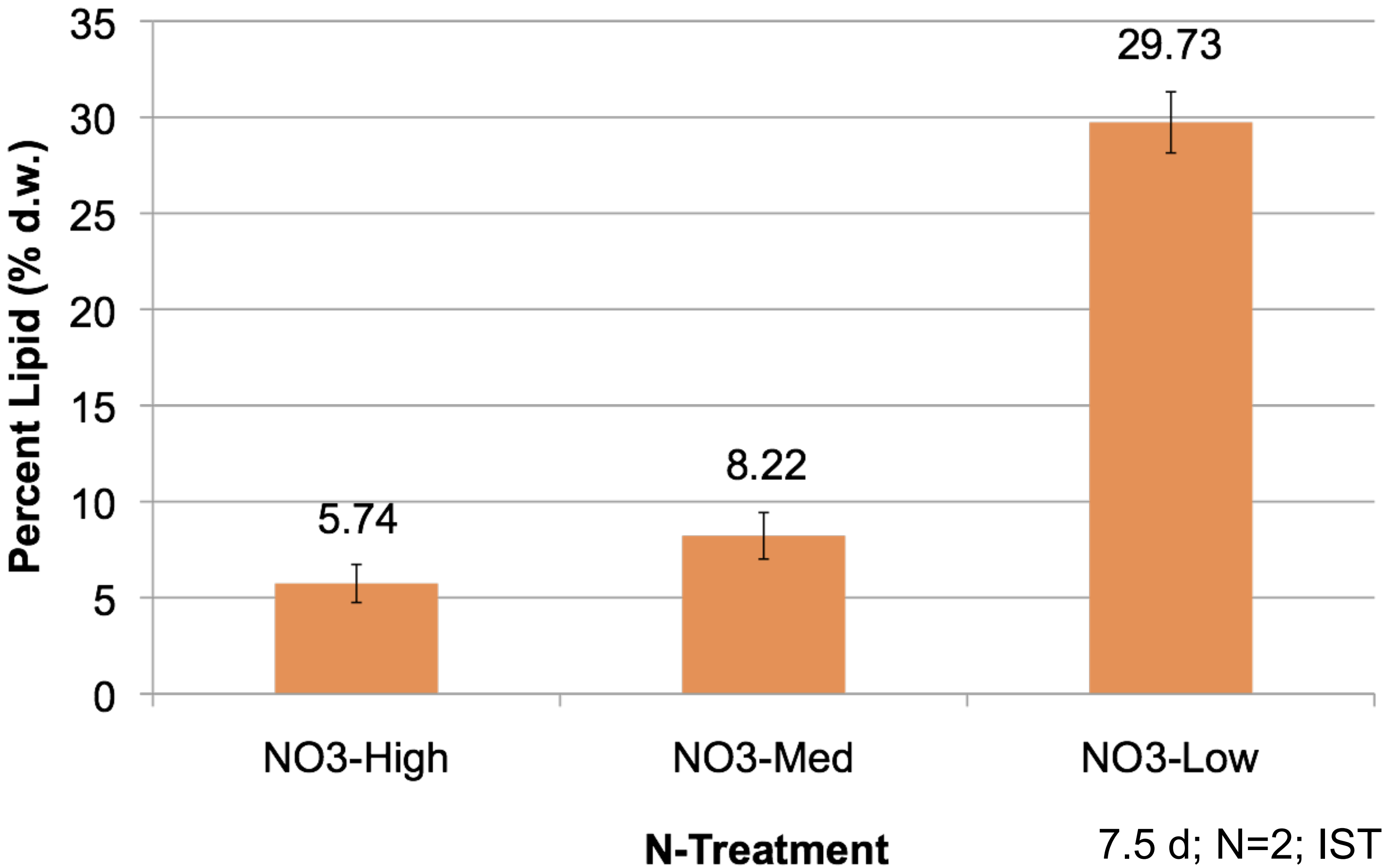
Transesterification

Fatty Acid Methyl Esters (FAME)



Algae — WT — Extraction — Biodiesel

N-stress induced lipid accumulation



7.5 d; N=2; IST extraction

Case Study: Blue Spruce Farm

Model	Units	Value
8-Months Average Solar Insolation[a]	Kwh/m^2/day	4.70
Total Yearly Energy[b]	Kwh/m^2	1128
	MJ/m^2	4061
PAR[c]	MJ/m^2	1909
Total Energy Converted[d]	MJ/m^2	95
Biomass Equivalent[e]	g algae/m^2/day	17.3
	kg algae/m^2	4.1
	MT algae/ha	41

[a] Solar insolation data taken from a 30-year average of monthly solar radiation (1961-1990) with a flat panel collector in Burlington, VT.
[b] Year energy incident per land area is computed with a year defined as 8 months or 240 days
[c] Assuming sunlight is 47% PAR
[d] Assuming 5% photosynthetic efficiency
[e] Assuming 23 MJ/kg dry algae, as determined by bomb calorimetry

Case Study: Blue Spruce Farm

Oil Equivalent[f]	g oil/m^2/day	4.9
	kg oil/m^2	1.2
	MT oil/ha	11.8
	L oil/ha	13,139
	gallons/ha	3,471
	gal/acre	1,404
Oil Revenue[g]	$/ha	12,253
	$/acre	4,957
	$/m^2	1.23

[f]Assuming dry biomass is 30% oil by mass; oil is extracted with 95% recovery with a density of 0.90 g/ml oil.

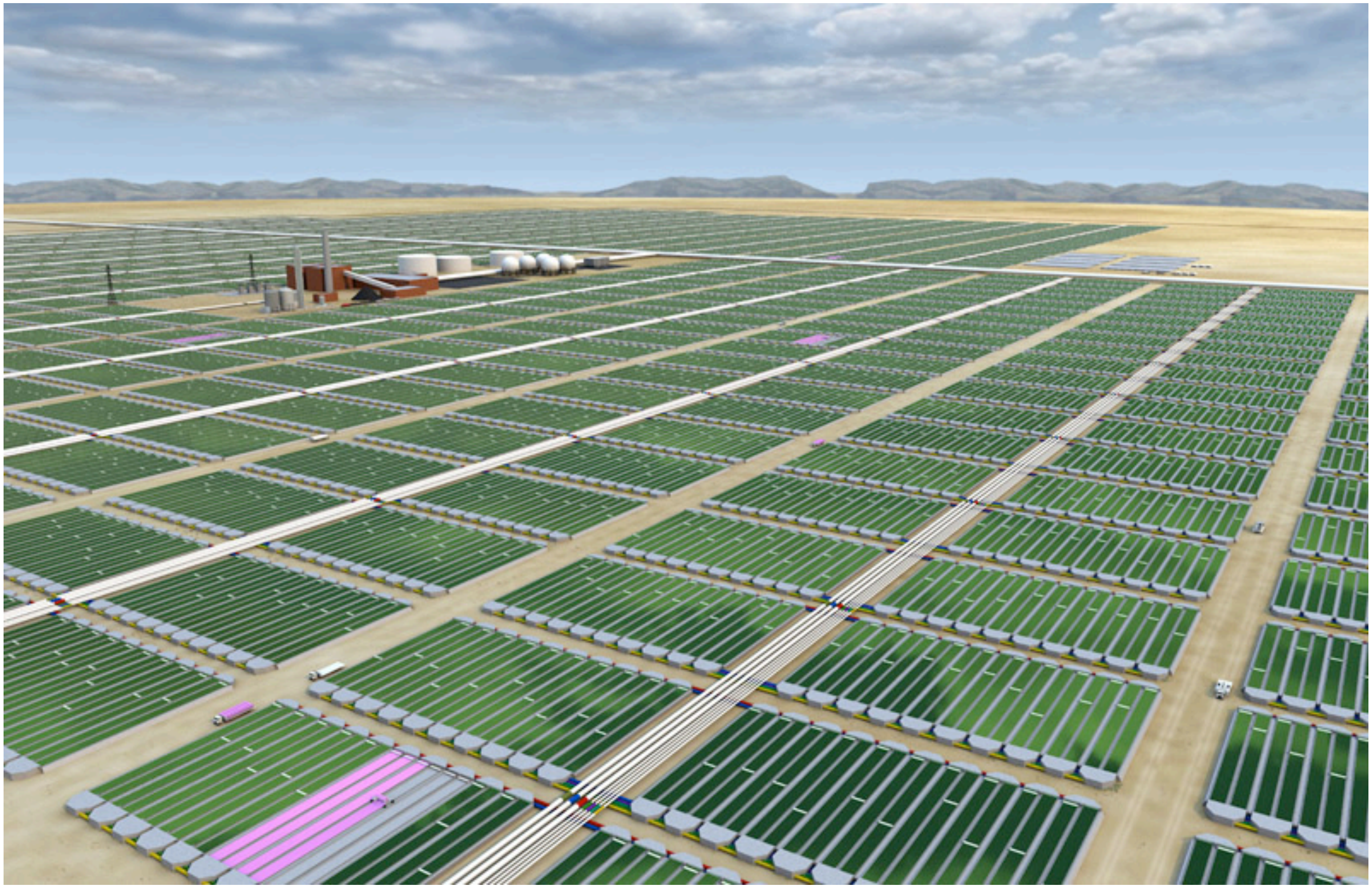
[g] Price per kg oil estimated from PFL Fuel Services biodiesel report for May 2nd, 2008. The cost of food-grade feedstock oil (bleached, deodorized, degummed) was 57.3 cents/lb. Since algae oil may not be refined on-site, a price of 47 cents/lb, which is 103.6 cents/kg or **$3.48/gal**, was assumed.

Case Study: Blue Spruce Farm

Model	Units	Value
Average Yearly TN/cow[a]	kg TN/yr	73
Number of Cows[b]	cows	1000
TN Destined for Algae Reactor[c]	MT N/yr	73
N-Uptake Rate into Algae Biomass[d]	MT/ha·yr	3.3
N-Supported Total Algae Reactor Area	ha	22.0
	acres	54.3
Biomass Production	MT total	913
Total Yearly Oil Production[f]	MT total	260
	L	288,958
	Gal	76,335
Total Yearly Oil Revenue[g]	USD$	269,469

Preliminary, Sensitive, and Simplistic

Is this possible?
You can help decide…



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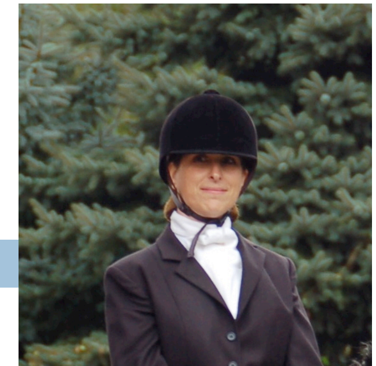

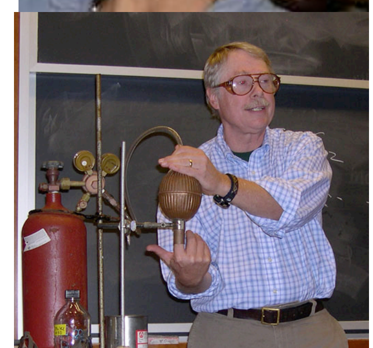

Q&A