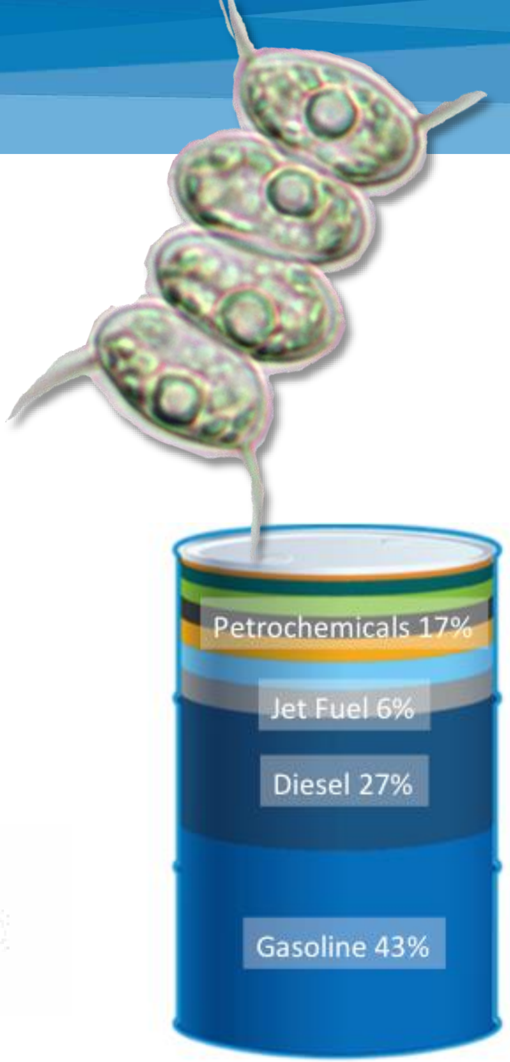
Algae Biorefinery Development for Biofuels and Bioproducts

Lieve Laurens

Bioenergy 2016
Washington, DC
July 14, 2016

Algae-derived Commercial Products



Reduce cost of algal biofuels:

- Harness unique position of algae as highly efficient **photosynthetic cell factories**
- Identify **key targets** to contribute to lowering the overall cost of algal biofuels production
- Quantify impact of major components supporting a **multi-product algal biorefinery model**

$$C_{\text{production}} = \sum_{i} C_{\text{capital},i} + \sum_{j} C_{\text{operating},j} - \sum_{k} C_{\text{co-products},k}$$

- Analogous to **replacing the whole barrel paradigm**; low volume product streams can provide large fraction of value
- **Integrate biomass composition** with cultivation and conversion performance

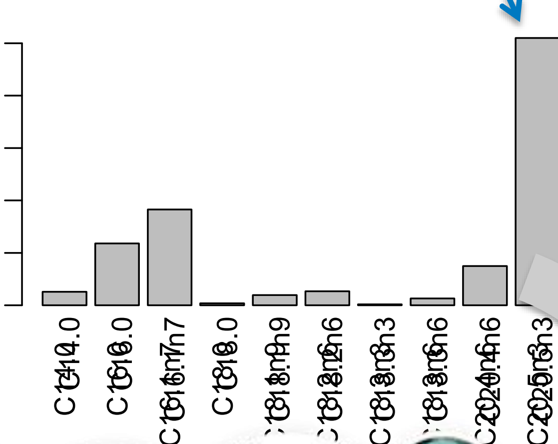
Algae as Photosynthetic Chemical Factories

Co-product criteria for commercial success:

1. Identical to an existing chemical
2. Functionally identical
3. New material with unique functional performance

Biomass components	Product
Polyunsaturated fatty acids	**Epoxies, polyols, nutraceuticals**
Phytol	**Surfactants, fuel additive**
Triglycerides	**Biopolymers, coatings, Rubber**
Glycerol	**Di-acids / nylon production**
Carbohydrate monomers	**Fermentation products (including ethanol and di-acids)**
Antioxidants	**Health food additives**
Whole biomass	**Food/feed markets**

EPA C20:5*n*3 fatty acid

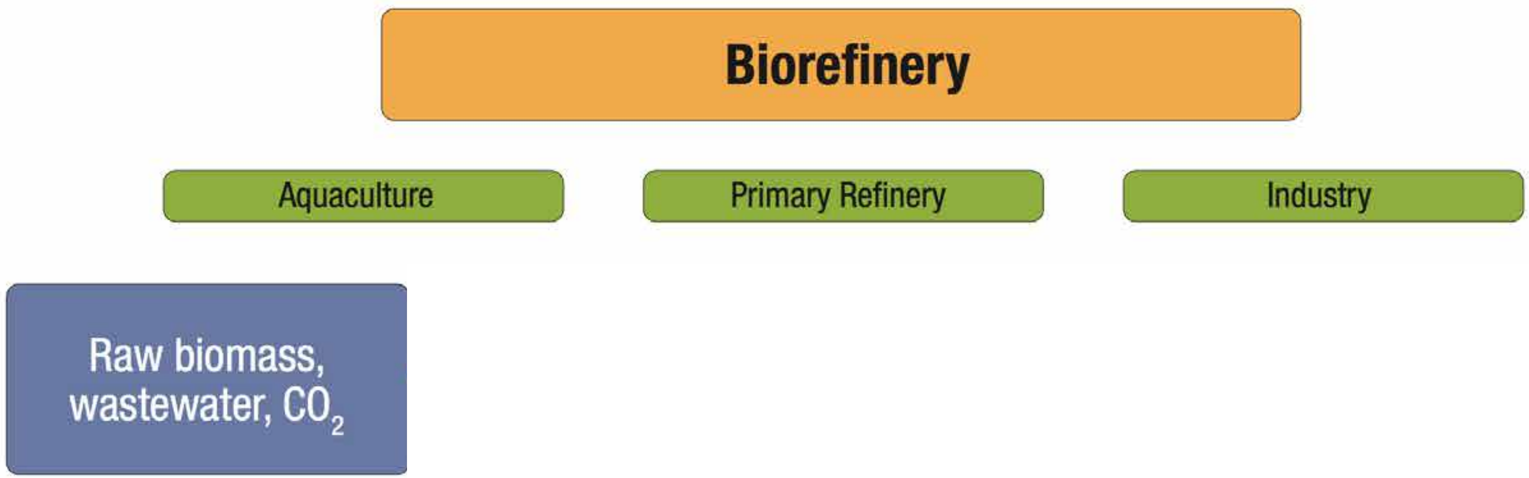


Biomass production cost: $491/ton*

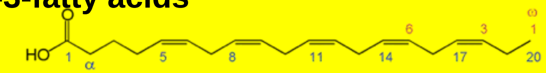
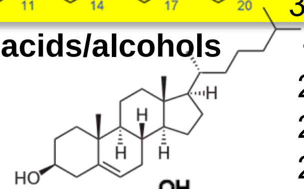
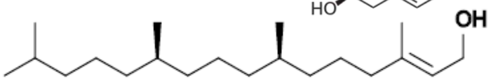
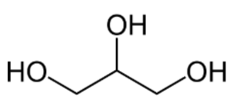
+ Co-products biomass value $500-$800/ton

*Davis et al 2016: http://www.nrel.gov/docs/fy16osti/64772.pdf

Algal Biorefinery

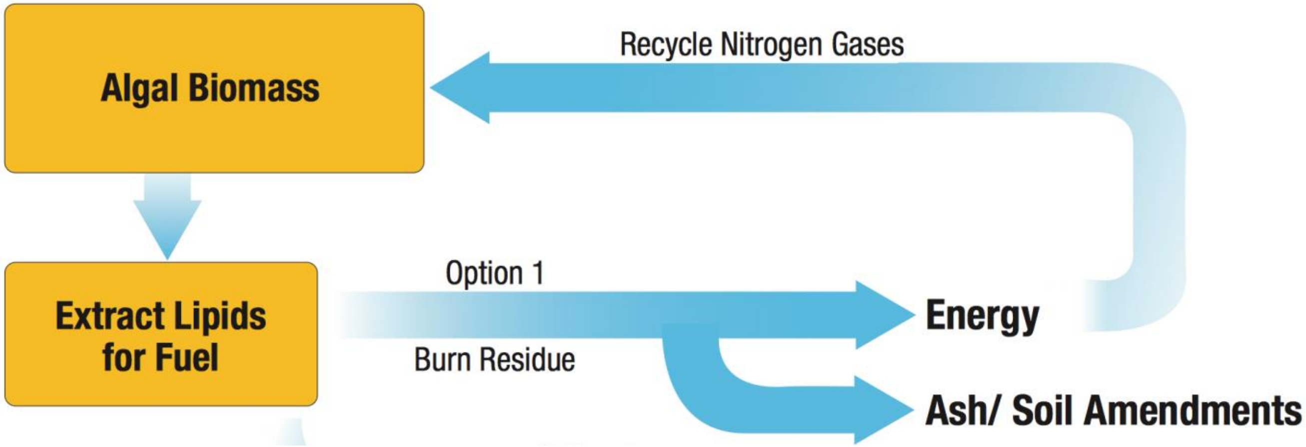


Algae Biorefinery Potential – high volume products

Biomass components	wt %	Product	Market* (ton/yr)
Fatty acids	10-45	Hydrocarbon fuel products (U.S. consumption)	16,000,000
Omega-3-fatty acids 	3-10	Polyols – epoxy resin – polyurethane	8,000,000 – 11,000,000
	3-10	Nutraceuticals	22,000
Hydroxy-, branched-, fatty acids/alcohols	~1	Surfactants, fuel additives	3,500,000
Sterols 	2-4	Surfactants	6,400,000
	2-4	Phytosterol nutra-/pharmaceuticals	25,000
	2-4	Emulsifiers	N/A
Phytol 	3-4	Raw material for vitamin E, fragrance, soaps…	1
	3-4	Surfactants, fuel additives	3,500,000
Polar lipids	10-35	Ethanolamine	600,000
	10-35	Phosphatidylcholine, phosphoinositol and phosphatidyl ethanolamine (lecithin)	20,000-30,000
Glycerol 	2-6	Di-acids for nylon production	2,500,000
	2-6	Feed, pharmaceuticals	25,000
Fermentable sugars (glucose, mannose)	10-45	Polylactic acid (PLA) polymers	300,000
	10-45	Di-acids (e.g. succinic, muconic, adipic acid)	2,500,000
	10-45	Ethanol	60,000,000
Mannitol	3-6	Polyether polyols	2,300,000¶
Alginate	~3-5	Alginate additives	N/A
Starch	5-40	Polysaccharide-derived bioplastics	2,000,000
Protein	19-40	Thermoplastics	5,000,000
Amino acids/peptides	19-20	Polyurethane	11,000,000
Amino acids/peptides	19-20	Biobutanol, mixed alcohol fuels	740,000
Whole biomass	100	Animal/Fish feed	16,000,000 – 190,000,000

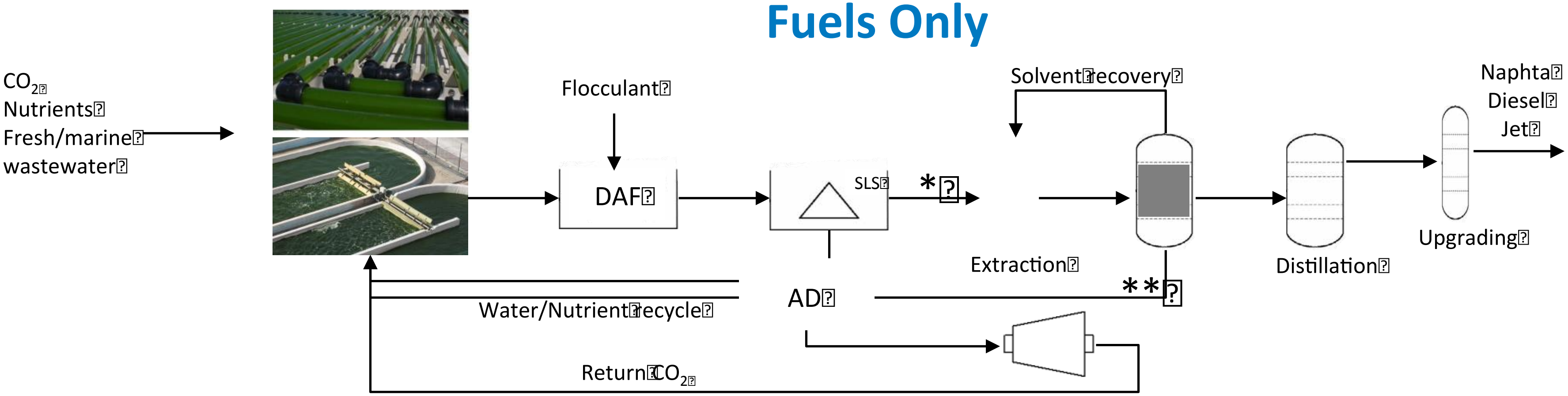
* Market size estimated based on displacement volumes ¶ based on sorbitol market size

5 Potential Options for co-Products

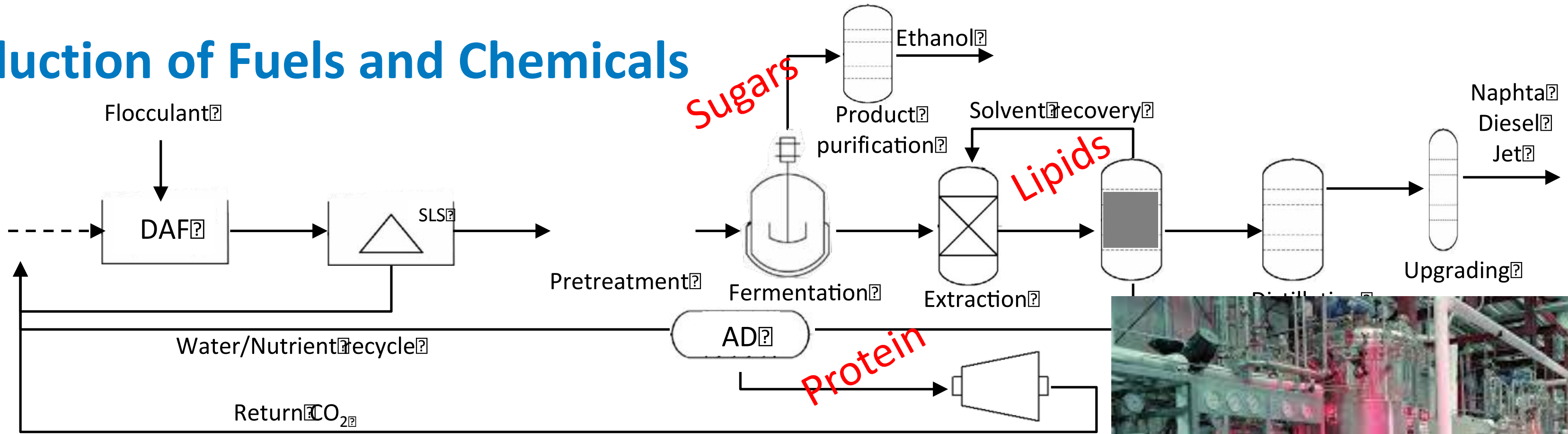


Algal Biorefinery Process

Fuels Only

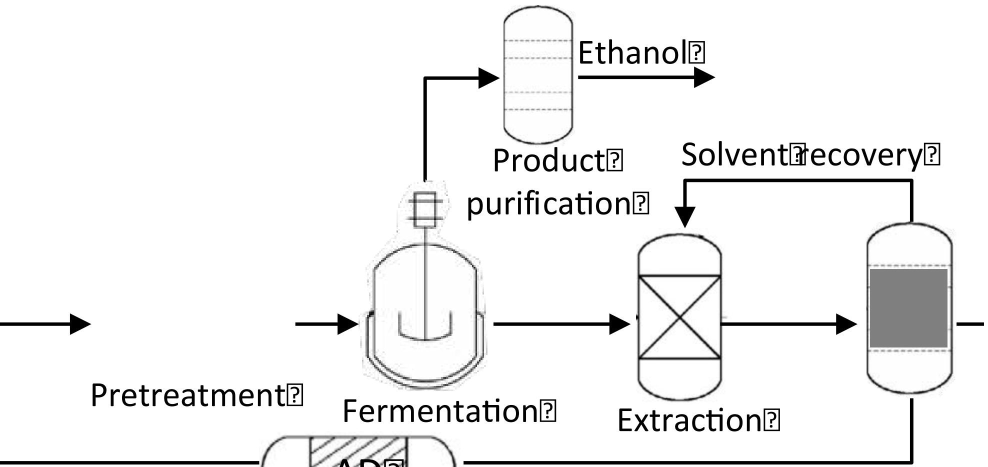


Co-production of Fuels and Chemicals

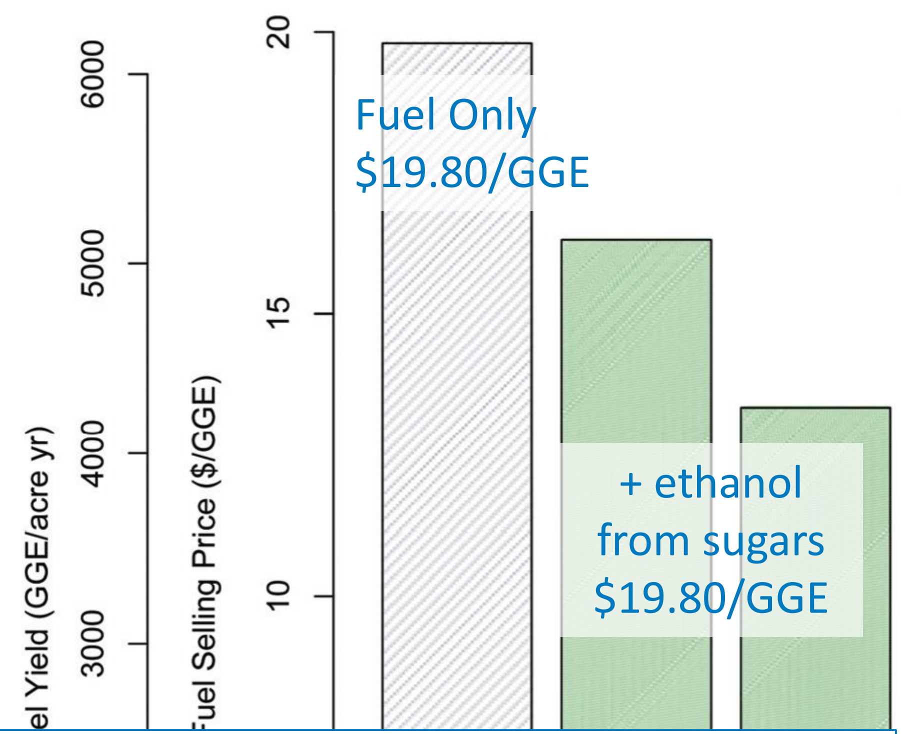


Davis et al 2014: www.nrel.gov/docs/fy14osti/62368.pdf
Laurens, L. et al., 2015, Green Chemistry, 2015, **17**, 1145-1158
Dong, T., et al., 2016. Algal Research, *doi:10.1016/j.algal.2015.12.021*

Algae Biorefinery



Fuel	Yield
Lipids (% DW)	27
Diesel Fuel Energy (10^3 btu/ton)	8,671
Fermentable Sugars (% DW)	48
Ethanol (gallon/ton)	
Gasoline Fuel Energy (10^3 btu/ton)	
Combined Energy (10^3 btu/ton)	
Total Gasoline Gallon Equivalent per ton biomass (GGE/ton)	



Algal Biomass Fractionation to Fuels Process Engineering Analysis

Dilute Acid Pretreatment, Sugar Fermentation, Lipid Extraction and Purification, Hydrotreating to Paraffins (RDB)

All Values in 2011$

MFSP (Gasoline-Equivalent Basis):		**$4.35 /GGE**
Contributions:	Feedstock	**$3.05 /GGE**
	Conversion	**$1.30 /GGE**
Total Fuel Production (RDB + Ethanol)		62.4 MMGGE/yr
RDB Production		46.3 MMGGE/yr (44.1 MM gal/yr)
Ethanol Production		16.1 MMGGE/yr (23.7 MM gal/yr)
Total Fuel Yield (RDB + Ethanol)		141.1 GGE / dry U.S. ton feedstock
Feedstock Cost		$430.00 /dry U.S. ton feedstock (ash-free dry weight)
Internal Rate of Return (After-Tax)		10%
Equity Percent of Total Investment		40%

Value Proposition – Focus on co-Products

Product	Revenue Potential ($MM/yr)	Yield (ton/yr)	Global Market Volume (ton/yr)	Process Complexity (Low/Medium/High)	Industry Involvement
Primary fuel product for reference					
Hydrocarbon fuels (from lipids)	$40.7	12.8 MM gal/yr	56,900 MM gal/yr[11] (U.S. Consumption)	Low	Sapphire, Cellana, GAI
Sugars					
Succinic acid (from sugars + glycerol)	$136.3	78,000	441,000[15-23 A]	High	Myriant, Bioamber, Succinity/BASF, Reverdia
Hydrocarbon fuels (from sugars + glycerol)	$20.7	6.4 MM gal/yr	56,900 MM gal/yr[11] (U.S. Consumption)	Medium	Amyris, Solazyme, LS9
Lipids					
Surfactants from sterols	$16.6	7,000	6,414,000[4]	Medium	BASF, Solazyme
Polyols via polyunsaturated fatty acids	$24.1	15,200	8,047,000[13]	High	Cargill, Dow, Urethane Soy Systems, Bio-Based Technologies, Arctic Foam (UCSD)
Protein					
Protein → C4+ OH (SNL/Liao process)	$9.7	9,100	734,400 as isobutanol[14] 36,400 as plasticizer[14]	Medium	[Early R&D]
Animal/fish feed	$4.0 - $16.0	45,700	16,538,000 - 190,126,000[6-9]	Low	Mars, GAI, Europe/Asia company interests
Bioplastics	$41.8	69,900	1,545,000[24]	Medium	Algix
Galdieria via mixotrophic growth on protein stillage + HTL	$20.3	6.4 MM gal/year[C]	56,900 MM gal/year[11] (U.S. Consumption)	Medium	[Early R&D]

IHS Chemical Economics Handbook, Epoxy Resins, May 2014 & Surfactants, Household Detergents and their raw materials, June 2013

*Based on mid-harvest *Scenedesmus* biomass and demonstrated composition

R. Davis (NREL) preliminary unpublished report

Summary

- Inclusion of co-products in algal biorefinery processes improves overall economics – **30% reduction in Fuel Selling Price**
- Value-added co-products are natively produced in **photosynthetic algal cell factories**
- Novel products may support **novel conversion process pathways** including co-product development alongside fuels
- **Biomass composition drives conversion** efficiency parameters and is highly linked with cultivation
- Future R&D to support advanced algal systems economics based on the isolation and commercial **harnessing of high-value, large market bioproducts** and mapping over cultivation

Algae Testbed Public-Private Partnership

U.S. DEPARTMENT OF ENERGY

Thank You!

Lieve.Laurens@nrel.gov

www.nrel.gov

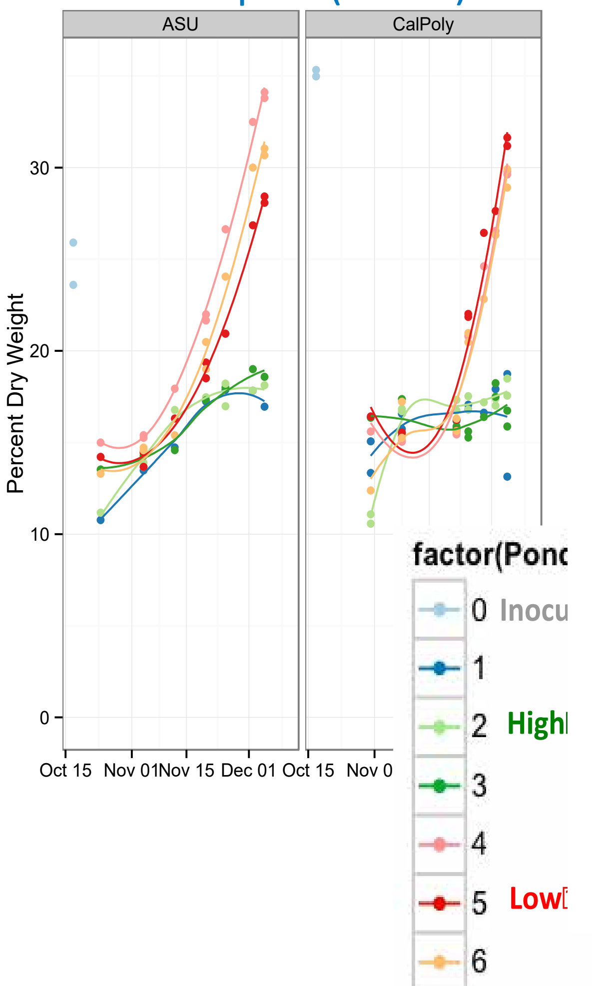
NREL

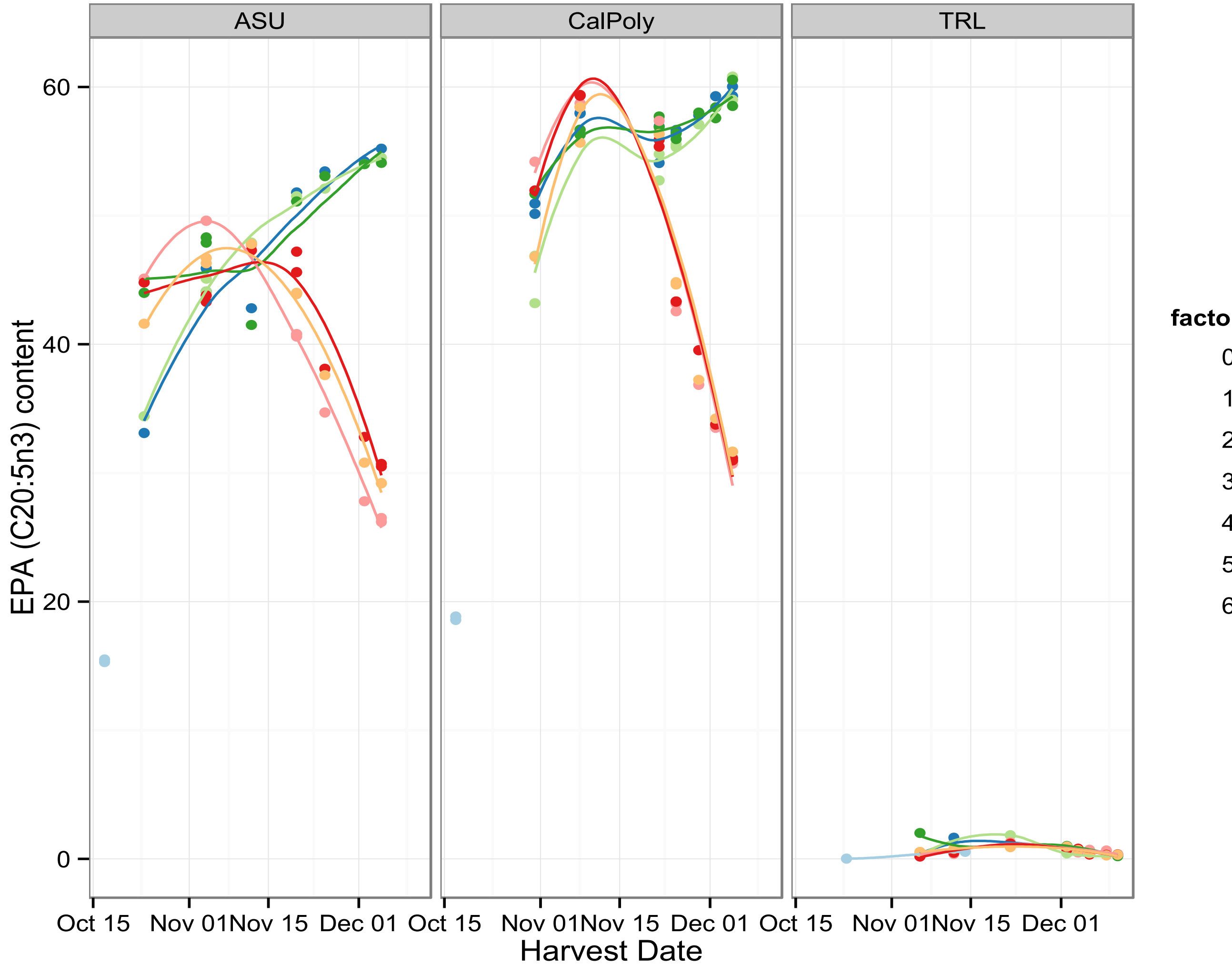
NATIONAL RENEWABLE ENERGY LABORATORY

Integration of Composition with Cultivation

Nannochloropsis

Lipids (FAME)





ATP3 Algae Testbed Public-Private Partnership