Algal Turf to Fuel (ATF)

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System overview and preliminary assessment of the p*roduction of biofuels from chemical, biochemical, and thermochemical processing and conversion of benthic polyculture biomass produced by algal turf cultivation*

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Engineering & Analysis Track Session:
Modeling a Sustainable Algae Industry

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ALGAE BIOMASS ORGANIZATION

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[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Turf algal biomass for fuels offers significant benefits over raceway monoculture systems

Algae Turf Scrubber

Hydromentia – Vero Beach, Florida

VS

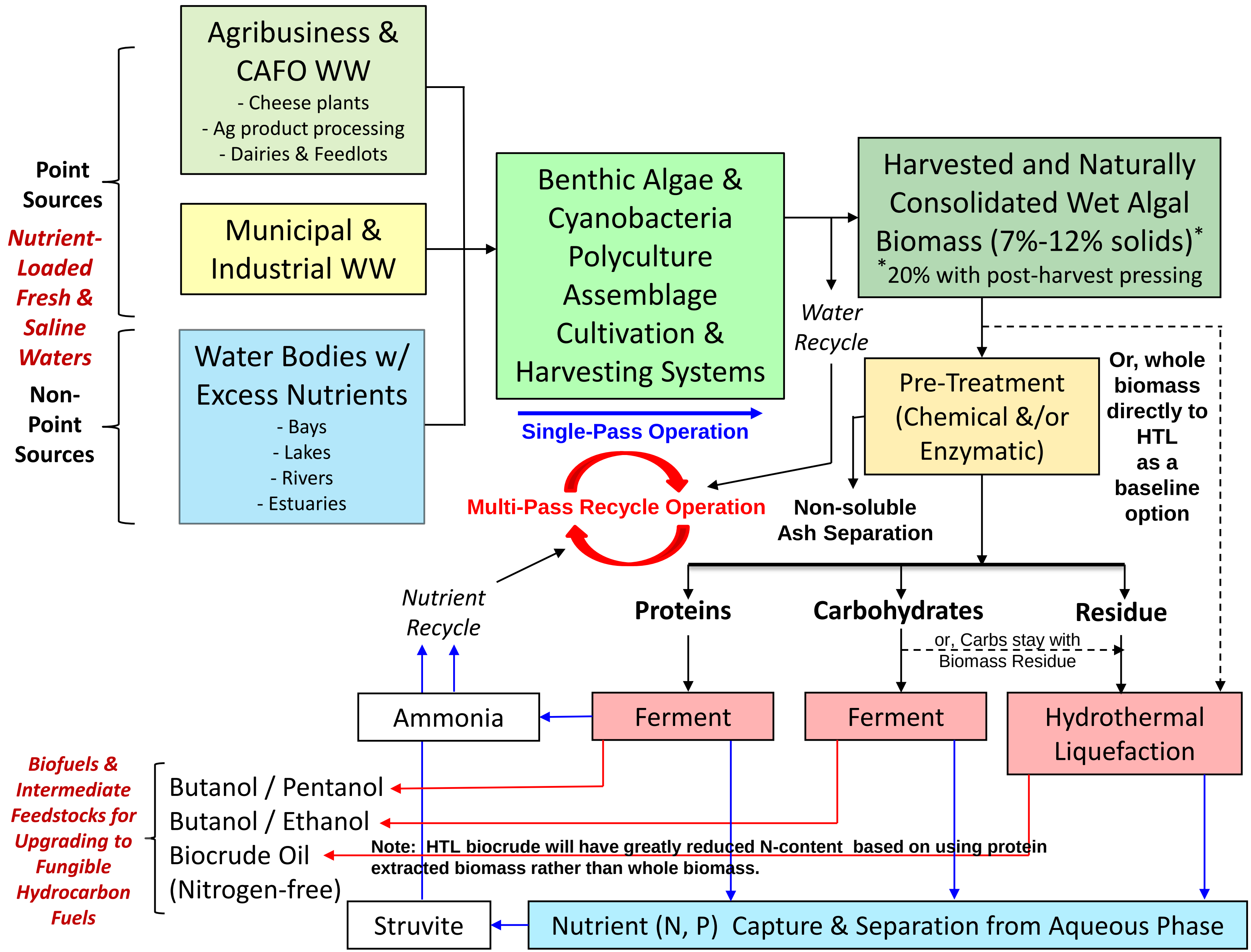
Algae Raceway

NBT – Eilat, Israel

- Polyculture – resilient to crashes
- Growth: 20+ g/m^2/day annual
- No added nutrients or external CO_2
- Harvesting & dewater – simple
- Biomass focus - low neutral lipids
- Similarities with open field agriculture

- Monoculture – vulnerable
- Growth – 2 to15 g/m^2/day
- Fertilizer and external CO_2
- Harvesting & dewater more difficult & energy-intensive
- Lipid focus (historical)

Algal Turf to Fuels (ATF) - Overview



Sandia Bioscience

Key Points

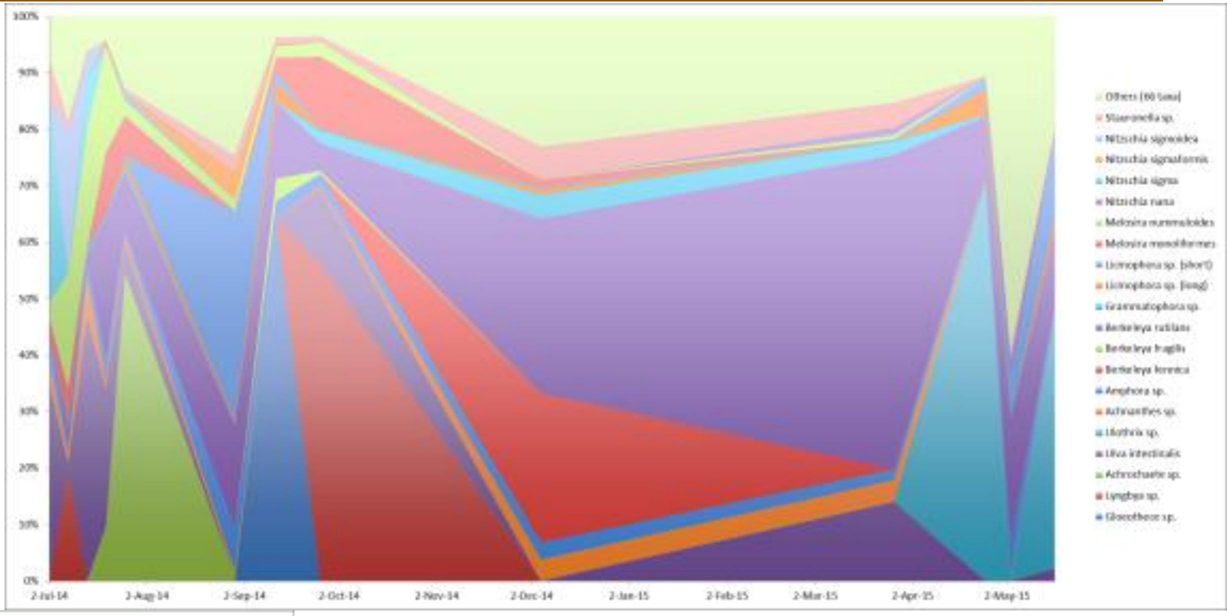
- Algal Turf to Fuels offers raceway alternative to overcome key barriers
  - Pond crashes – Cultivation resiliency
  - Expensive harvesting & dewatering (centrifuges, etc.)
  - Costly CO_2 addition &/or co-location w/ industrial source (eg, power plant)
  - Fertilizer / nutrient costs
- Turf algae pioneered by Walter Adey in 1980s and commercialized by HydroMentia for water treatment
- Robust algae production 20-30 tons ac^{-1} yr^{-1} AFDW (15-20+ g m^{-2} d^{-1}) demonstrated 10+ years of operation
- Conversion of total algae biomass to fuels and bioproducts is key
  - HTL conversion to crude oil
  - Biochemical conversion of carbohydrates and proteins to alcohols/hydrocarbons and/or other bioproduct feedstocks
    - Maximize product yields
    - Recycle nutrients as ammonium and phosphates
    - Reduce nitrogen in biomass residue & subsequent HTL crude oil.

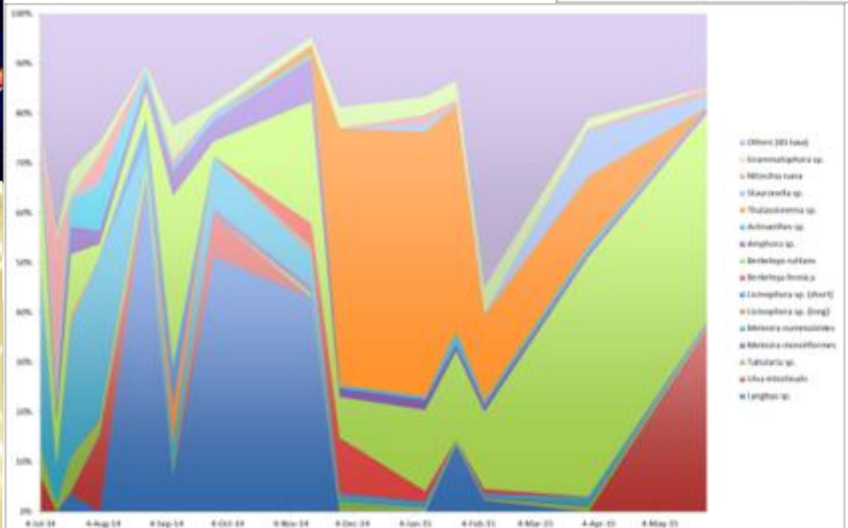
Advantages of benthic algal polyculture turf for biofuels

- Simple cultivation system configuration - more like open field ag
  - Utilizes pulsed, shallow, turbulent flow with excellent solar insolation exposure and gaseous exchange with atmosphere
  - Stable, diversified cultivation … extremely resilient and resistant to crashes
  - Years of commercial experience w/ multi-acre systems for water cleaning
- One-pass operation (typically used for water cleaning)
  - Annual average AFDW biomass production of 15 -to- $>$20 g m^{-2} d^{-1}
  - No engineered addition of CO_2 or nutrients required under single-pass operation
  - System improvement potential for 25 to ≥35 g m^{-2} d^{-1} AFDW productivity
  - Recycle system operation can expand sustainable deployment opportunities
- Ease of scale-up and low-energy harvesting/dewatering
  - Scale up to larger acreage simple matter of duplication of multi-acre “field” modules
  - Simple mechanical harvesting approaches consistent w/ ag operations
  - Immediately provides 8% to $>$15% solids content wet biomass

Sample of Benthic Algal Polyculture Turf System Diversity over Multi-Year Period

Normalized plots of dominant 15-20 species found provided courtesy of Walter Adey[1]





[1] Data and analysis from:
Haywood Dail Laughinghouse IV, "Studies of Periphytic Algae on Algal Turf Scrubbers® Along the Chesapeake Bay - Community Structure, Systematics, and Influencing Factors", PhD Thesis, U. of MD – College Park, 2012.

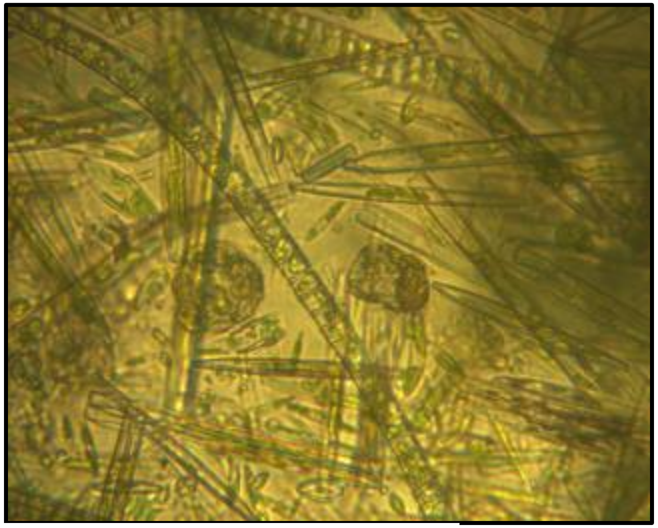
Challenges with algal turf biomass processing & conversion to fuels

- Low neutral lipid content (< 10%)
  - high in protein and carbohydrates
- High ash content (~ 30-50+%) in raw harvested material seen with current systems (*not optimized for reduced ash*)
  - Ash is combination of biogenic and exogenous environmental material
  - Improvement possible with cultivation and harvesting systems & ops
  - Dilute acid pre-treatment & separation provides ash reduction
- Heterogeneous polyculture biomass characteristics
  - Dynamically changes with season, water source chemistry
  - Provides robust and resilient culture immune to “crashes”
- HTL biocrude can have high nitrogen content (~5+%)
  - Biochem pretreatment of proteins can reduce and recycle nitrogen
  - Resulting HTL biocrude from residue has N-content <1%
- Preliminary TEA looks promising for achieving cost-effective biofuels at large scale

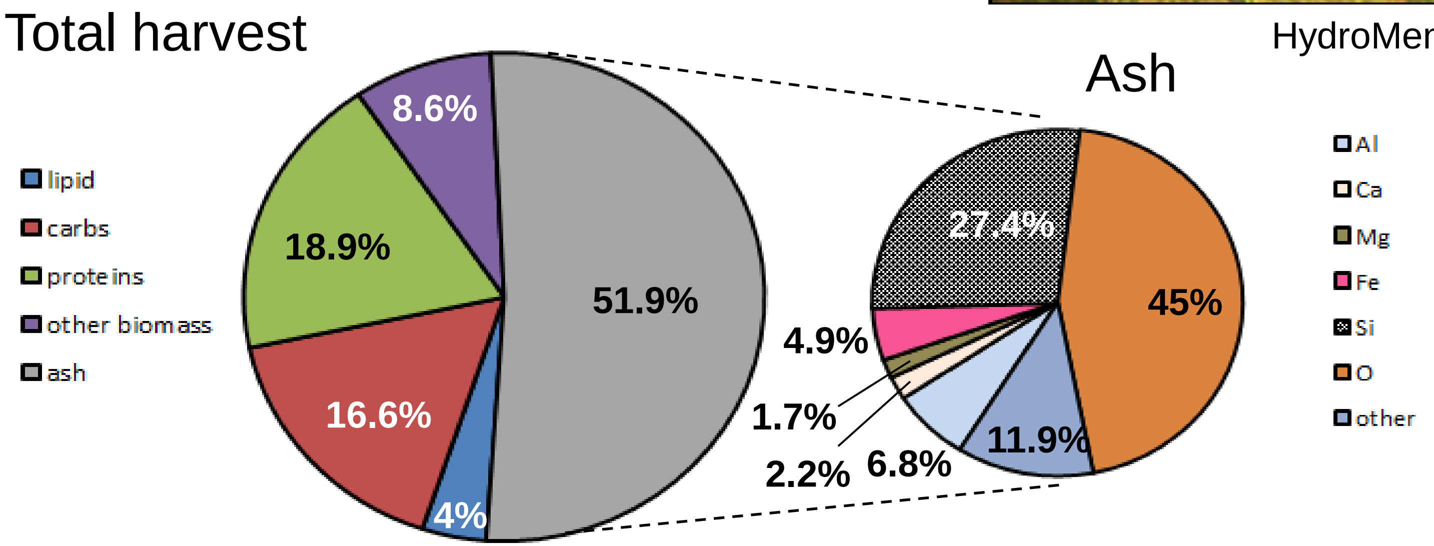
Algal turf biomass characterization*

*** Systems non-optimized for increased AFDW biomass w/ reduced ash**

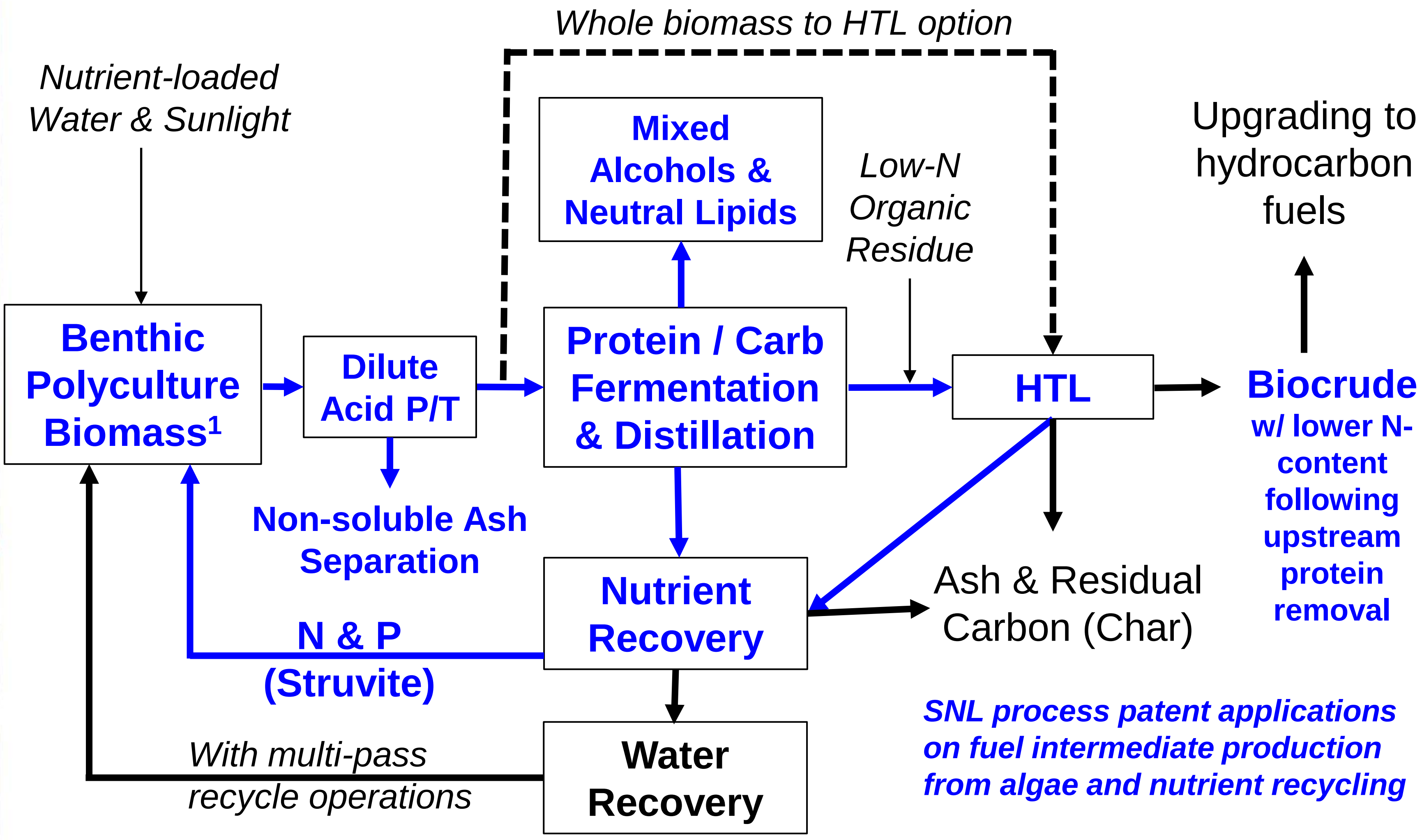
- Variable composition: dependent on water source, climate, season
- Composed of multiple phylogenetic groups: dominant clades include chlorophyta, diatoms, and cyanobacteria
- Low lipid content
- Biogenic and non-biogenic ash content
- System not optimized for ash reduction



HydroMentia sample



Processing & Recycling Pathways



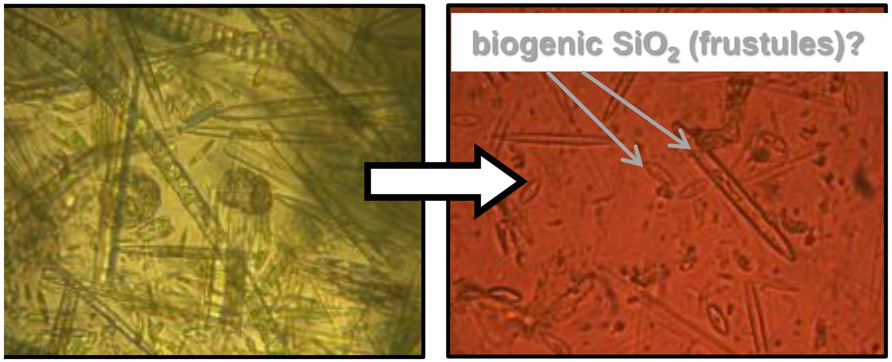
[1] Benthic algal polyculture turf will also include entrained planktonic species

Biomass pretreatment:

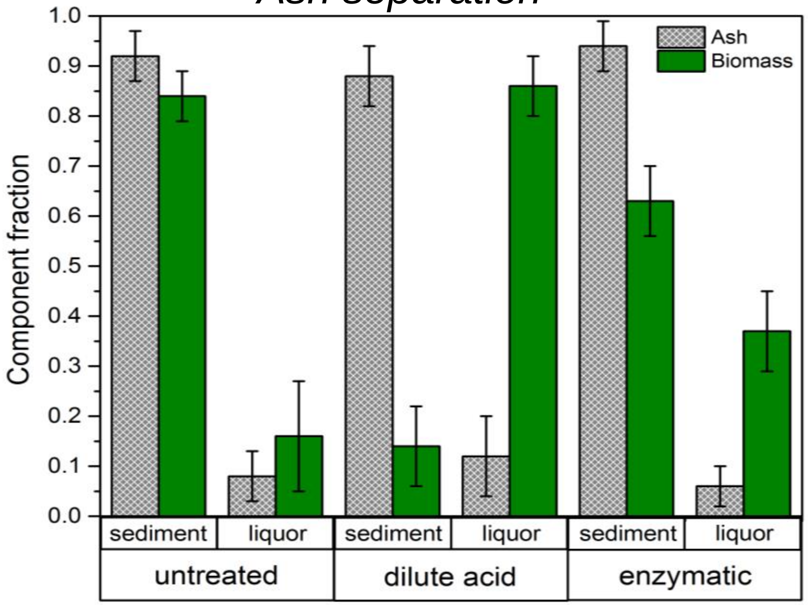
ash removal, solubilization, and hydrolysis

- Dilute acid and enzymatic treatments are each effective for separating ash
- Dilute acid is effective for solubilizing the protein and carb fractions, and carb hydrolysis, but additional enzymatic treatment is necessary for protein hydrolysis
- Large fraction of biogenic ash

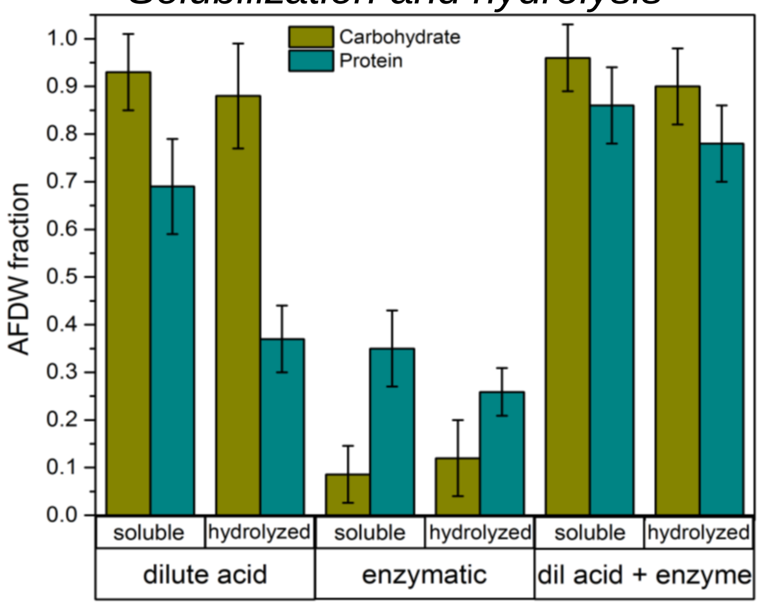
Native biomass *Pretreated residuals*



Ash separation

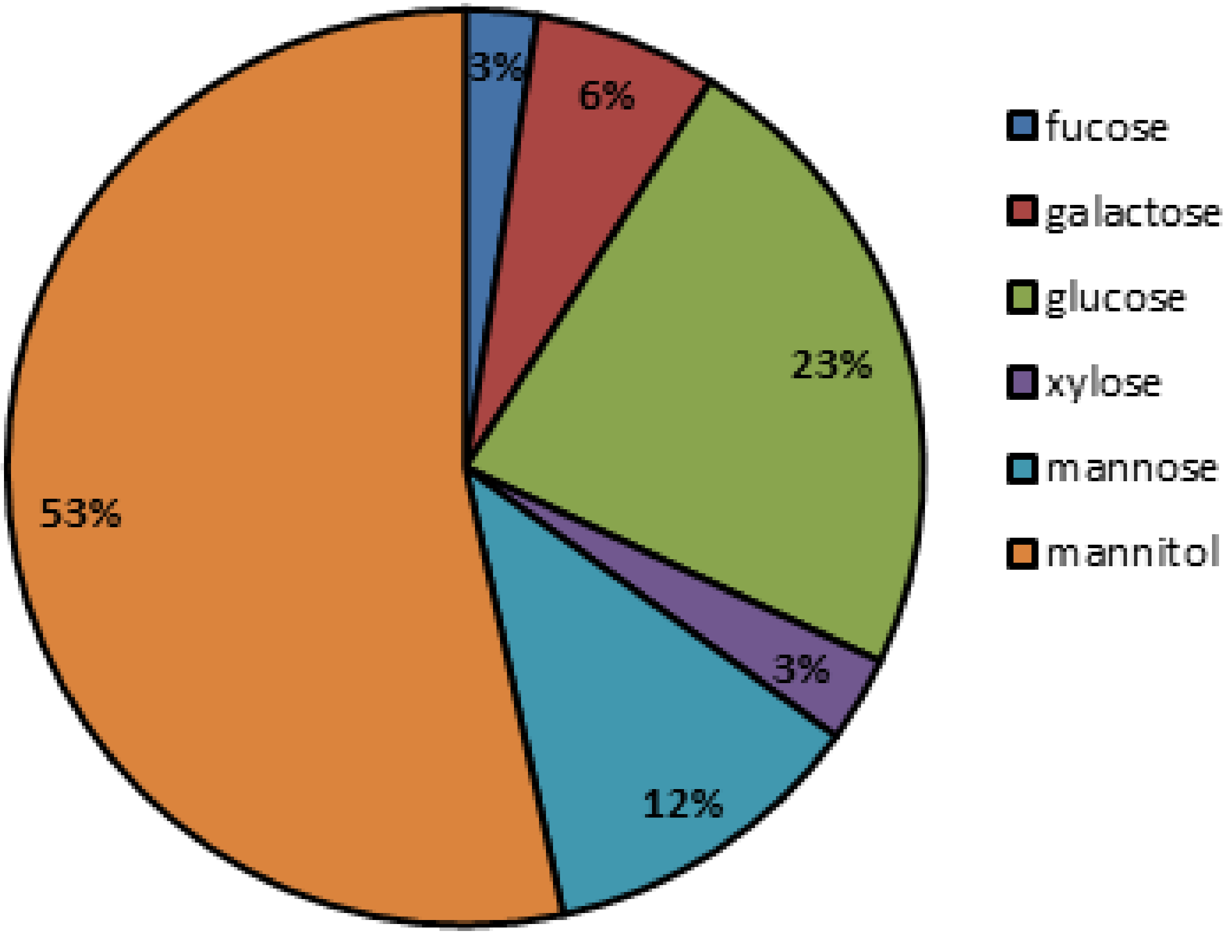


Solubilization and hydrolysis



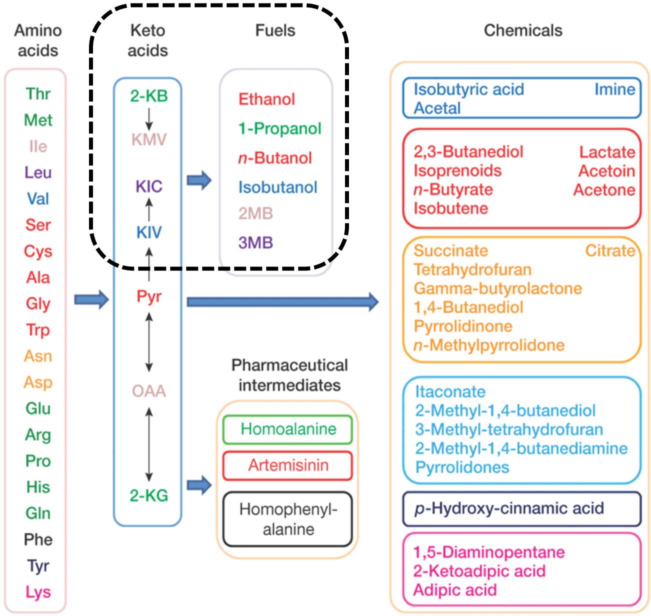
Carbohydrate Profile Data*

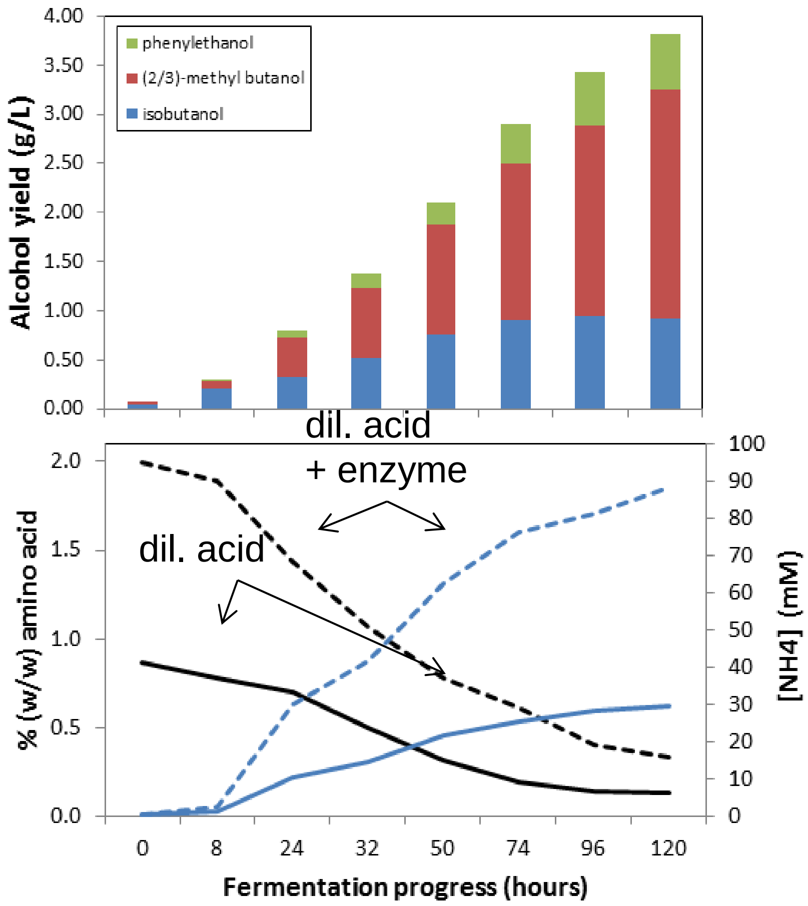
**** Based on algal turf sample from HydroMentia***



Biochemical conversion: sugar & protein fermentation

- Sugar fermentation strain: *Zymomonas sp.* for utilization of C5 and C6 sugars
- Protein fermentation strain: *E.coli* YH83 for conversion of amino acids to >C2 alcohols + NH_4, developed by collaborator Liao & coworkers (Huo *Nat. Biotech* 2011)

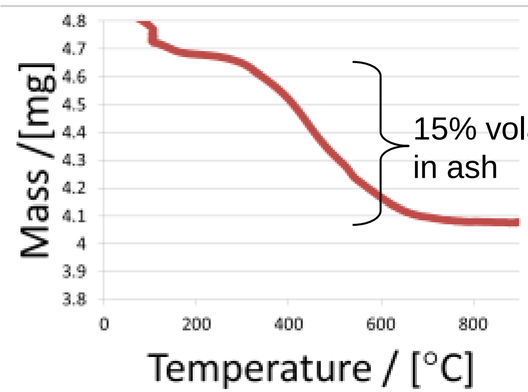


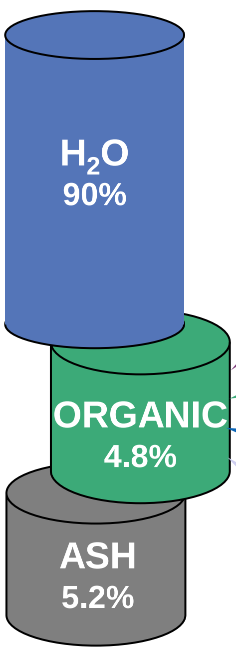


- 70% of theoretical protein conversion achieved with bench scale testing

Thermochemical conversion:
Un-optimized HTL gives >40% biocrude yields

- 44% biocrude achieved
- C in aqueous co-product/solids can potentially be recovered to increase this yield
- Gas composition mostly NH_3, CO_2 and some CH_4
- Solids yield is mixture of oil and char; char TBD





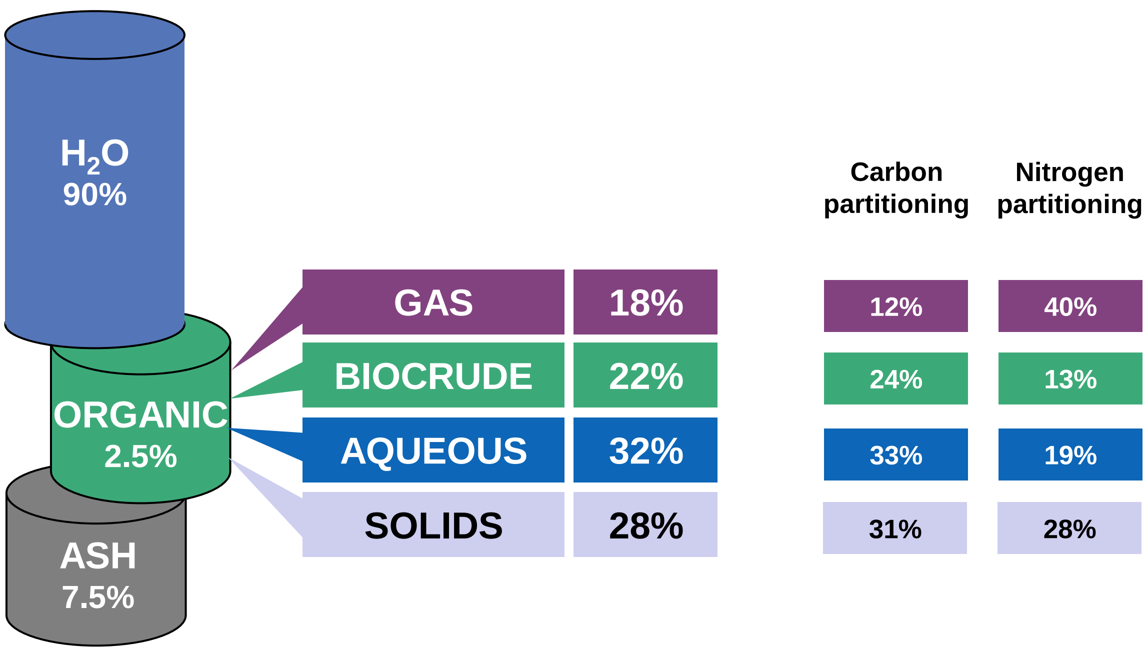
		Carbon partitioning	Nitrogen partitioning
GAS	14%	9%	42%
BIOCRUDE	44%	43%	17%
AQUEOUS	25%	30%	26%
SOLIDS	17%	18%	15%

Biocrude N content: 4.5%

Based on wet biomass w/ 10% SOLIDS

Thermochemical conversion:
Un-optimized residue HTL reduces N by > 80%

- 22% biocrude achieved from residue, process unoptimized
- C in aqueous co-product and solids can be recovered to increase this yield
- Higher content ash likely changing heat/mass transfer profiles and affecting yield
- High heating value of 38.7 MJ/kg compared . (Typical upgraded HTL oil 46 MJ/Kg versus 45 MJ/kg gasoline*)



Biocrude N content: 0.89%

Based on wet biomass w/ 10% SOLIDS

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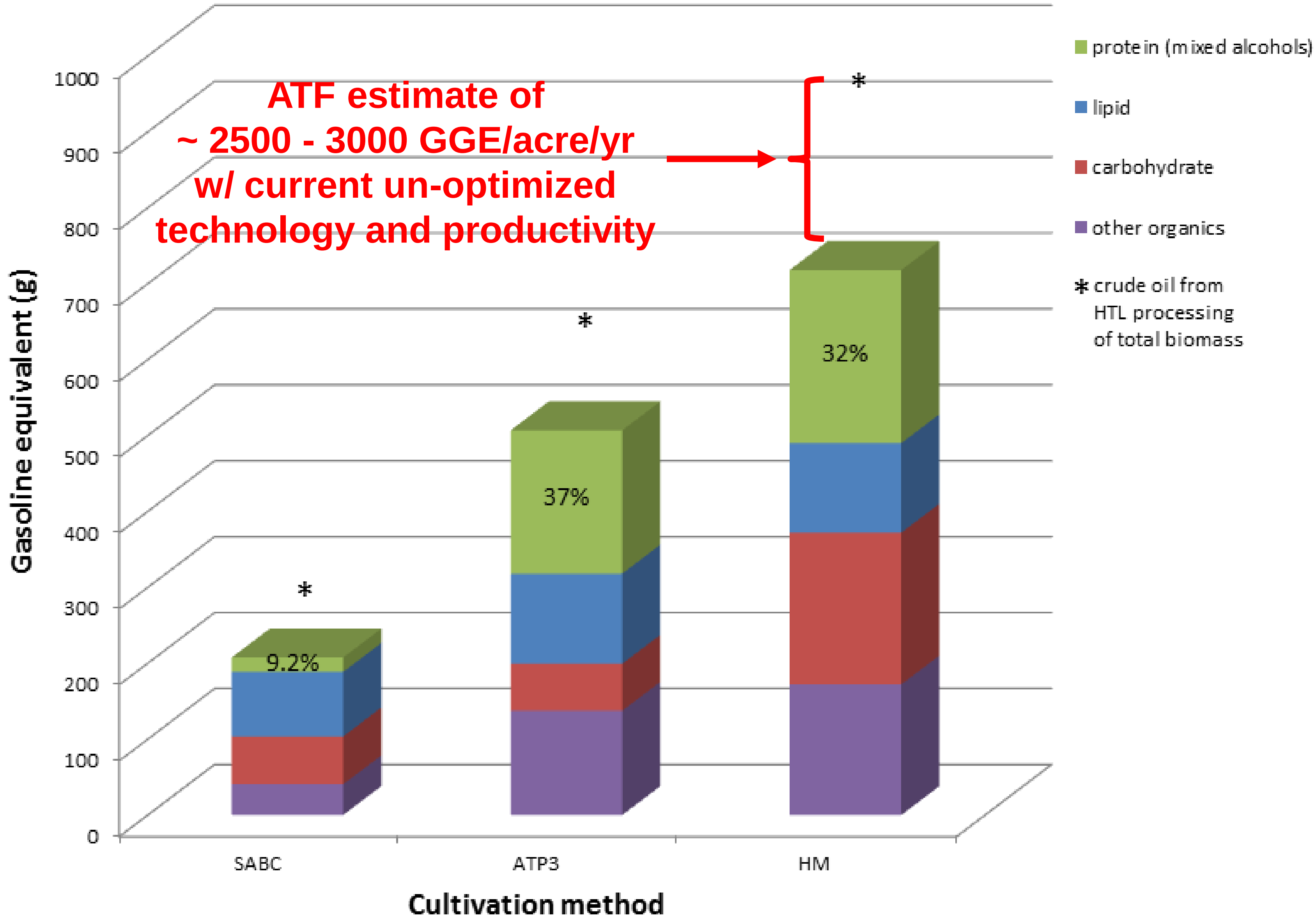
Comparative Estimates of Biofuel Yield

Incorporating Different Algal Biomass Productivity & Composition



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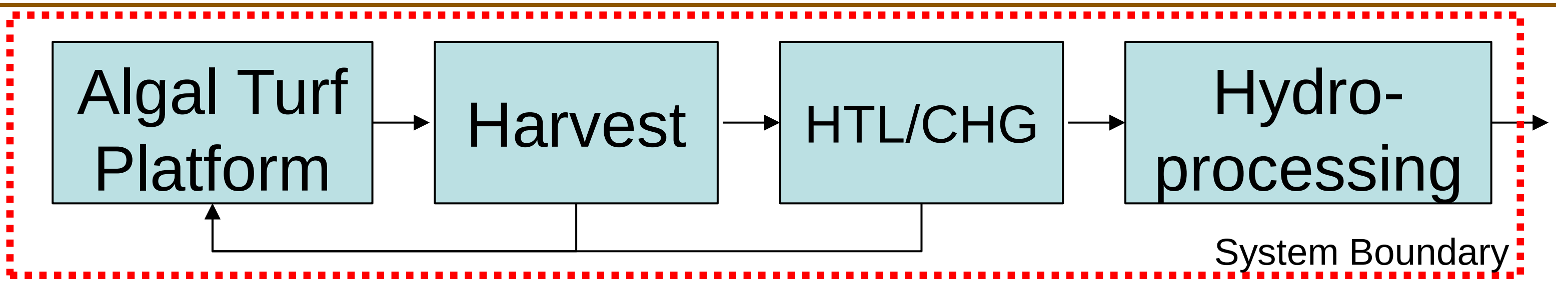
Foundational TEA Assumptions*

* Using HTL/CHG + Hydroprocessing performance based on PNNL 2014 report



- Economic Assumptions
  - Similar to process design case studies by NREL & PNNL

Input	Value
Equity	40%
Loan Interest Rate	8%
Loan Term	10 yrs
Internal Rate of Return	10%
Income Tax Rate	35%
Plant Life	30 yrs
Build Time	3 yrs
Annual Fuel Production	46 Mgal
ATS Cultivation Acreage	15000 acres

Core Process Assumptions

for current non-optimized ash content case

ATS Growth	
Growth Rate (AFDW)	20 g m^{-2} d^{-1}
Pumping Duty Cycle	14 hr d^{-1}
Pumping η	67%
Pumping Head	4 m
ATS Length	152 m
Biomass (AFDW) Flow	1340 ton d^{-1}
Capital Cost	\$10 m^{-2}

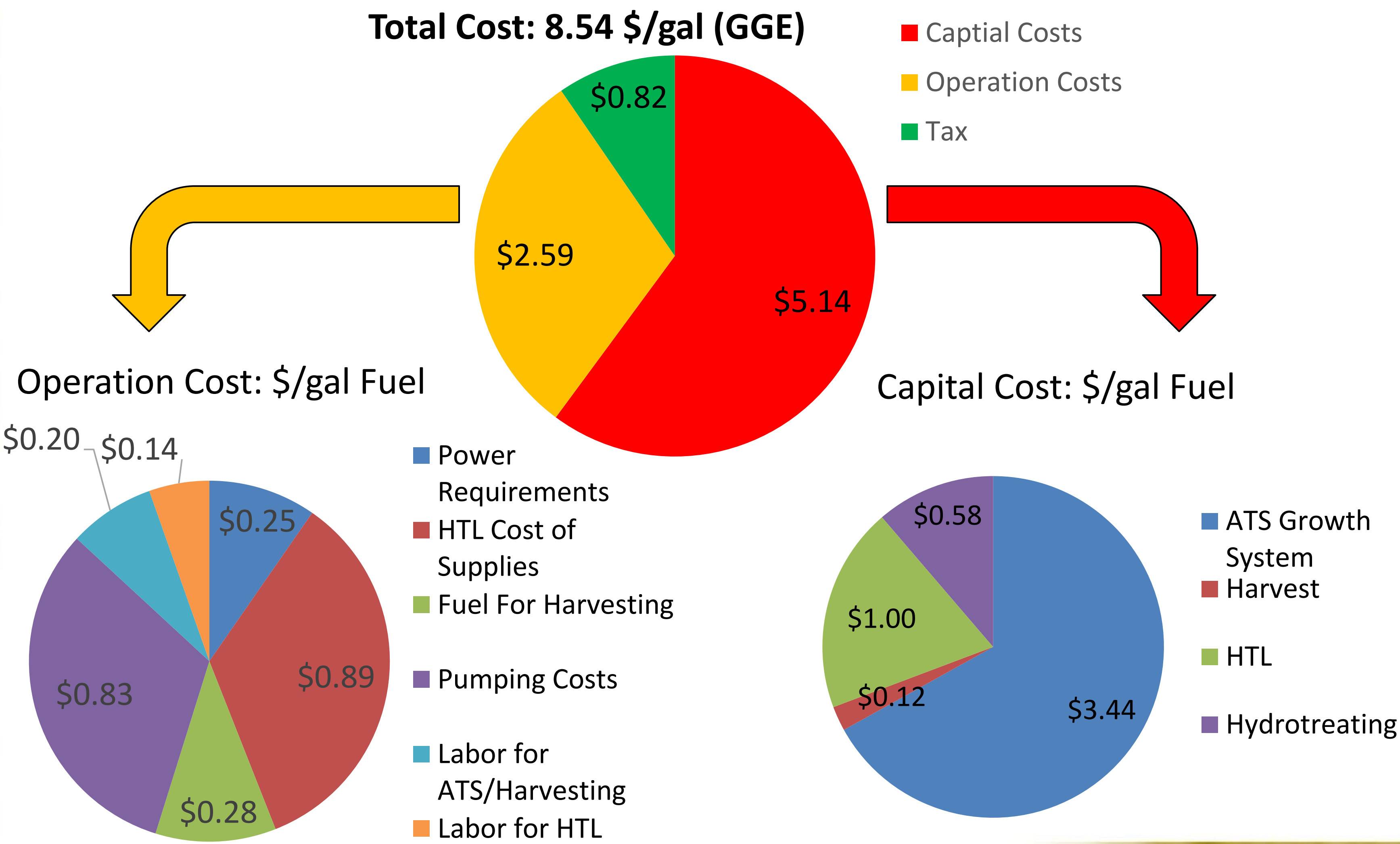
Harvest	
Harvest Density	20% solids
Ash Content	50%
Harvest Frequency	7 days
Operation Cost	\$0.23 $m^{-2}yr^{-1}$
Capital Cost	\$0.35 m^{-2}

HTL/CHG Processing	
NG Energy	3.7 M-MJ d^{-1}
Electrical Energy	120 MWh d^{-1}
Capital Cost	\$183 M
Oil Yield	47%
Aqueous Yield	40%
Ash Content	50%
Gas	3%

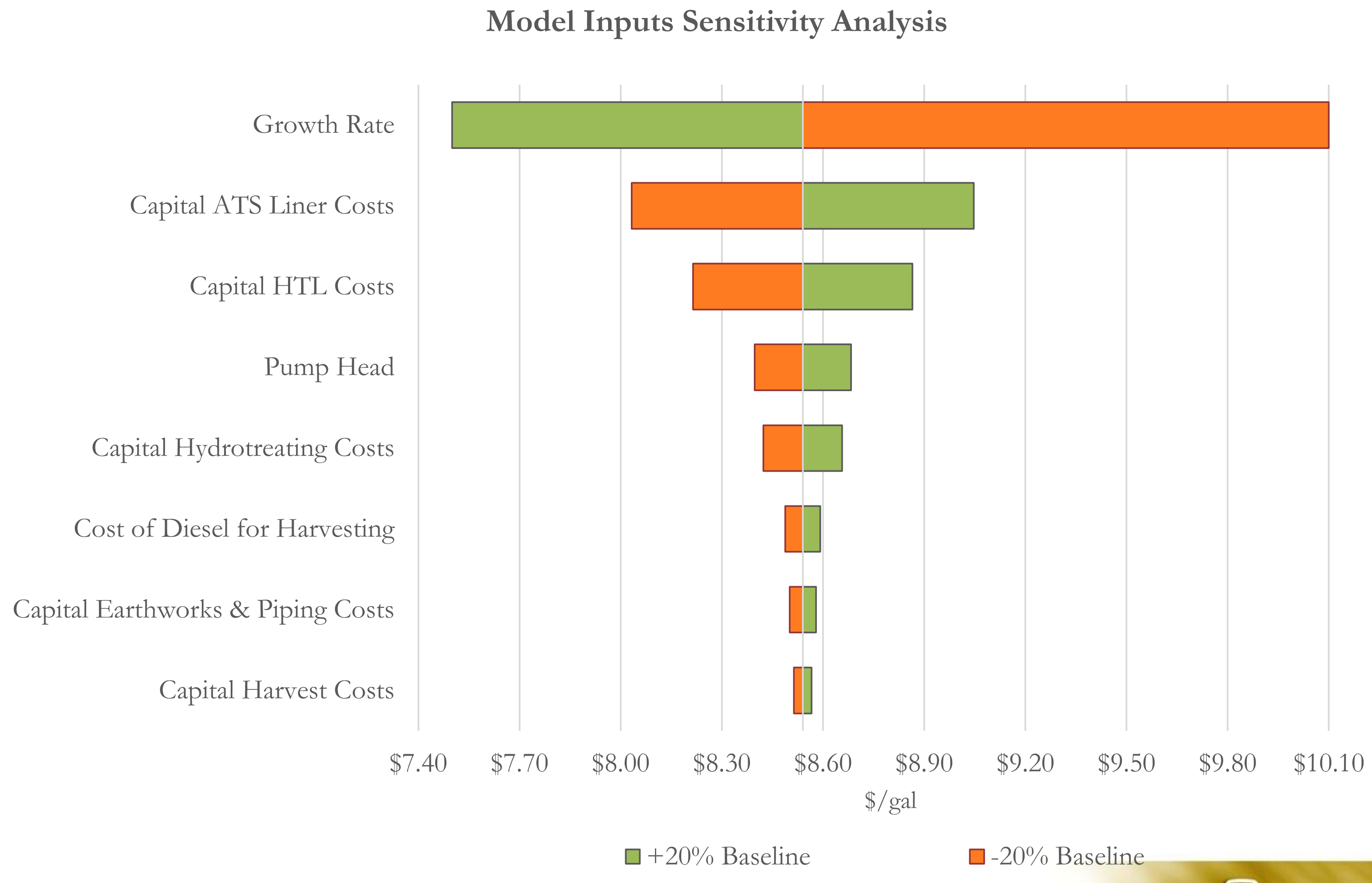
Hydrotreating	
Fuel Yield	78%
Capital Costs	\$69 M
Processing Capacity	153 kgal d^{-1}
Diesel Yield	83%
Naphtha Yield	17%

Results for HTL processing of raw algal turf biomass from current systems*

* High ash content (50%) biomass to HTL processing

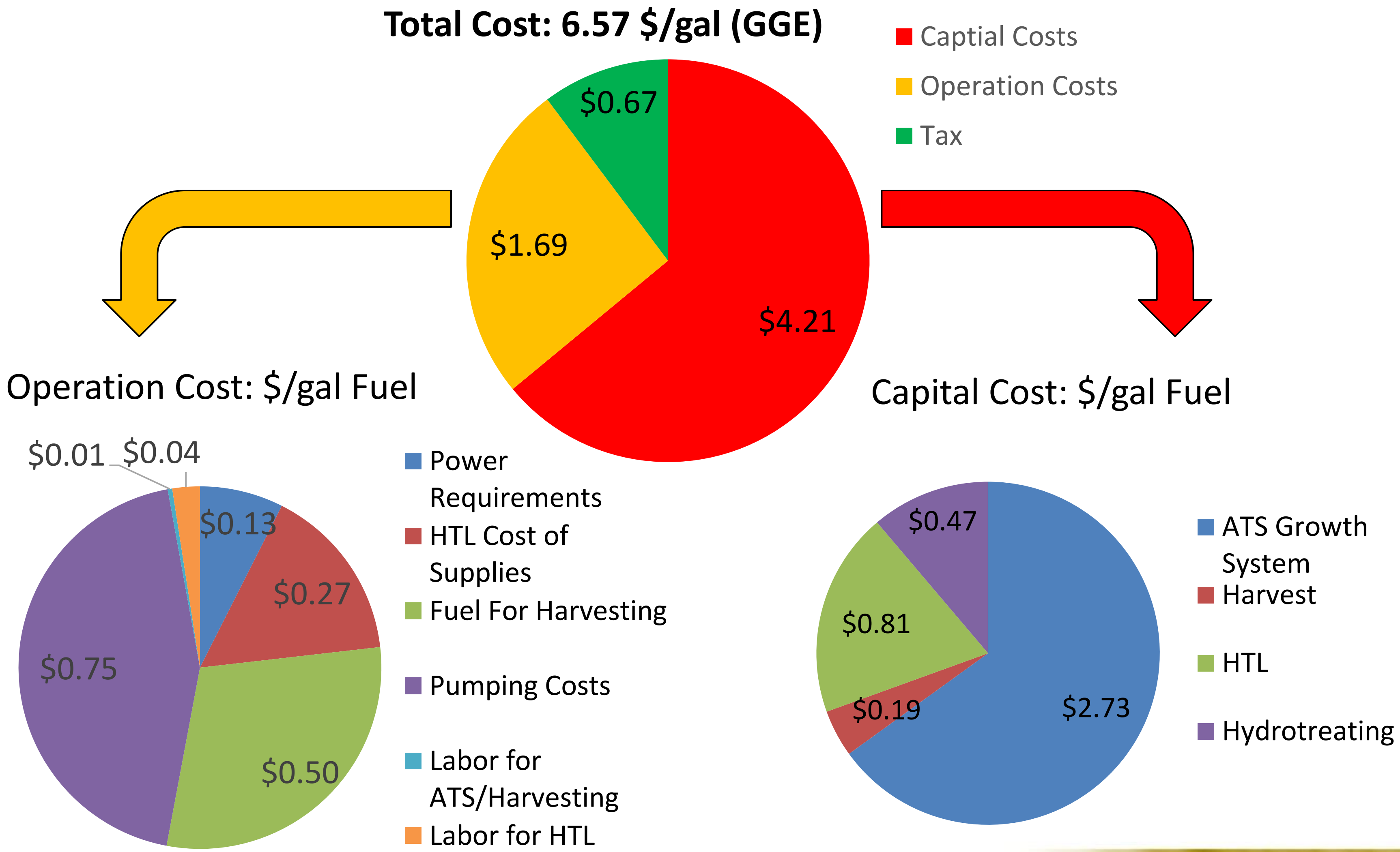


Sensitivity Analysis
Current Non-optimzed Case*
* High ash content (50%) biomass to HTL processing

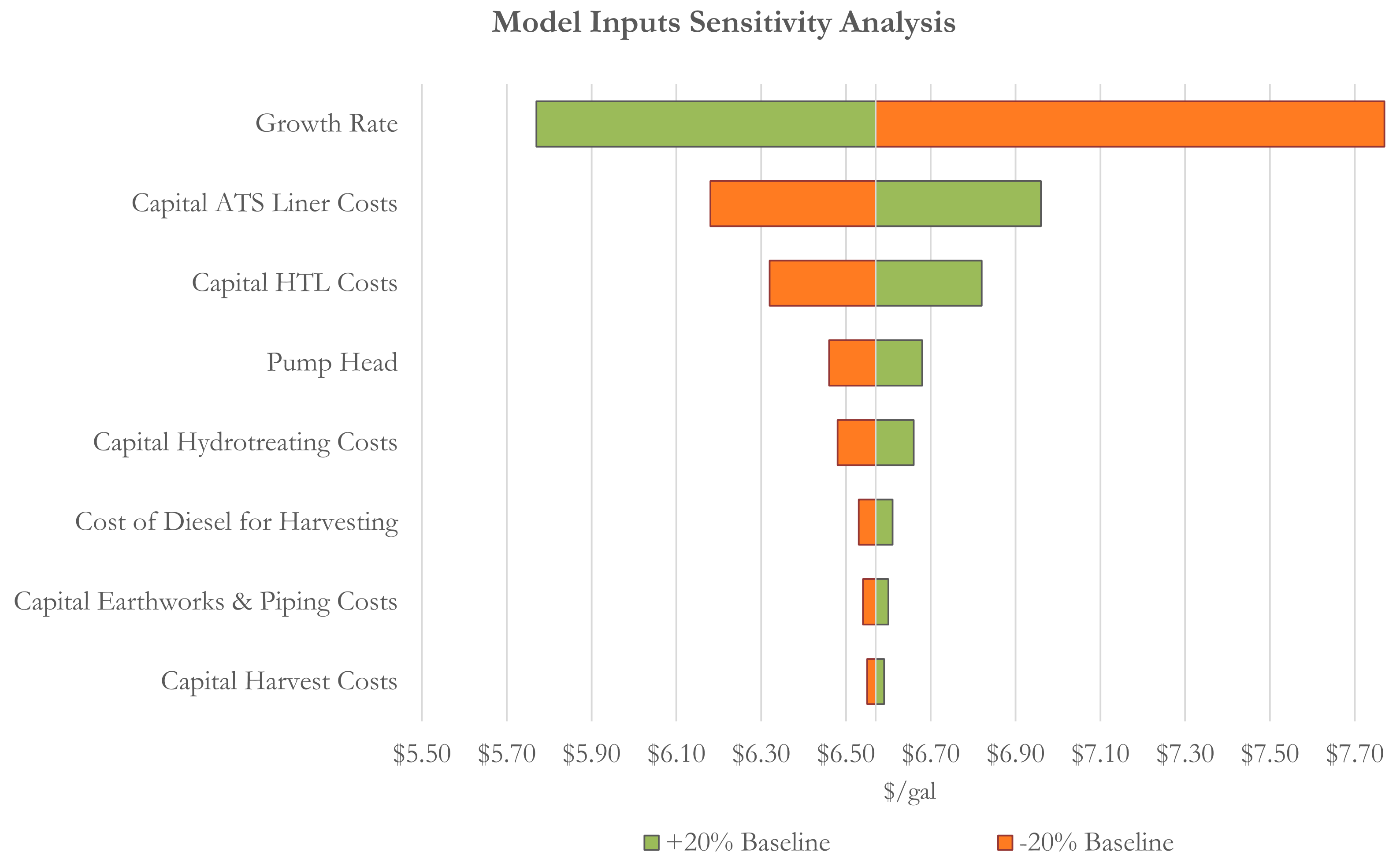


Results for HTL processing of improved (lower ash content) algal turf biomass*

* Lower ash content (13%) biomass to HTL processing

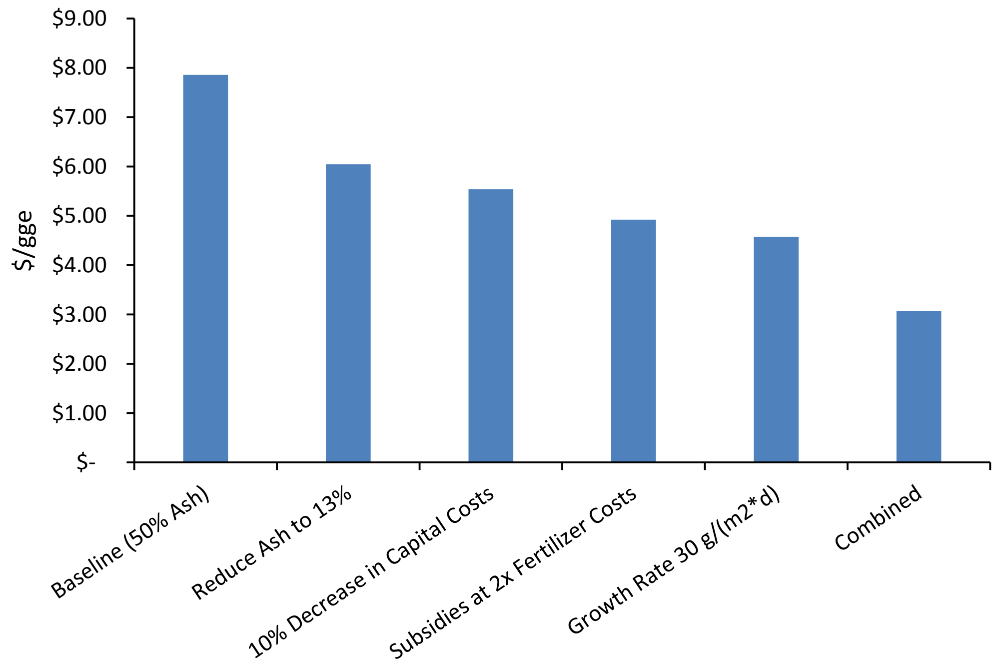


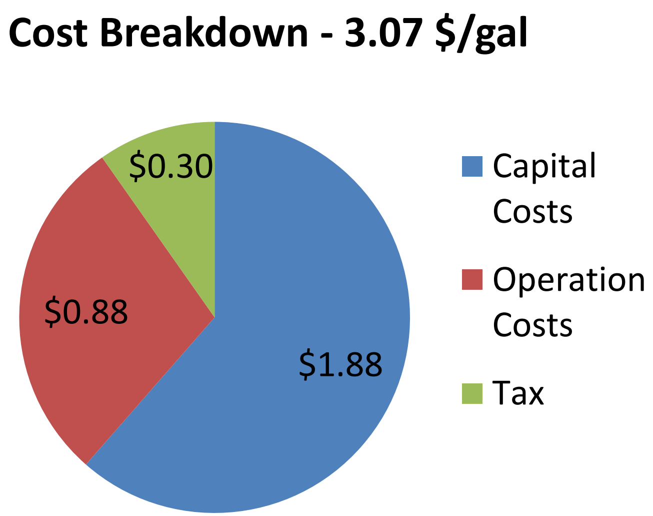
Sensitivity Analysis
Improved Lower Ash Content Case*
* Lower ash content (13%) biomass to HTL processing



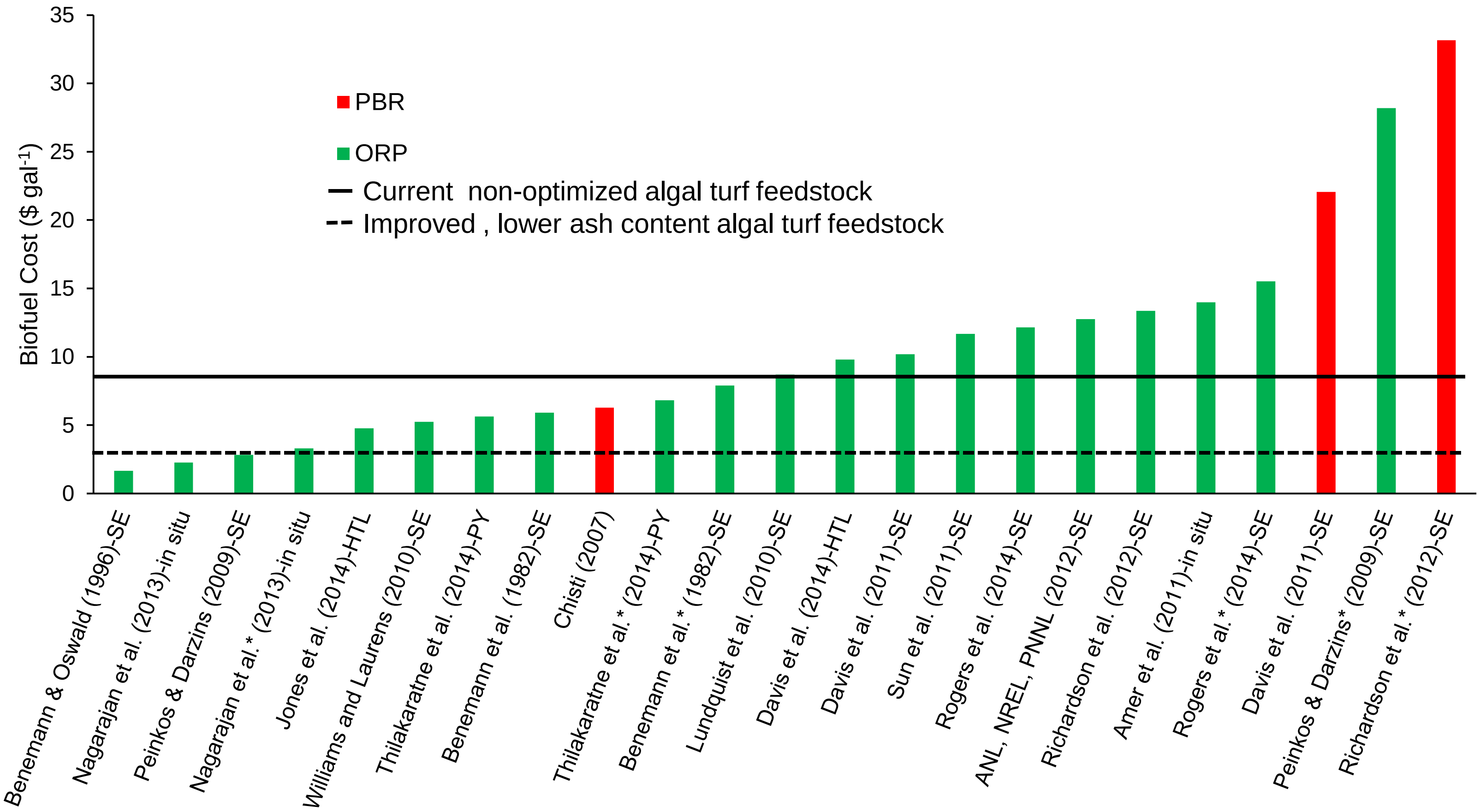
Example Path to ~$3 per GGE

- Reduce ash content to ≤13% (Improved case)
  - Reduced ash in raw cultivated & harvested material (systems & ops)
  - Ash reduction via pre-processing prior to conversion processing
- Increase in annual growth rate to 30 g/m^2/day (AFDW)
- 10% Decrease in Capital Costs
- Subsidies at 2x Fertilizer Costs (environmental service)
- Results in estimated cost of $3.07/gal





Biofuel Cost Comparison (GGE) to Past Studies



Scale-up Feasibility TEA … Next Steps in Progress

- Include biochemical processing pathways
  - Protein &/or carb conversion to sugars, mixed alcohols, other compounds that provide fuel intermediates and blend stock
  - Feedstock for higher-value products
- HTL/CHG + Hydroprocessing on residue
- Integration of nutrient recycling processes
  - Production of fungible fertilizer material for other markets
  - Recycling to support upstream algal cultivation
- Cost trade-offs of processing & products paths
- Environmental credits for water clean-up
  - Co-service income stream to offset fuel & bioproduct costs
  - With point source WW and non-point source water bodies

Conclusions

- Benthic algal turf polyculture assemblages offer a promising alternative approach to algal biofuels
- Polyculture algal turf systems have demonstrated long-term (multi-year) culture stability at large scales with relatively high annual average biomass productivities (~15-20 g m^{-2} d^{-1}) w/ low energy-intensity harvesting & dewatering
  - *Based on the use of systems focused on efficient water cleaning*

    … not yet optimized for biomass production and ash reduction
  - *Without the need for supplemental CO_2 or commercial nutrients (N, P)*
  - *Significant opportunities for improvement for high productivity of lower-ash content biomass*
- Preliminary (rough) estimates show potential for ≥1 BGY U.S. biofuel production using nutrients & CO_2 from non-pt. sources
  - Using single-pass operation … greater potential with recycle operation
- Initial/Preliminary TEA performance looks promising
- Future work includes LCA and resource assessment

Thank you! - Questions?

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HydroMentia WATER TREATMENT TECHNOLOGIES

UtahStateUniversity

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