Algal Turf to Fuel (ATF)

SAND2014-18367PE

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

2014 Algal Biomass Summit
San Diego, California
September 29 – October 2, 2014

ALGAE BIOMASS ORGANIZATION

Draft – updates in progress

Working on shortening and simplifying

SAND2014-15119PE

[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.

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Key Points

- Turf algal fuels offers raceway alternative to overcoming key barriers
  - Pond crashes
  - Expensive harvesting (centrifuges)
  - Costly CO_2 addition/Co-location with power plant
  - Fertilizer costs
- Turf algae pioneered by Walter Adey 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
    - Maximize product yields
    - Recycle nutrients as ammonium and phosphates
    - Reduce of nitrogen in biomass and subsequent HTL crude oil.

Turf algal fuel offers significant benefits over raceway monoculture systems

Algae Turf Scrubber

Hydromentia – Vero Beach, Florida

- Polyculture – resilient to crashes
- Growth: 20 g/m^2/day annual
- No added nutrients or external CO_2
- Harvesting – simple
- Biomass focus

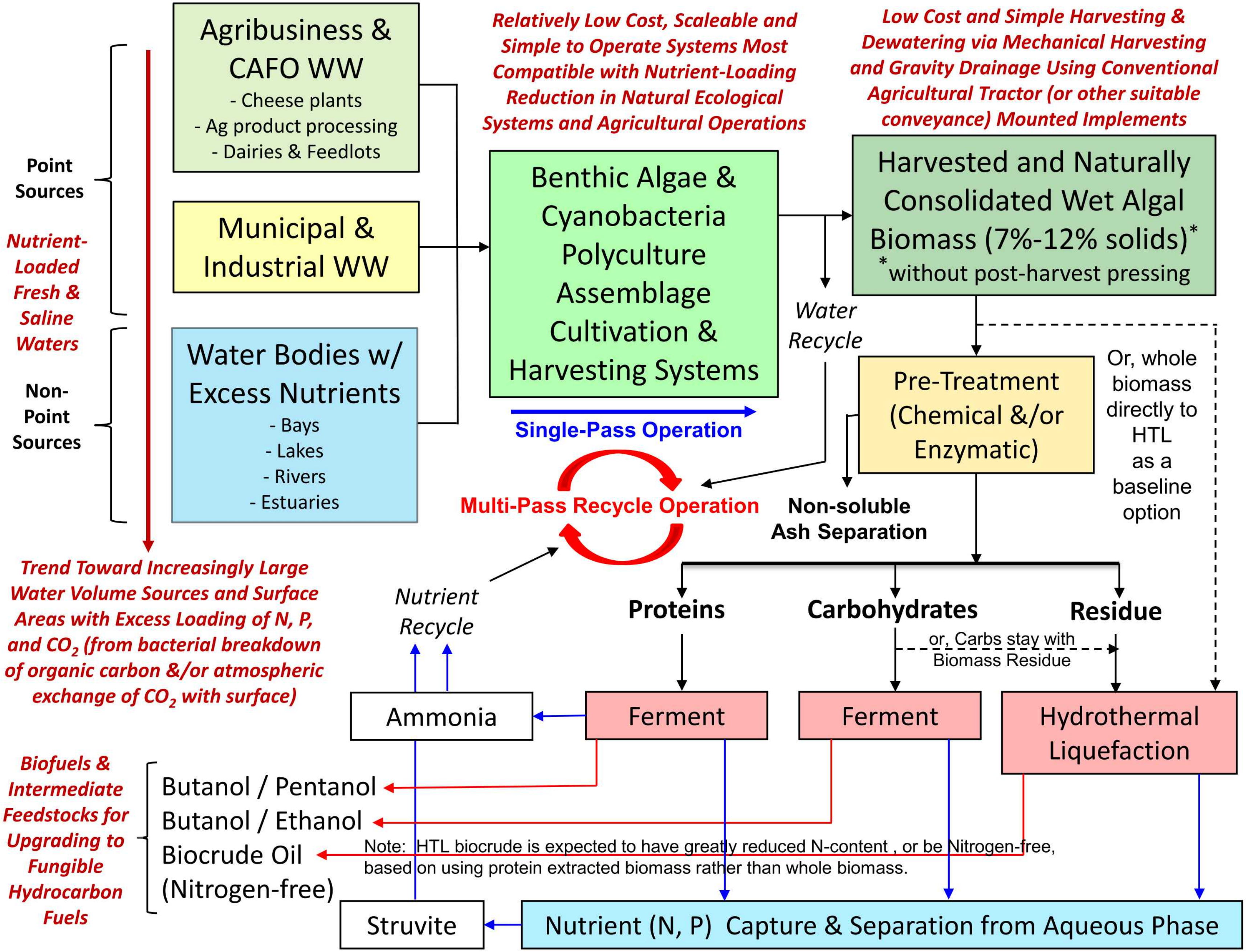
VS

Algae Raceway

NBT – Eilat, Israel

- Monoculture – vulnerable
- Growth – 2 to15 g/m^2/day
- Fertilizer and external CO_2
- Harvesting with centrifuge
- Lipid focus

Overview of ATS-to-Fuel system concept



Point Sources

Nutrient-Loaded Fresh & Saline Waters

Non-Point Sources

Agribusiness & CAFO WW
- Cheese plants
- Ag product processing
- Dairies & Feedlots

Municipal & Industrial WW

Water Bodies w/ Excess Nutrients
- Bays
- Lakes
- Rivers
- Estuaries

Trend Toward Increasingly Large Water Volume Sources and Surface Areas with Excess Loading of N, P, and CO_2 (from bacterial breakdown of organic carbon &/or atmospheric exchange of CO_2 with surface)

Relatively Low Cost, Scaleable and Simple to Operate Systems Most Compatible with Nutrient-Loading Reduction in Natural Ecological Systems and Agricultural Operations

Benthic Algae & Cyanobacteria Polyculture Assemblage Cultivation & Harvesting Systems

Single-Pass Operation

Multi-Pass Recycle Operation

Low Cost and Simple Harvesting & Dewatering via Mechanical Harvesting and Gravity Drainage Using Conventional Agricultural Tractor (or other suitable conveyance) Mounted Implements

Harvested and Naturally Consolidated Wet Algal Biomass (7%-12% solids)*

*without post-harvest pressing

Water Recycle

Pre-Treatment (Chemical &/or Enzymatic)

Non-soluble Ash Separation

Or, whole biomass directly to HTL as a baseline option

Nutrient Recycle

Proteins

Carbohydrates

Residue

or, Carbs stay with Biomass Residue

Ammonia

Ferment

Ferment

Hydrothermal Liquefaction

Biofuels & Intermediate Feedstocks for Upgrading to Fungible Hydrocarbon Fuels

Butanol / Pentanol

Butanol / Ethanol

Biocrude Oil (Nitrogen-free)

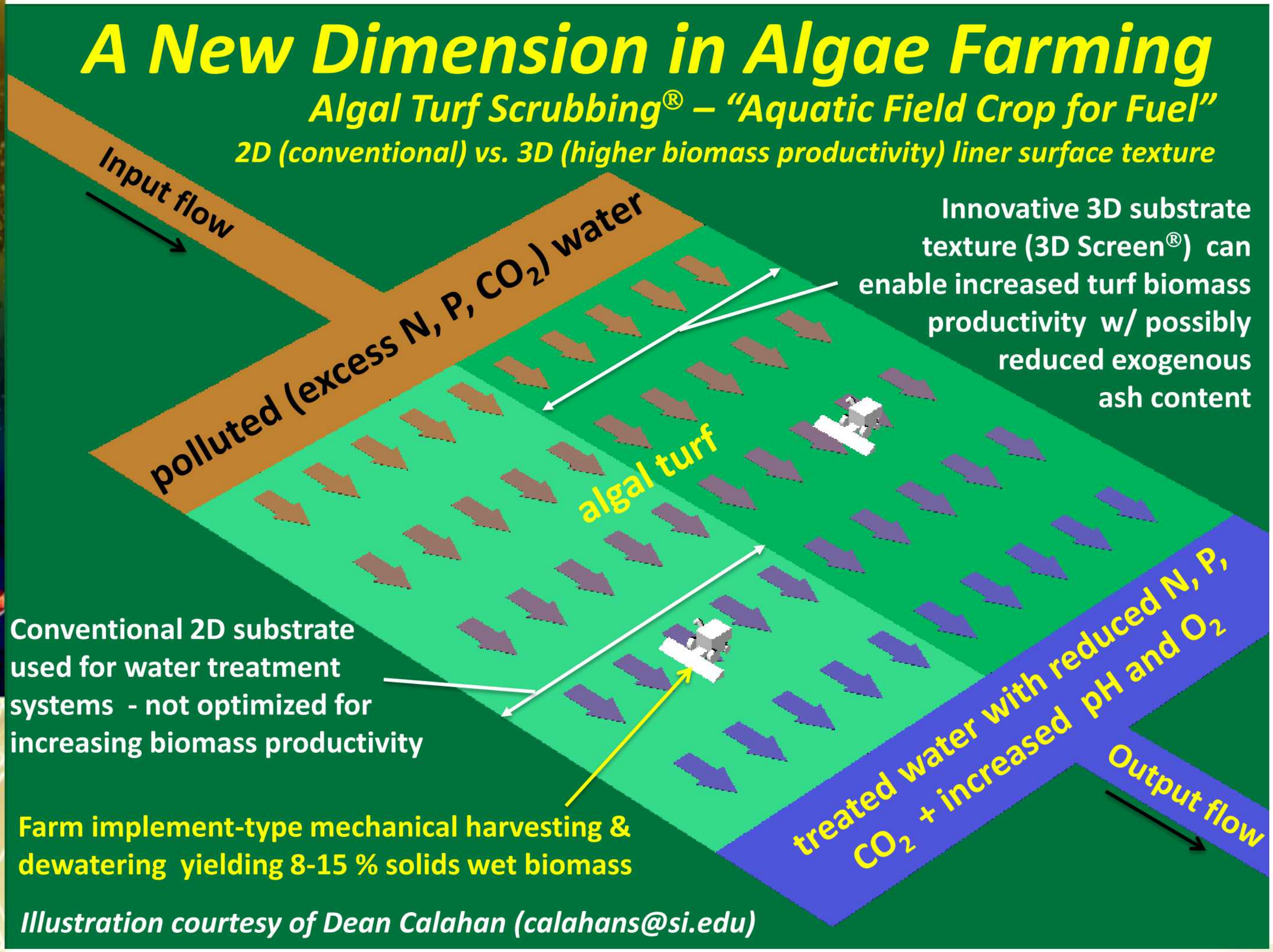
Note: HTL biocrude is expected to have greatly reduced N-content , or be Nitrogen-free, based on using protein extracted biomass rather than whole biomass.

Struvite

Nutrient (N, P) Capture & Separation from Aqueous Phase

Multi-function application of planar substrate benthic polyculture algal turf systems:

Cleaning water while producing biomass for biofuels



A New Dimension in Algae Farming

Algal Turf Scrubbing® – "Aquatic Field Crop for Fuel"

2D (conventional) vs. 3D (higher biomass productivity) liner surface texture

Innovative 3D substrate texture (3D Screen®) can enable increased turf biomass productivity w/ possibly reduced exogenous ash content

Conventional 2D substrate used for water treatment systems - not optimized for increasing biomass productivity

Farm implement-type mechanical harvesting & dewatering yielding 8-15 % solids wet biomass

Illustration courtesy of Dean Calahan (calahans@si.edu)

Consists of slightly tilted & lined planar open-field systems using pulsed, shallow, turbulent water flow and mechanical harvesting compatible with conventional agriculture.

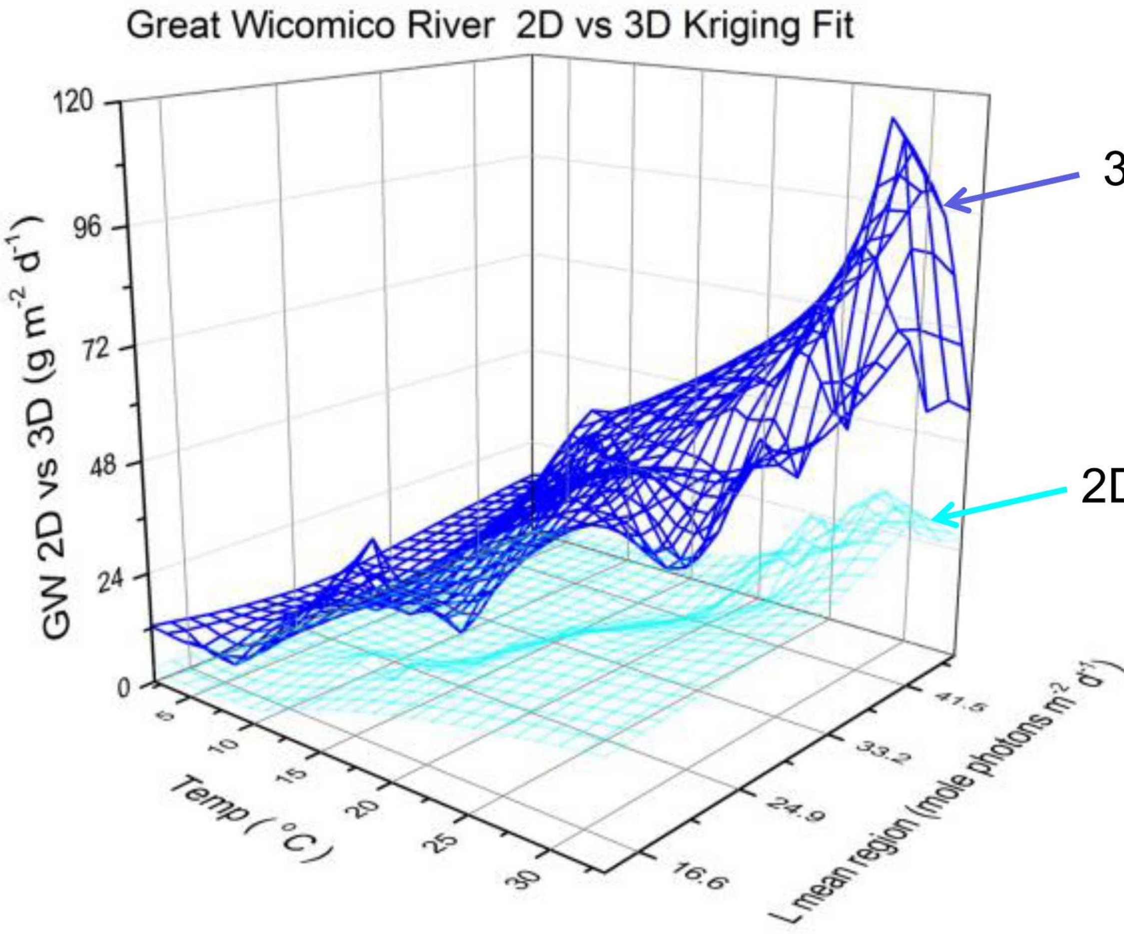
Commercial multi-acre scale systems have been developed and used for water treatment.

Advantages of benthic algal polyculture turf for biofuels

- Simple cultivation system configuration - more like open field ag
  - Planar surface gravity flow systems, with liner expected to be required
  - 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} (w/ ~50% ash) in systems and sites non-optimized for increased biomass and reduced ash
  - No engineered addition of CO_2 or nutrients required under single-pass operation
  - Pilot tests w/ 3D substrates show potential annual av. of 25 to ≥40 g m^{-2} d^{-1} AFDW
- Recycle system opportunities
  - Potential production improvements from (1) site selection, (2) improved flow channel substrate configuration & dynamics, (3) active nutrient addition, (4) periodic poly-species innoculum addition? (5) no CO_2 addition? - TBD
- 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

Algal Turf System Biomass Productivity

2D vs. 3D Substrate Surface Treatment



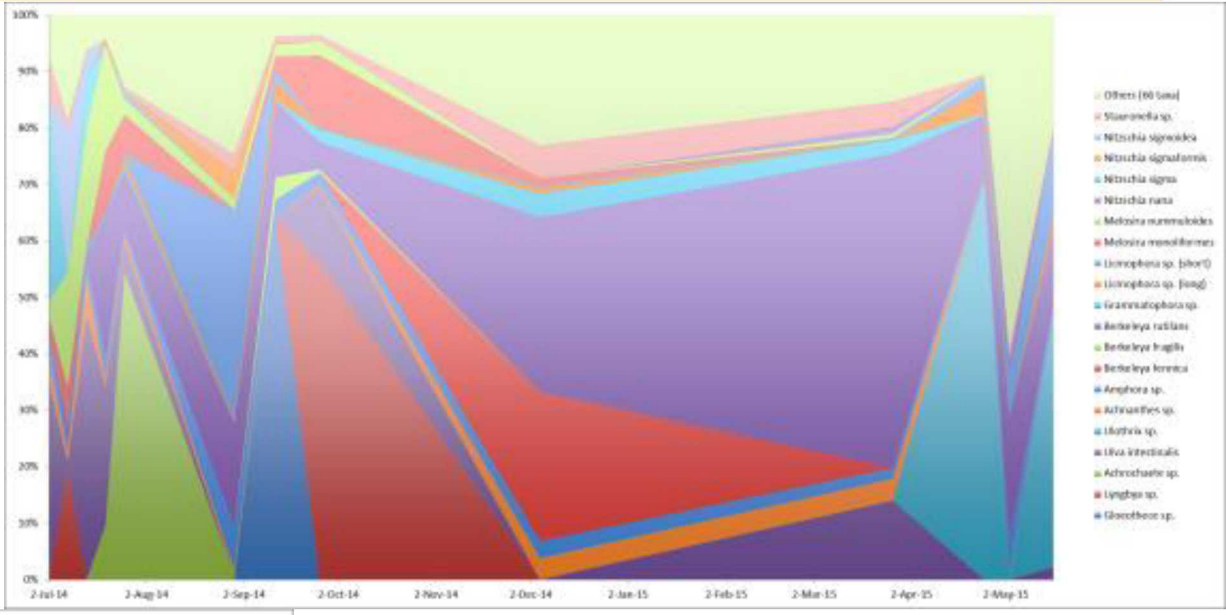
3D substrate

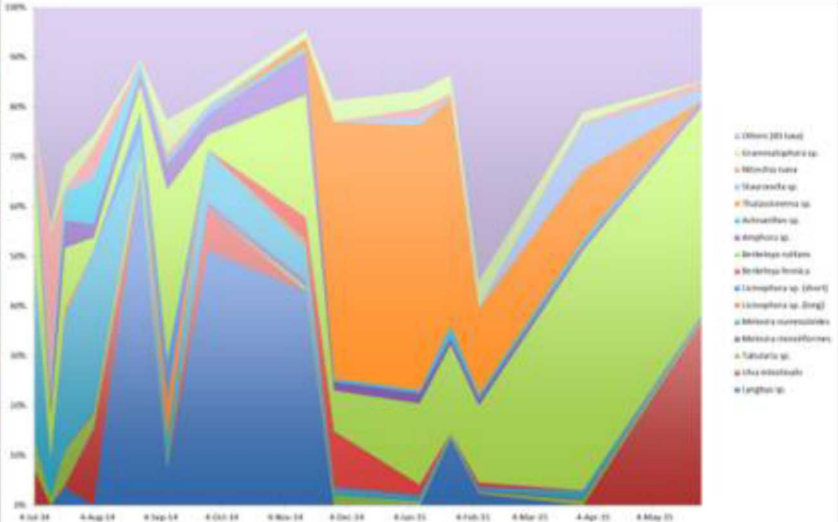
2D substrate

Plot courtesy of Walter Adey, Smithsonian Institution

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]





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[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.

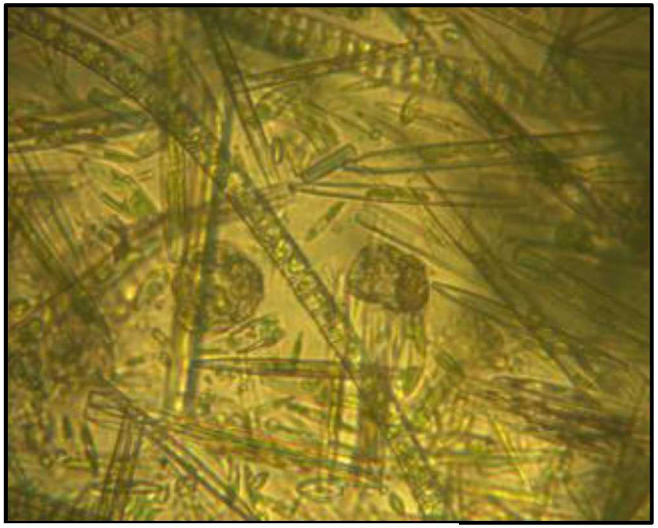
Challenges with algal turf biomass processing & conversion to fuels

- Generally low neutral lipid content
- High ash content (~ 30-50+%) seen with current systems
  - Potential impact on downstream HTL processing/conversion
  - Early characterization indicates large fraction of ash is inorganic debris (‘dirt’) … can be reduced via optimized systems & ops
  - Dilute acid pre-treatment & separation looks very promising
- Heterogeneous polyculture biomass characteristics
  - Location, water source, season specific, and dynamic
  - Can have impact on biochemical & thermochemical processes
  - 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%
- Overall cost effectiveness for biofuel looks promising

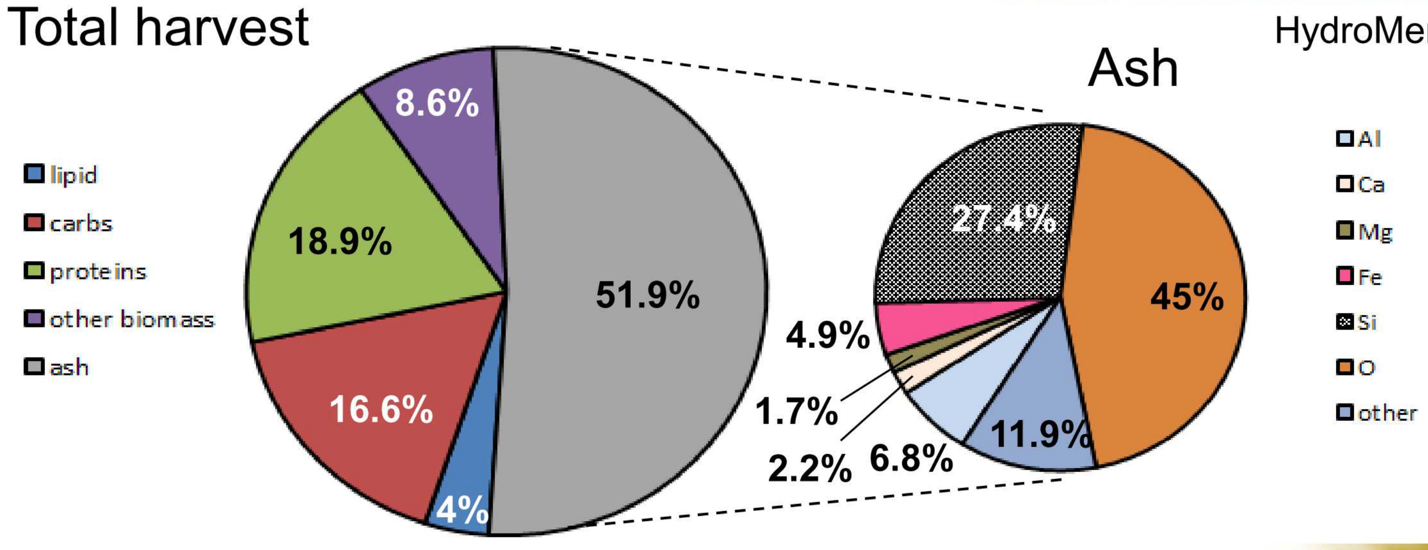
Algal turf biomass characterization*

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

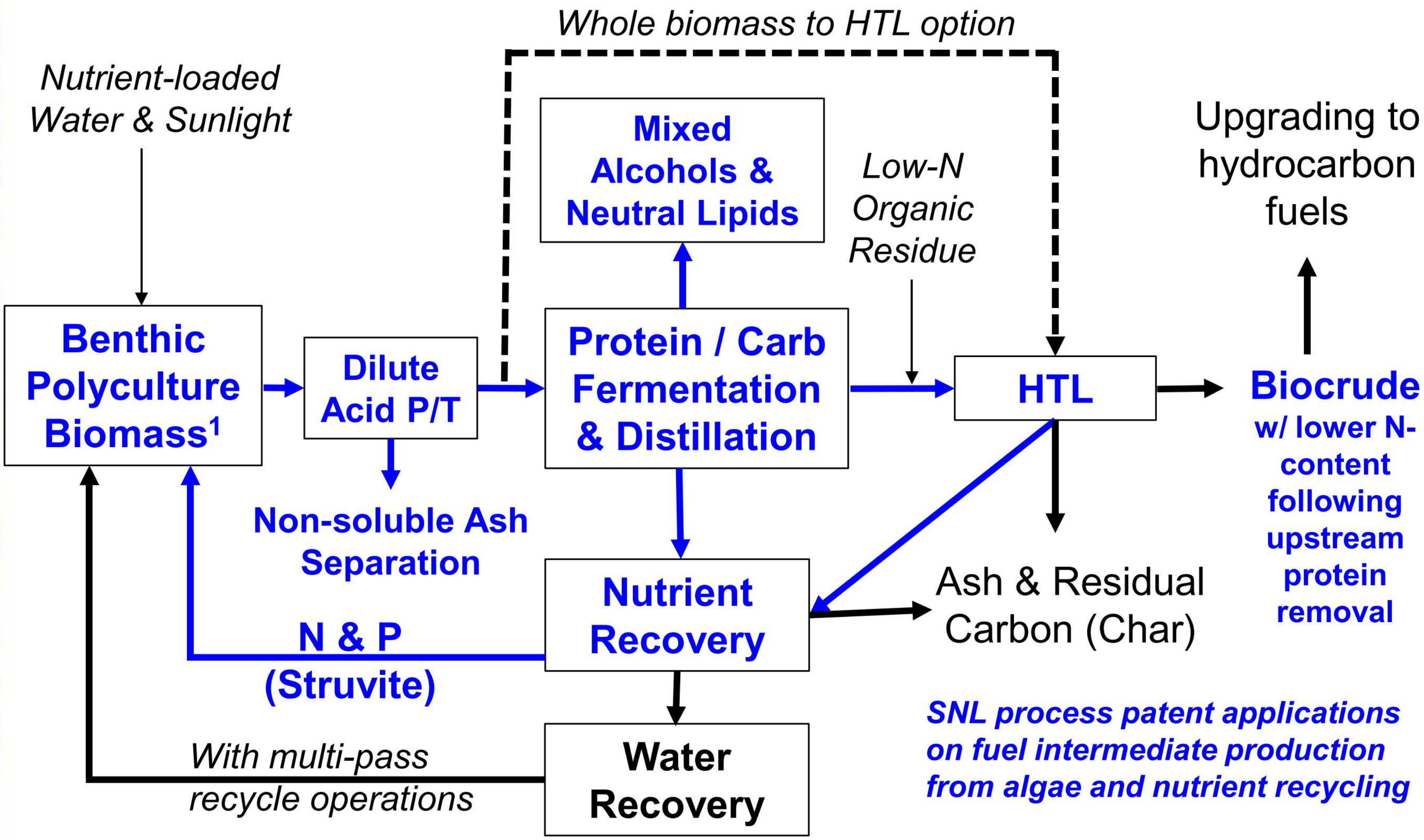
- Variable composition: dependent on water source, climate, season
- Composed of multiple phylogenetic groups: dominant clades include chlorophyta, diatoms, and cyanobacteria
- Low lipid content
- Biogenic and non-biogenic ash content
- System not optimized for ash reduction



HydroMentia sample



Key processing & recycling pathways



Whole biomass to HTL option

Nutrient-loaded Water & Sunlight

Benthic Polyculture Biomass[1]

Dilute Acid P/T

Non-soluble Ash Separation

Mixed Alcohols & Neutral Lipids

Protein / Carb Fermentation & Distillation

Low-N Organic Residue

HTL

Upgrading to hydrocarbon fuels

Biocrude w/ lower N-content following upstream protein removal

Ash & Residual Carbon (Char)

Nutrient Recovery

N & P (Struvite)

Water Recovery

With multi-pass recycle operations

SNL process patent applications on fuel intermediate production from algae and nutrient recycling

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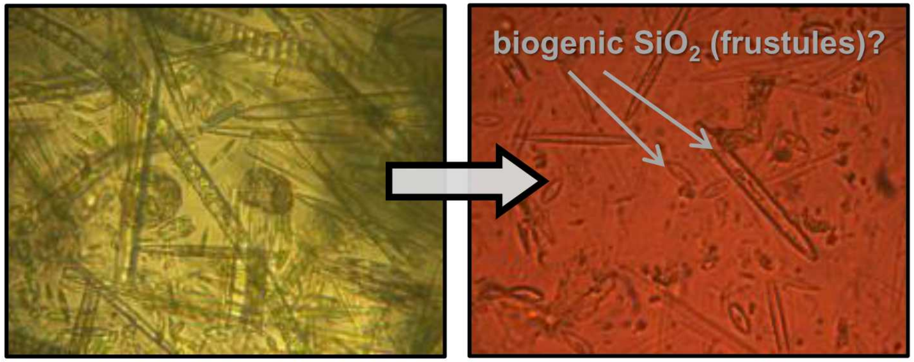
[1] *Benthic algal polyculture turf will also include entrained planktonic species*

Biomass pretreatment:

ash removal, solubilization, and hydrolysis

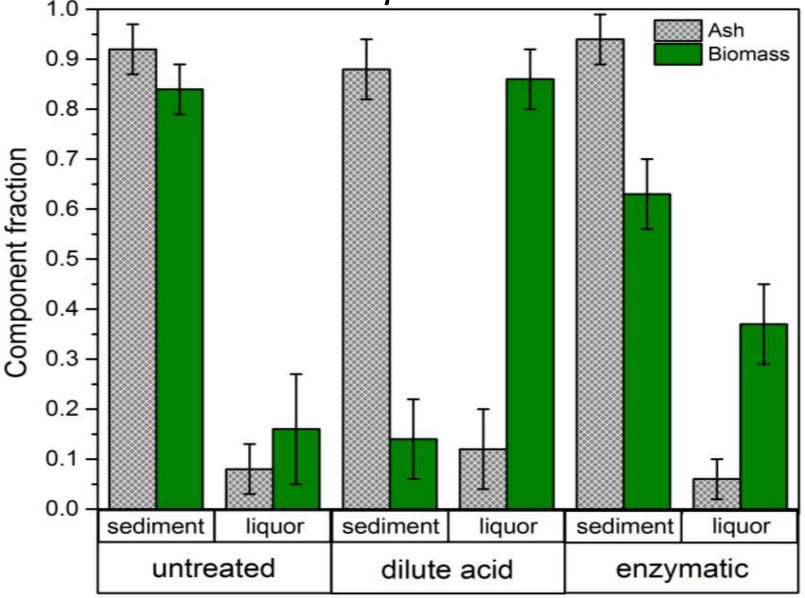
- Dilute acid and enzymatic treatments are each effective for separating ash
- Dilute acid is effective for solubilizing the protein and carb fractions, and carb hydrolysis, but additional enzymatic treatment is necessary for protein hydrolysis
- Large fraction of biogenic ash



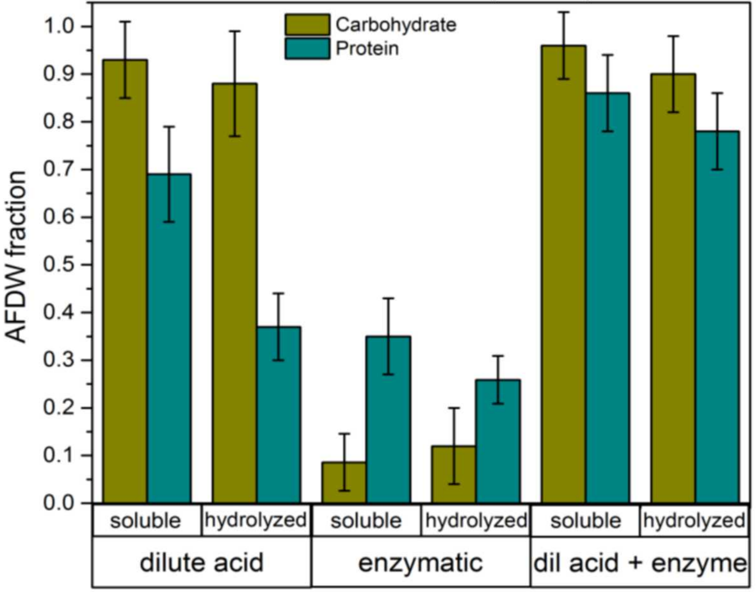
Native biomass *Pretreated residuals*

biogenic SiO_2 (frustules)?

Ash separation

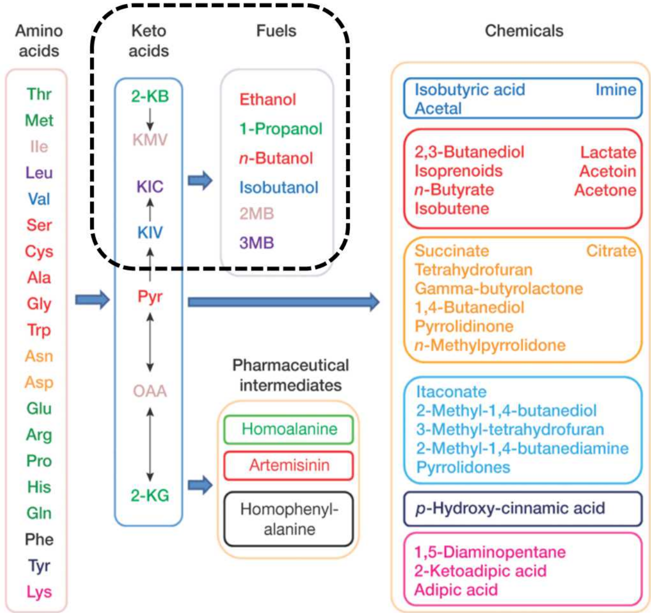


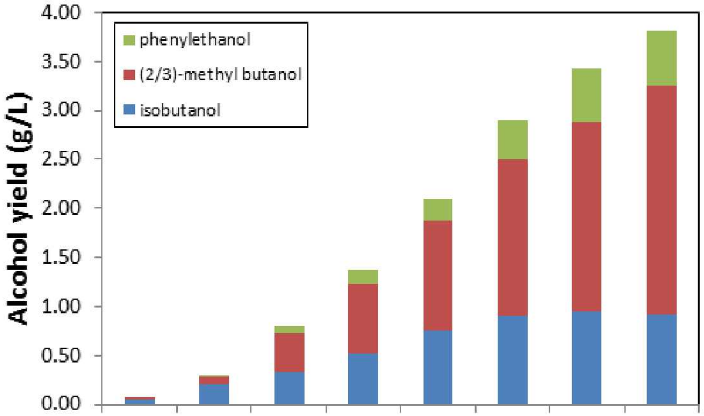
Solubilization and hydrolysis

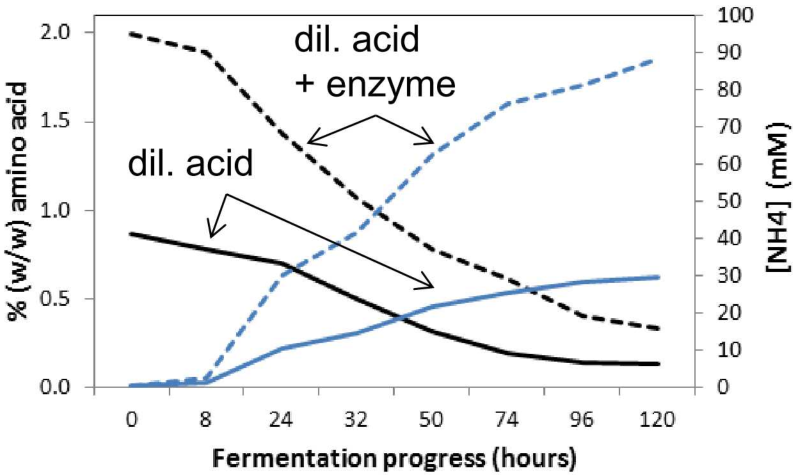


Biochemical conversion:
sugar & protein fermentation

- 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)

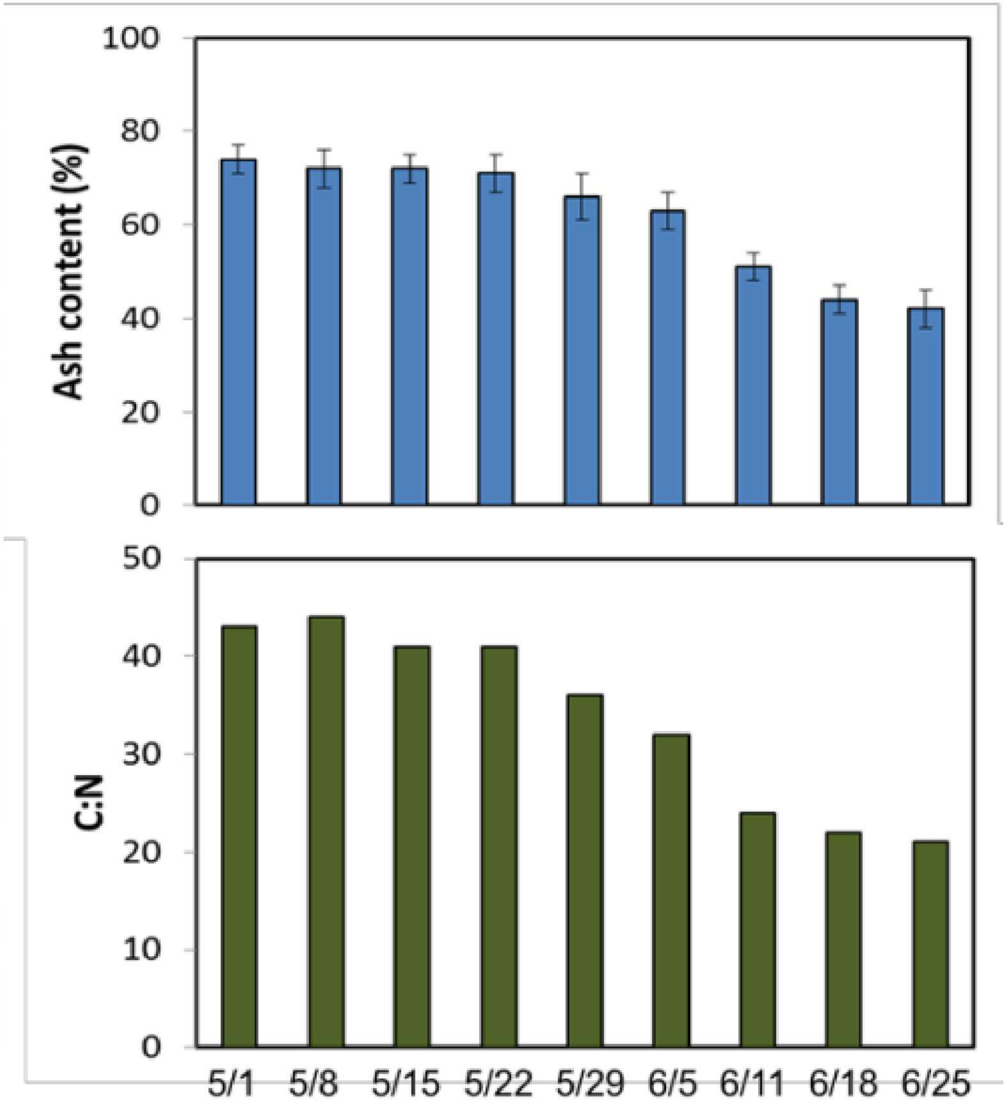






- 70% of theoretical protein conversion achieved with bench scale testing

Algal Turf Sample Characterization

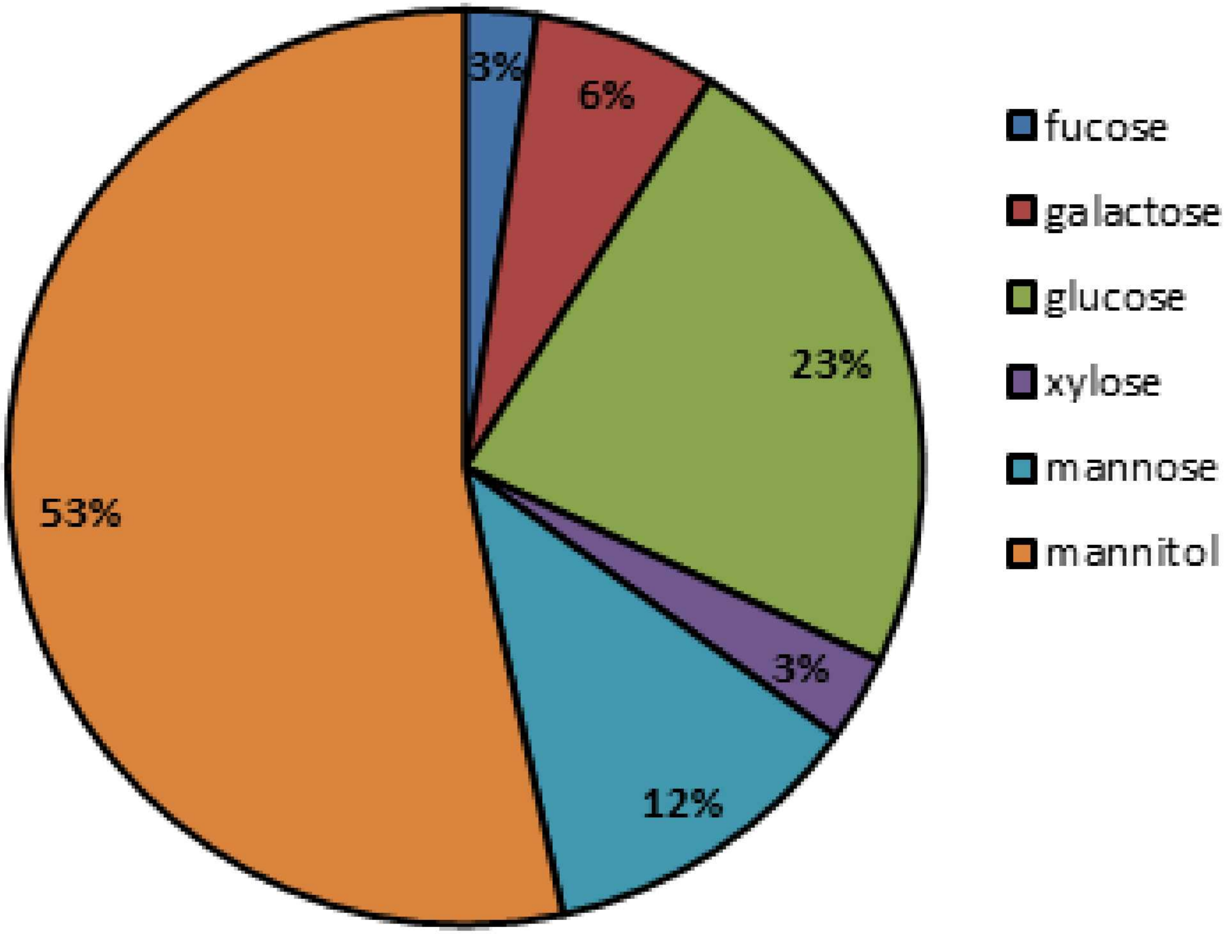


Here is the ash and C:N data for the GWR harvest time series.

May not use this … we'll see

Carbohydrate Profile Data*

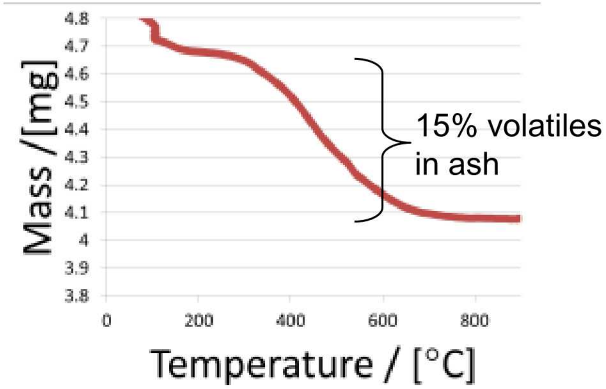
Algal Turf Biomass Sample from HydroMentia

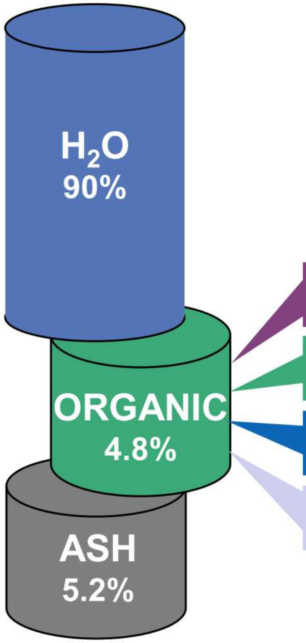


Thermochemical conversion:

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%

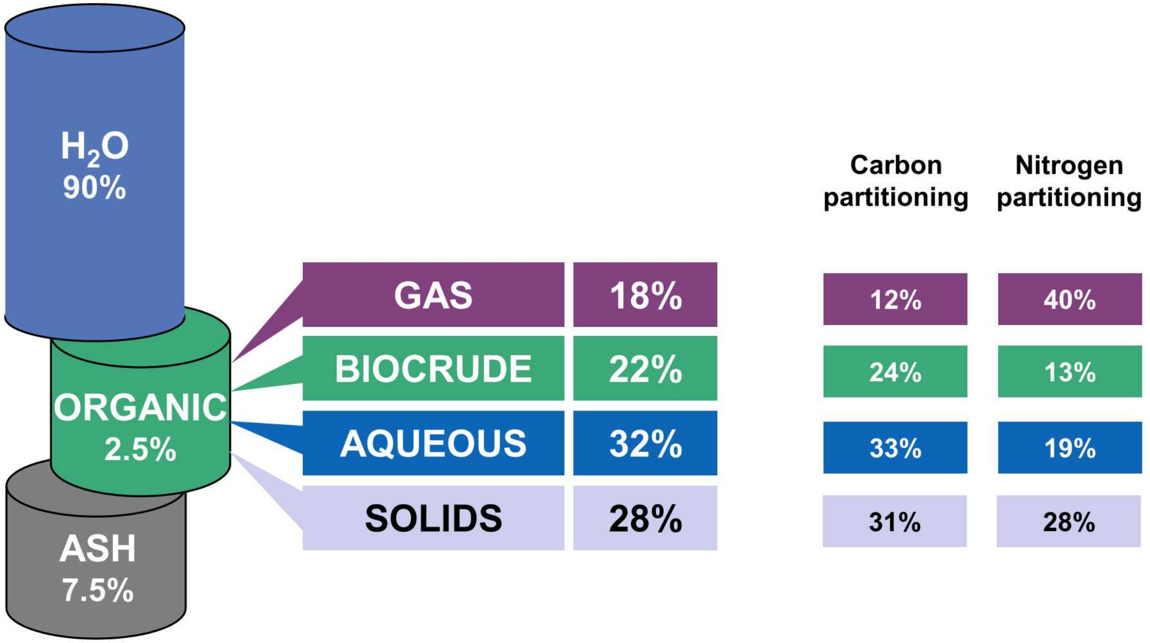
Biocrude N content: 4.5%

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*)



H_2O 90%

ORGANIC 2.5%

ASH 7.5%

		Carbon partitioning	Nitrogen partitioning
GAS	18%	12%	40%
BIOCRUDE	22%	24%	13%
AQUEOUS	32%	33%	19%
SOLIDS	28%	31%	28%

Biocrude N content: 0.89%

Based on wet biomass w/ 10% SOLIDS

DOI: 10.1016/j.algal.2013.07.003

Biochemical Path Forward

- Pretreatment to separate non-soluble ash
- Leverage existing BETO projects on protein fermentation to evaluate denitrification and fuel production from ATS biomass
- Consolidation of carbohydrate (ethanol) and protein fermentations (mixed >C2 alcohols)
- Use process to facilitate remineralization and capture of N and P from the biomass (e.g. as Struvite)
- Continuous fermentations with consolidation of alcohol and algal residue HTL biocrude recovery

Hydrothermal Path Forward

- Initial testing of HTL conversion with planktonic algae monoculture biomass to validate bench-scale methodology
- Currently conducting HTL conversion of algal turf biomass to biocrude – neat at bench-scale
  - Identify desired operation conditions
    - T = 300-350 C, time = 5-60 min, loading = 5-20%
  - Identify barriers to scale-up, e.g.
    - ash, refractory materials
- Future HTL conversion of denitrified algal turf biomass (residue from protein fermentation) to validate reduced N-content of biocrude

Scale-up Feasibility TEA Path Forward

- TEA modeling underway at SNL and USU
- Using scale-up assumptions to be consistent with BETO Algae Biofuels Harmonization Study[1]
- Upstream cultivation based on scale-up of algal turf scrubber® (ATS™) type system modules[2]
- Downstream processing based on preliminary scale-up assumptions for chem/biochem[3,4] and HTL[3,5,6] unit operations (informed by referenced work)

May need to remove reference 5 – checking with Ryan Davis at NREL

1 – 2012 BETO Algae Biofuels Harmonization Report
2 – Reality-check feedback from algal turf water treatment industry (HydroMentia)
3 – Current SNL testing and evaluation at bench scale
4 – PNNL design case report for HTL processing of algae (published March 2014)
5 – NREL design case report for chem/biochem processing of algae (in peer review)
6 – Independent HTL engineering scale-up modeling/assessment at Utah State University

Placeholder for Intro to Initial TEA results … will describe verbally

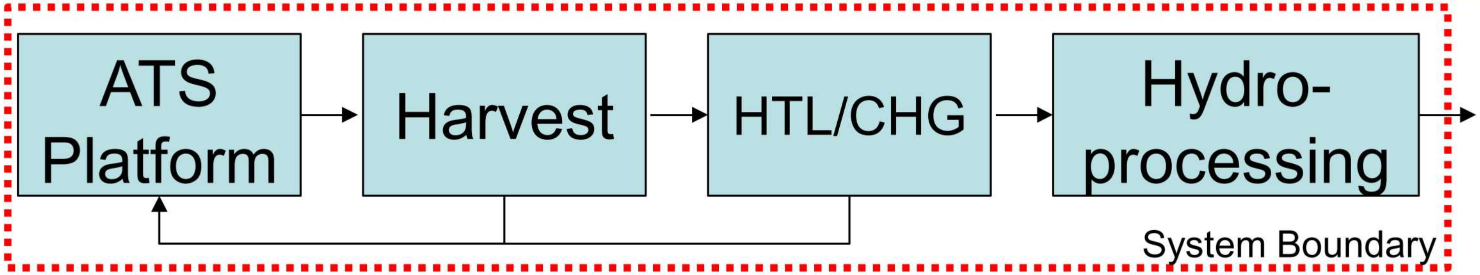
Will remove this slide in final !

- Based on downstream processing of whole algal turf biomass with HTL and upgrading to HC fuel using modeling at Utah State University based on PNNL Report
- Comparative modeling of multiple pathways of whole algae HTL processing and biochemical pre-processing followed by HTL of residues is still in progress at SNL ...

Cost results (GGE) of HTL/Hydrotreatment processing to fuels:
Scenario 1 (50% ash): $8.54/gal
Scenario 2 (25% ash): $6.98/gal
Scenario 3 (13% ash): $6.57/gal

Foundational TEA Assumptions*

* Using HTL/CHG-Hydroprocessing performance from PNNL 2014 report



- Economic Assumption
  - Similar to process design case studies by NREL

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 Production	1340 ton d^{-1}
Capital Cost	\$10 m^{-2}

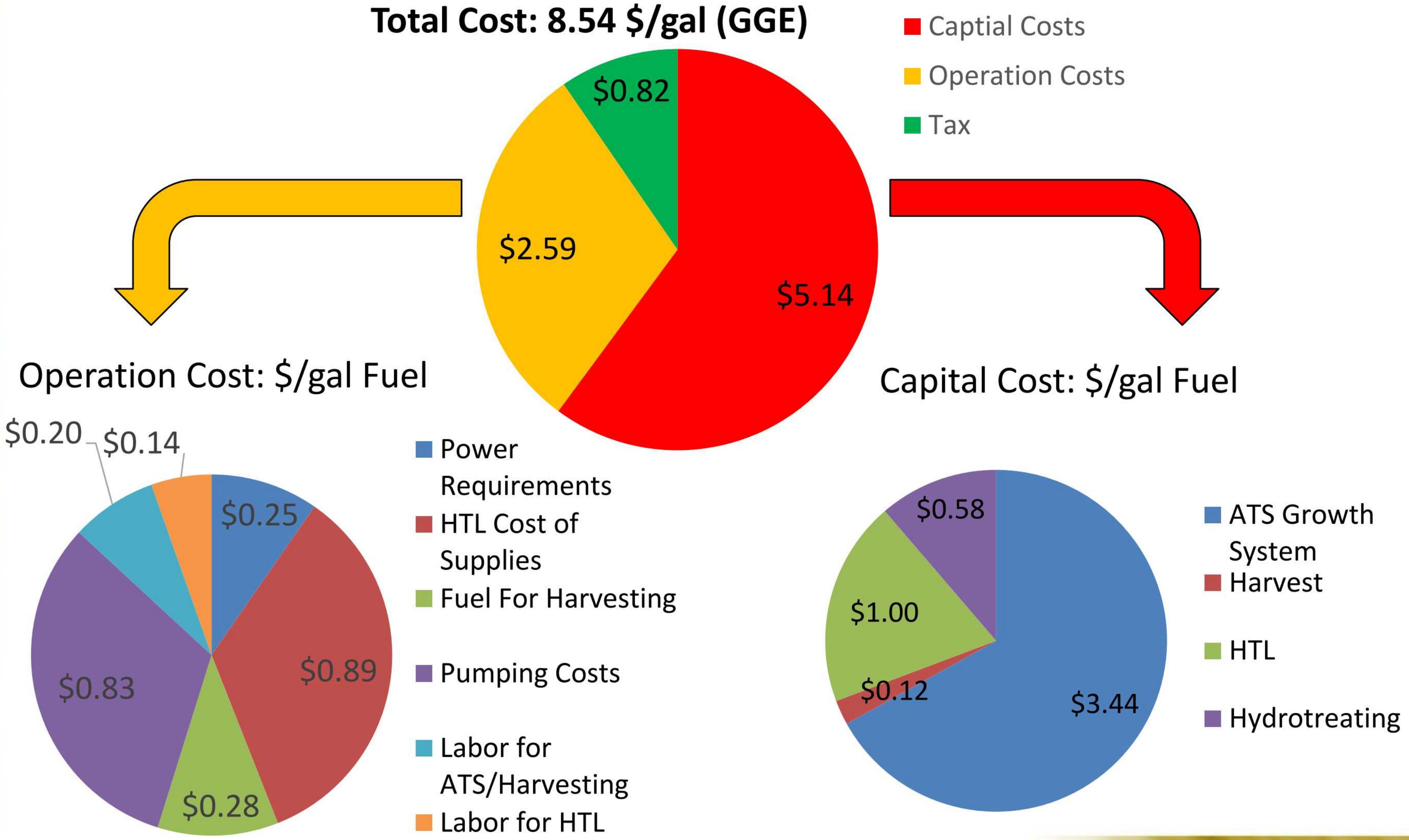
Harvest	
Harvest Density	20% solids
Ash Content	50%
Harvest Frequency	7 days
Operation Cost	\$0.23 m^{-2}yr^{-1}
Capital Cost	\$0.35 m^{-2}

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*

* non-optimized for ash content reduction

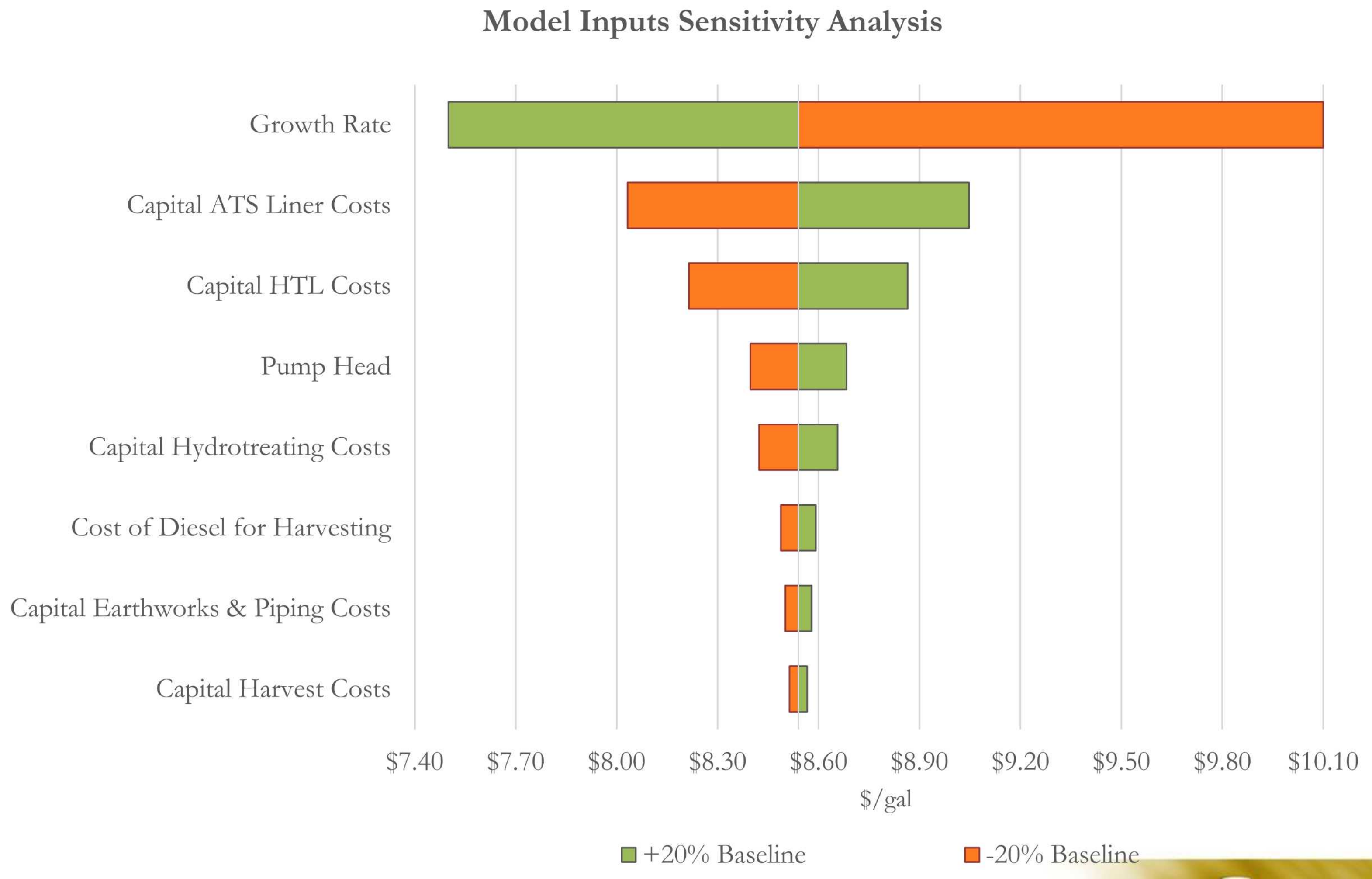


Total Cost: 8.54 $/gal (GGE)

Operation Cost: $/gal Fuel

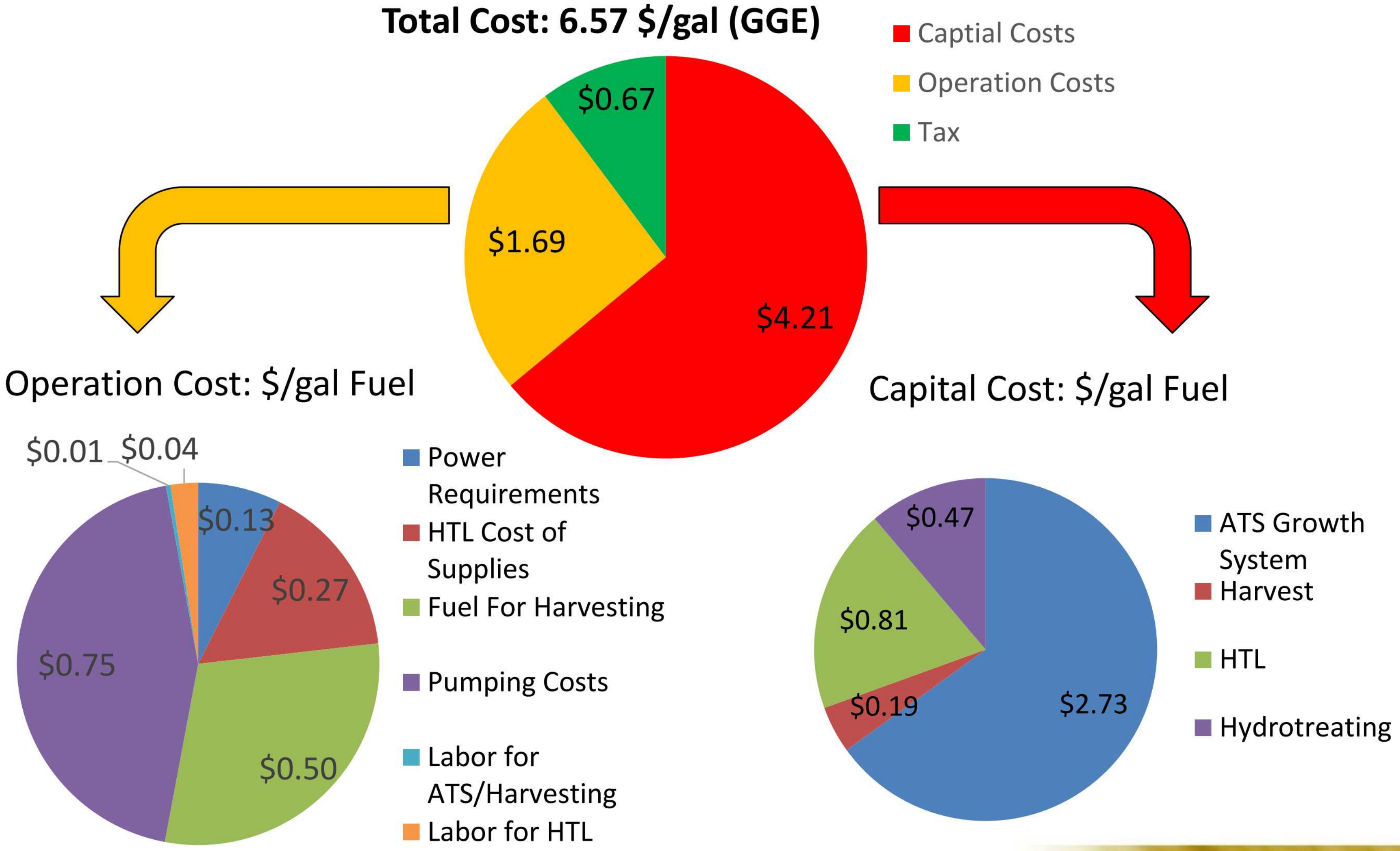
Capital Cost: $/gal Fuel

Sensitivity Analysis
Current Non-optimzed Case*
* non-optimized for ash content reduction



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

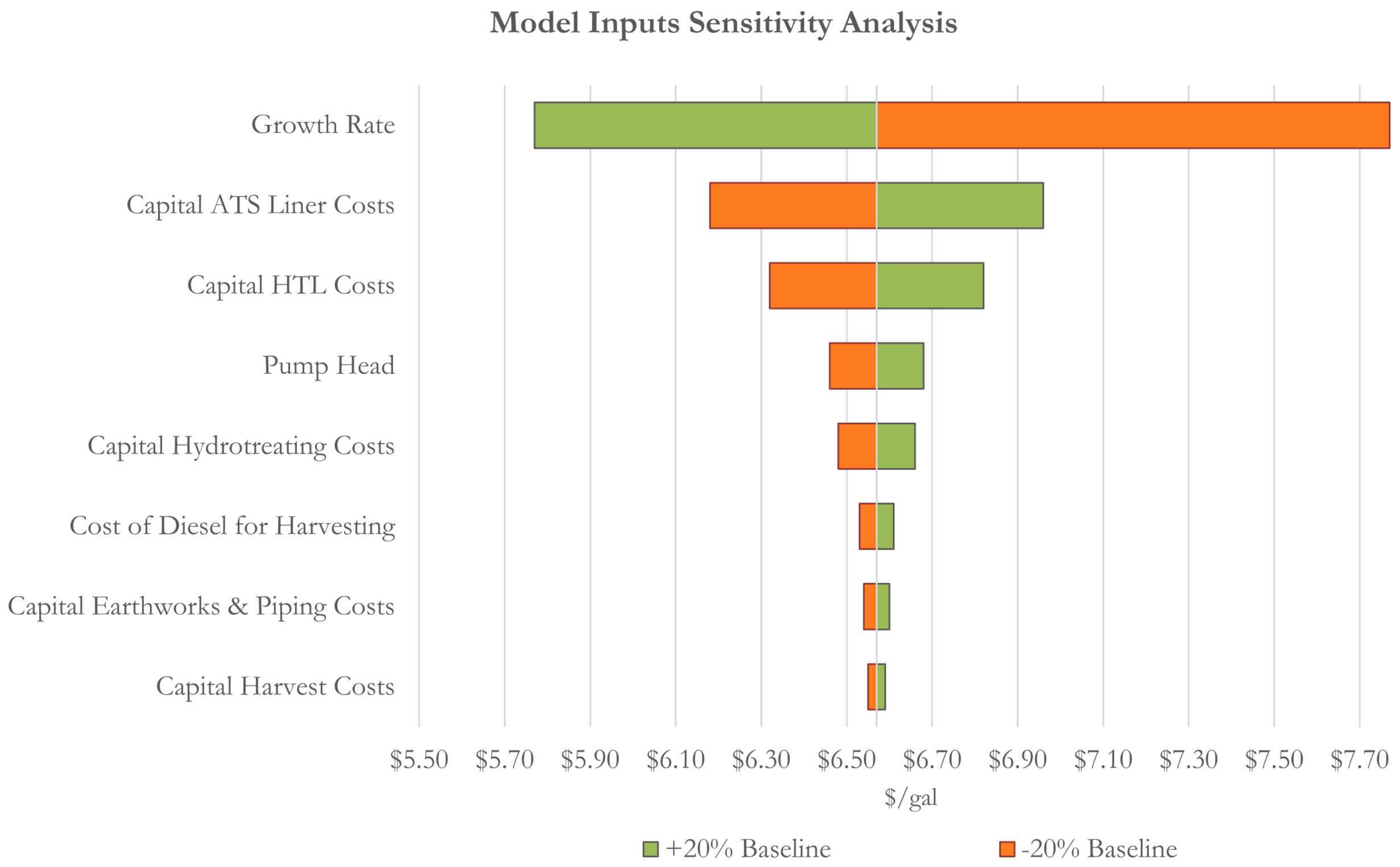
* Improved for ash content reduction


Total Cost: 6.57 $/gal (GGE)

Operation Cost: $/gal Fuel

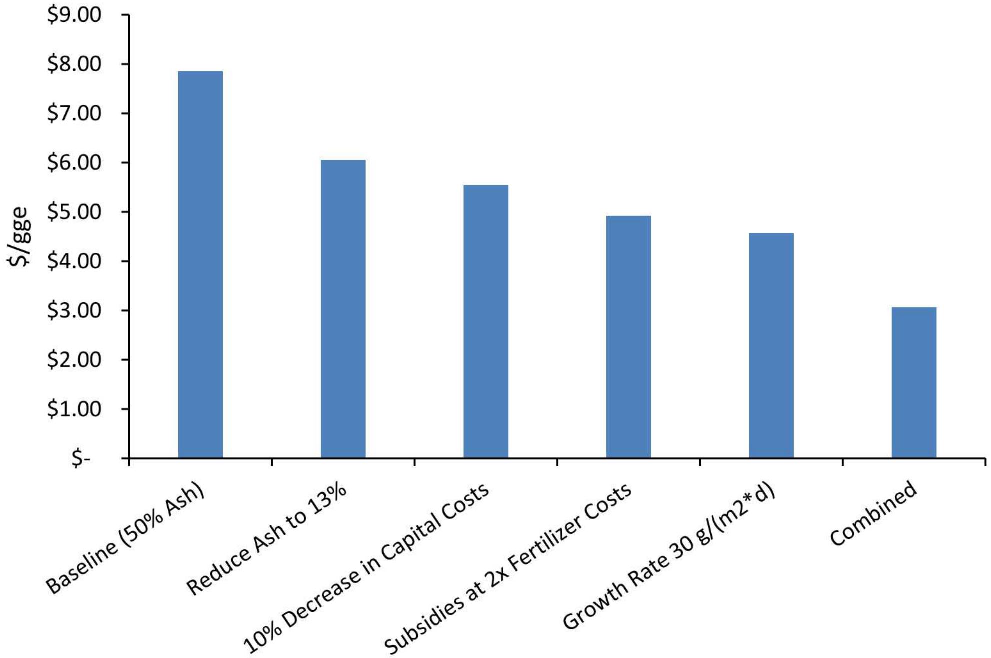
Capital Cost: $/gal Fuel

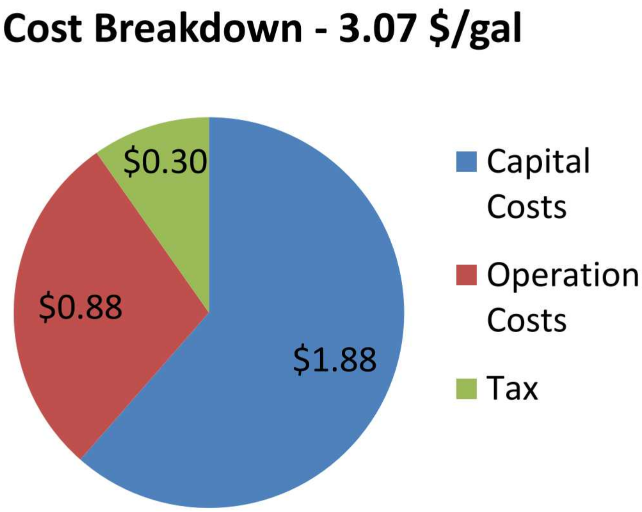
Sensitivity Analysis
Improved Lower Ash Content Case*
*Optimized for ash content reduction



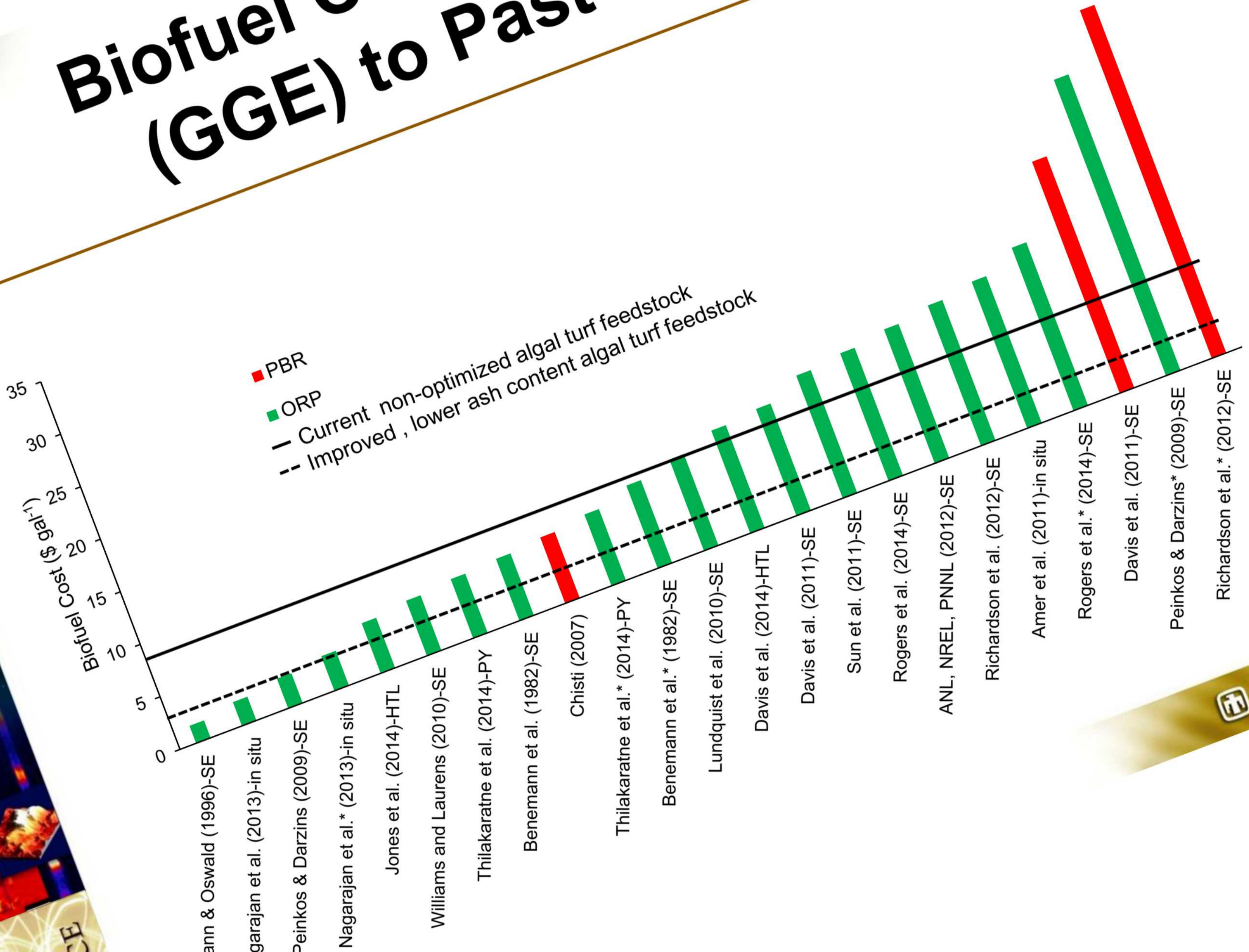
Example Path to $3 GGE

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





Biofuel Cost Compa (GGE) to Past Studies



Scale-up Feasibility TEA
Next Steps …

- Add upstream biochemical processing pathways
  - Protein &/or carb conversion to sugars, mixed alcohols, other compounds
  - Production of fuel intermediates / blend stock
  - Feedstock for higher-value products
- Use downstream HTL/CHG + Hydroprocessing on residue
- Add nutrient capture/recycling from downstream processing
  - Production of fertilizer for other markets
  - Recycling to upstream algal biomass production
- Assess cost trade-offs with alternate processing paths to fuels and other co-products
- Environmental credits for water clean-up can also be factored in as co-service to reduce fuel costs

Conclusions

- Benthic algal turf polyculture assemblages offer a promising alternative approach to algal biofuels
  - *Includes robust mix of benthic and entrapped planktonic species*
- 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
  - *Without the need for supplemental CO_2 or commercial nutrients (N, P)*
  - *Significant opportunities for improvement for high productivity of lower-ash content biomass*
- Un-optimized HTL testing with 44% conversion suggests biocrude yield of 3000 - 3500 gal/acre with annual average biomass of 20 g m^{-2} d^{-1} (~ 30 metric tons ac^{-1} yr^{-1} AFDW biomass)

Conclusions … continued

- Bench scale conversion of biomass protein fraction has achieved 70% of theoretical maximum
    - *Combined with ethanol production from fermentation of carbohydrate fraction and neutral lipid extraction*
    - *Produces higher-valued fuel products (e.g., potential drop-in or blend stock butanol, EtOH, and extracted lipids)*
    - *Allows recycle of N as ammonium from protein fermentation and P and N as struvite from other processes*
- Preliminary TEA results show promise and pathways for achieving affordable biofuels production at large scale
    - *Practical approach more consistent with open field agriculture*
    - *Room for improvement in both performance and cost reduction*
- Potential exists for ≥1 BGY biofuel production using nutrients and CO_2 from surface waters in the U.S.
- More detailed LCA and resource assessment is needed

Thank you! - Questions?

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Dean Calahan, Smithsonian Institution

Jason Quinn, Utah State University

Justin Hoffman, Utah State University

Possibly add SI Logo ?
Have requested from
Walter/Dean

HydroMentia
WATER TREATMENT TECHNOLOGIES

UtahStateUniversity

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Back-up and/or discarded slides

Benthic Algal Polyculture Turf Biomass Cultivation, Harvesting & De-Watering

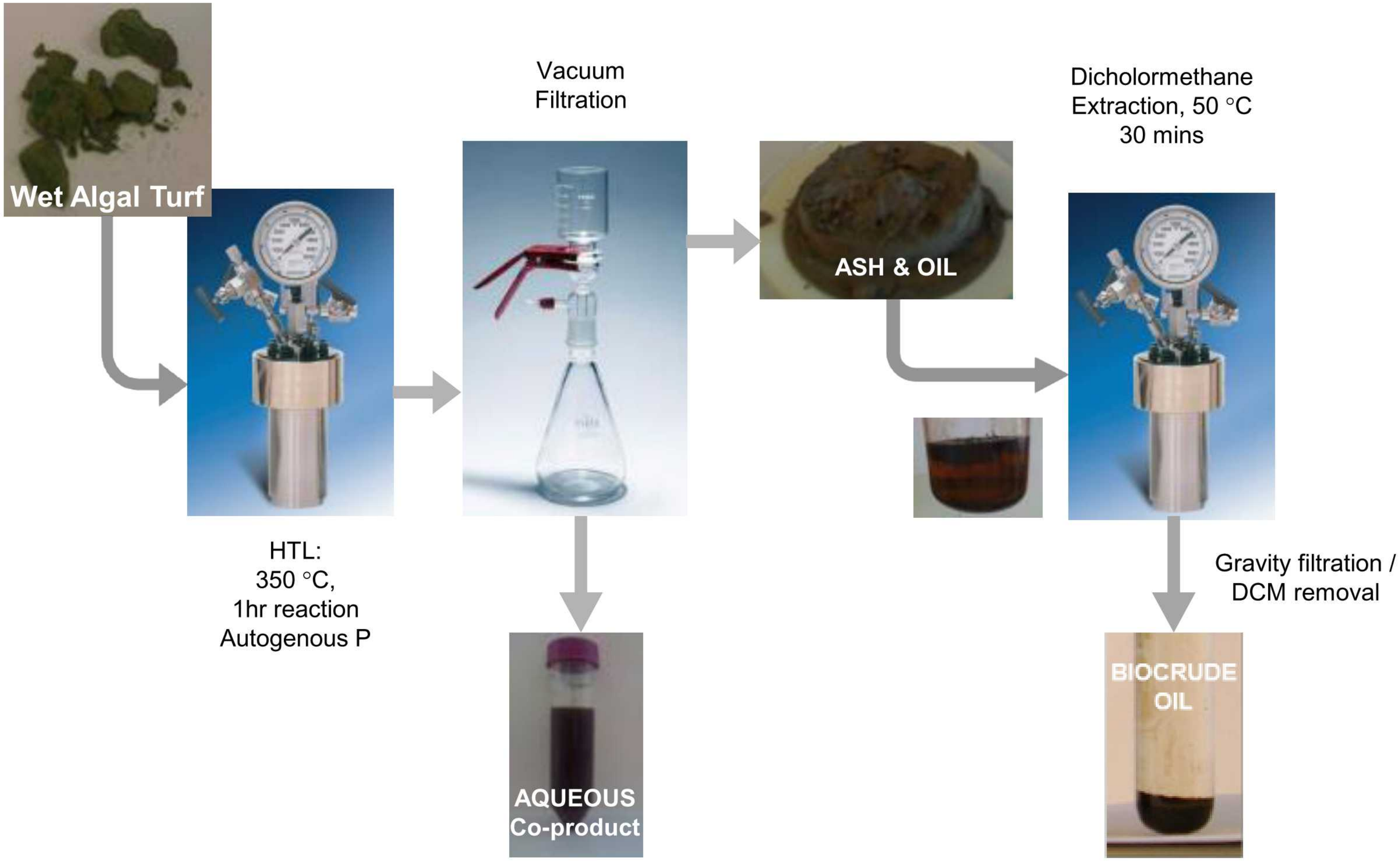
Photos courtesy of HydroMentia and Walter Adey

Key Points

- Benthic polyculture algal consortia offer a promising alternative approach to algal biofuels
- Fixed planar substrate, and rotating cylindrical substrate system approaches are currently being used by industry and researchers
  - Fixed planar: e.g., Algal Turf Scrubber® (ATS™) developed by Walter Adey & later commercialized by HydroMentia for water treatment
  - Rotating cylindrical: e.g., Bioprocess Algae, Utah State University
- Emphasis in this discussion is on the planar fixed substrate approach
- Robust cultivation stability and harvests of ~20-30 metric tons ac^{-1} yr^{-1} AFDW (15-20 $g\ m^{-2}\ d^{-1}$) demonstrated over multi-year operations
  - based on actual performance with **non-optimized systems**, discounting for 50% ash content - **can use fresh, brackish, and saline water sources**
  - significant room for improvement and optimization for increased performance (e.g., higher biomass productivity with reduced ash) & reduced costs
  - Simple low energy intensity harvesting & dewatering with agriculture-type systems
  - No supplemental CO_2 (for single-pass operations with large non-point sources)
  - No commercial fertilizer (for single-pass operations with nutrient-laden sources)
- High Ash and Low Lipids – Chem/Biochem/HTL processing required
- TEA - Preliminary studies currently underway by SNL and Utah State University with early results looking promising

Thermochemical conversion:

HTL conversion and oil extraction



Wet Algal Turf

HTL:
350 °C,
1hr reaction
Autogenous P

Vacuum
Filtration

AQUEOUS
Co-product

ASH & OIL

Dicholormethane
Extraction, 50 °C
30 mins

Gravity filtration /
DCM removal

BIOCRUDE
OIL