U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Algal Polyculture Conversion & Analysis

24 March 2015

Algae Technology Area

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Ron Pate

Sandia National Laboratories

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.

Goal Statement

Alternative path to affordable & scalable algal biofuels

- New paradigm not focused on monoculture, lipids, and PBRs & raceway pond cultivation approaches
- Emphasis on benthic algal turf polyculture for practical scale-up
  - Robust, resilient polyculture biomass cultivation
  - Potential for high biomass productivity with ease of harvesting & dewatering
  - Potential avoidance of need for supplemental CO2 & commercial fertilizers
  - Potential for tapping water clean-up credits as a co-product / co-service
  - Conversion of all components of low-lipid algal polyculture biomass to fuel intermediates using optimized tandem biochemical and/or HTL processing.

Relevance and Outcomes

- Show feasibility and path for integrated scale-up to meet MYPP[1] targets of 5000 GGE/acre @ $3/GGE

[1] *DOE/EERE-BETO, Multi-Year Program Plan, November 2014.*

Quad Chart Overview

Timeline

Project start date: August 13, 2013
Project end date: September 30, 2017
Percent complete: 28%

Budget

	Total Costs FY 10 –FY 12	FY 13 Costs	FY 14 Costs	Total Planned Funding (FY 15-Project End Date
DOE Funded	N/A	$13K	$433K	$5,275K
INL	N/A	N/A	N/A	$2,150K
ORNL	N/A	N/A	N/A	$975K
PNNL	N/A	N/A	N/A	$300K
SNL	N/A	$13K	$433K	$1850K

Prior to Hub (FY 13 Costs, FY 14 Costs) — Hub (Total Planned Funding)

Barriers

- AFt-A. Biomass Availability and Cost
- AFt-B. Sustainable Algae Production
- AFt-D. Sustainable Harvesting
- AFt-H. Overall Integration & Scale-up
- AFt-I. Algal Feedstock Preprocessing

Partners

National Laboratories (level of effort) – Hub

- INL (41%)
- ORNL (18%)
- SNL (35%)
- PNNL (6%)

Collaborators (Hub and otherwise)

- University of California San Diego (Hub)
- University of Kansas (ORNL)
- Boise State University (INL)
- Hydromentia (SNL)
- SI & Ecological Systems Technology (SNL)
- Utah State University (SNL)

1 - Project Overview

History and Context

- FY09/10 - SNL interest in polyculture algal turf began as possible alternative to address challenges for monoculture PBR/pond/lipid pathway to algal biofuels;
- FY13 - SNL-led "Algal Turf to Fuel" team proposal to ABY FOA;
- Late-FY13 - SNL asked to help BETO investigate polyculture potential via new AOP project - Polyculture Conversion & Analysis:
  - Quick-dive polyculture literature search and consulting of colleagues active in field w/ findings reported to BETO 1QFY14: **Promising for resilience, Improved productivity TBD**
  - Initiated algal turf sample characterization and biochemical & HTL processing of wet algal turf in Q2/FY14 – leveraging work under former SABC (BETO-funded) project;
  - TEA feasibility analysis of "algal turf to fuels" initiated late-FY14 for whole HTL;
- FY15 – Continued SNL testing/analysis; TEA of tandem biochem + HTL
- FY15 – Initiation of coordination & collaboration of SNL project with multi-lab "Polyculture Hub"

High-Level Objectives

- Identify & develop cost-effective and scalable path for producing fuels from low-lipid algal polyculture biomass, with emphasis on benthic algal turf

2 – Approach (Technical)

Emphasis:

- Benthic polyculture algal turf biomass characterization, productivity and quality improvement for fuels;
- Tandem biochemical and/or HTL conversion of low-lipid biomass to fuels;
- Algal turf-to-fuels TEA, LCA, and sustainable scale-up feasibility assessment;
- Hub Collaboration - Comparative assessment of productivity, stability, and conversion efficiency relative to pond-based monoculture & polyculture.

Challenges:

- Improving algal turf biomass productivity & quality (lower ash) without need for supplemental CO2 and fertilizer – nutrient recycling included;
- Affordable & scalable conversion of low-lipid and higher-ash biomass to fuels.

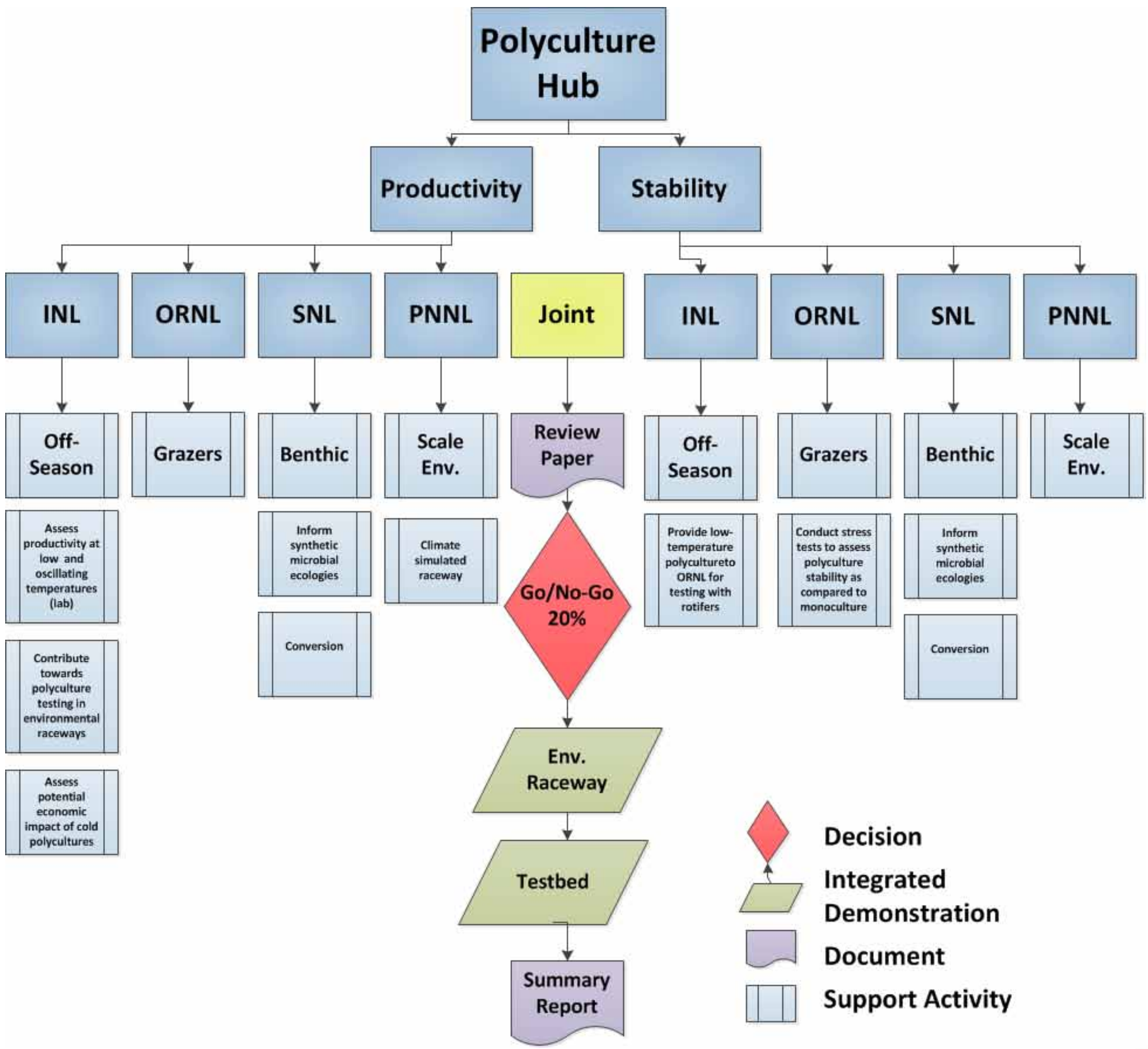
Critical success factors:

- **Go/No-Go**: Demonstrate annual average productivity of ≥20 g m^{-2} d^{-1} (AFDW) and conversion of wet biomass to fuels with target yields of ≥40%;
- TEA & LCA performance – LCA still to come, refined TEA in progress;
- **Industry and lab partnering to enable affordable fuels scale-up.**

2 – Approach (Management) – SNL

- **Focus on critical success factors that will define path with technical and commercial viability**
  - Biomass productivity, quality, and fuel conversion efficiency;
  - Fuel production cost reduction potential and path;
  - Fuel production scale-up potential and path;
  - Leverage value from co-products & co-services.
- **Risk Management**
  - Leverage mature, commercialized, and scalable algal turf production technology for water treatment;
  - Pursue complementary alternative Biochemical and HTL processing pathways, including nutrient recycling ;
  - Coordinate/Collaborate with other BETO labs under Algal Polyculture Hub.

2 – Approach (Management) - Hub

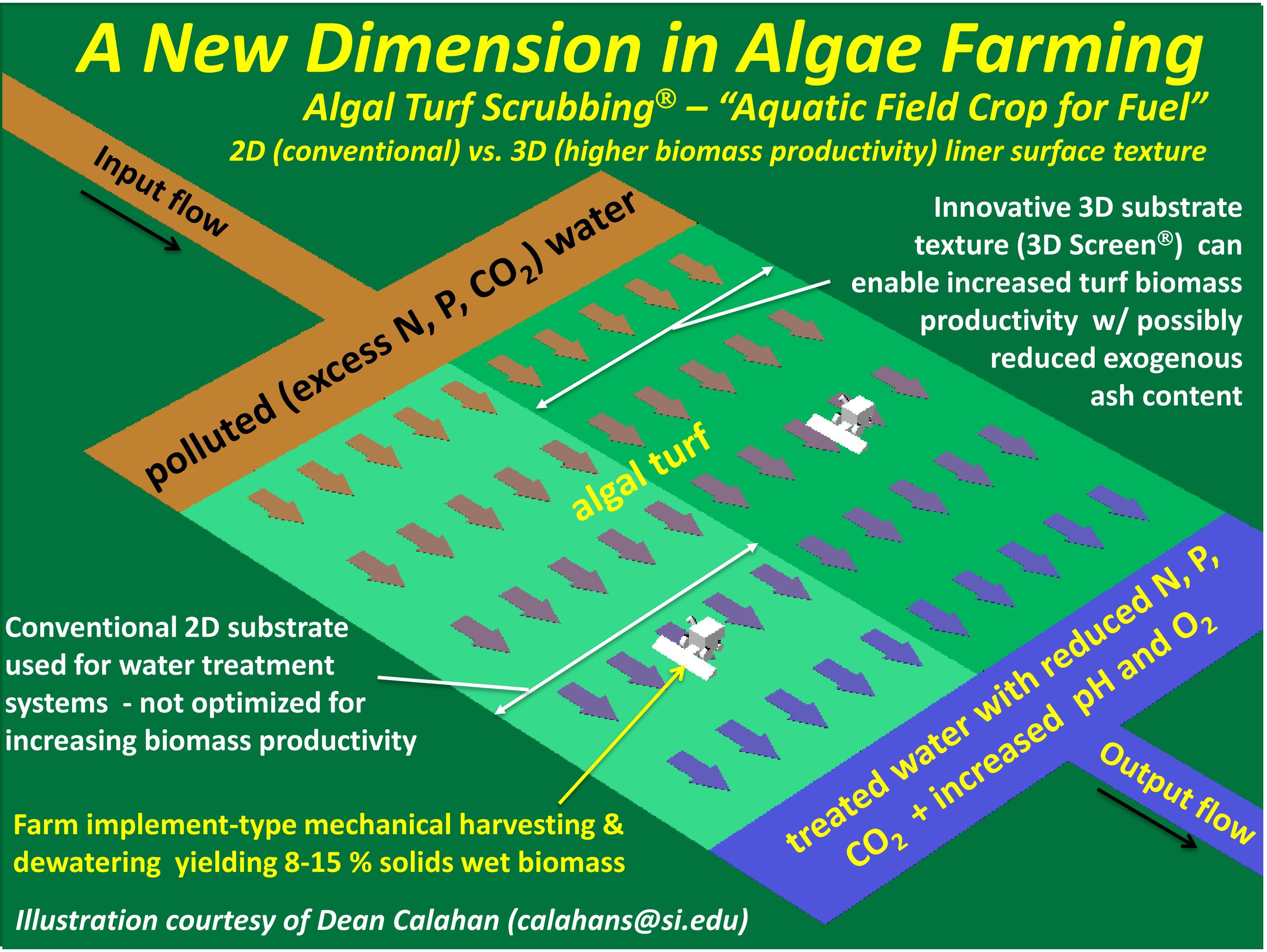


Coordination Plan

- Individual laboratory AOPs
- Lab specific milestones
- Joint milestones
- Scaled demonstrations
- Project integration
- Monthly PI calls
- Quarterly HQ calls
- Quarterly reports to BETO
- Go To Meetings
- SharePoint Site
- Common framework for data when possible
- Hub-- Extension of expertise through university collaborators

Algal Turf System - Open Field Algal Farming

Cleaning water while producing biomass

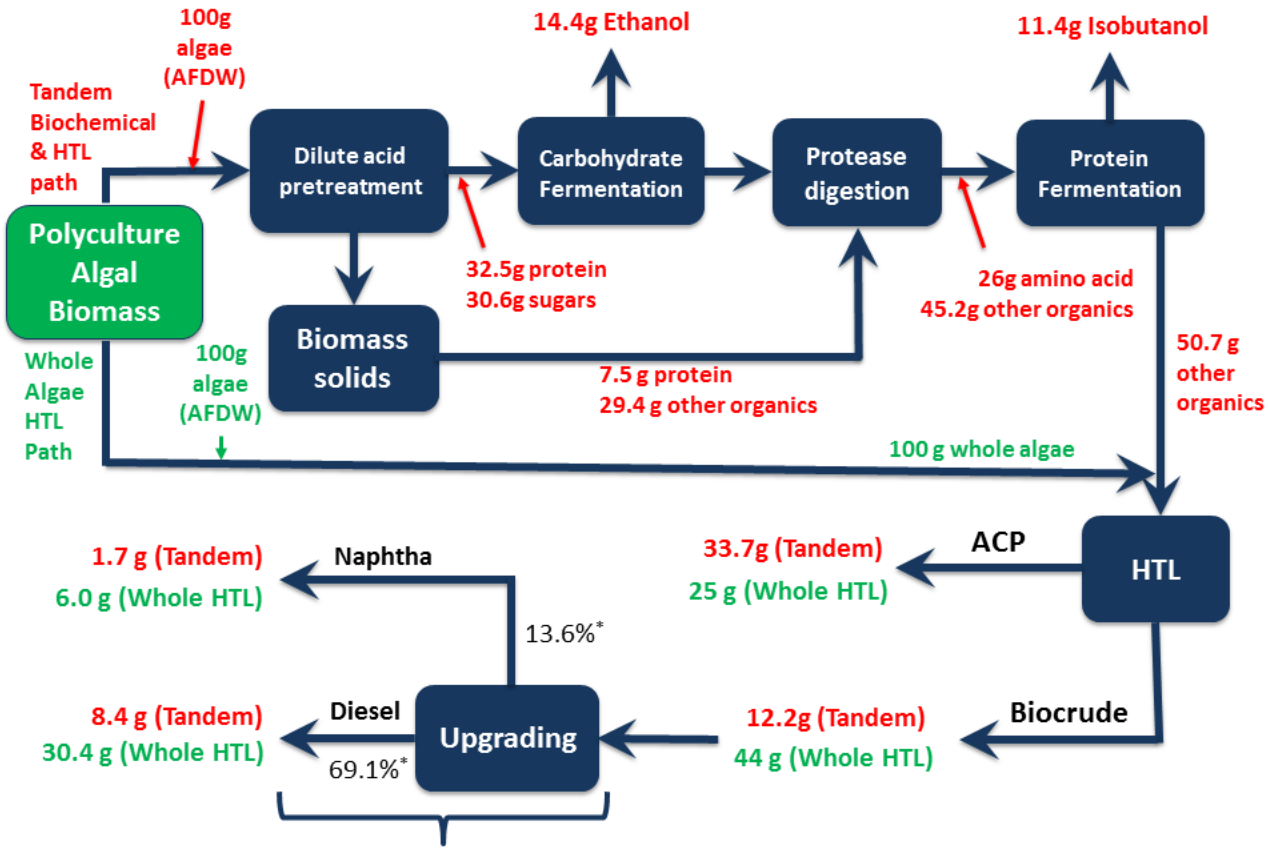


Consists of slightly tilted & lined planar open-field systems using pulsed, shallow, turbulent water flow and mechanical harvesting compatible with conventional agriculture.

Two Paths to Fuel - Tandem Biochemical + HTL & Whole Algae HTL Processing

~1500-3000 GGE/Acre Fuel Potential** with Algal Turf Productivity of 10-15 g m^{-2} d^{-1} (AFDW)

~3700-6000 GGE/Acre Fuel Potential** with Algal Turf Productivity of 25-30 g m^{-2} d^{-1} (AFDW)



** Assumed HTL biocrude upgrade conversion factors from: Jones, et al., AHTL Process Design Report, PNNL-23227, March 2014.*

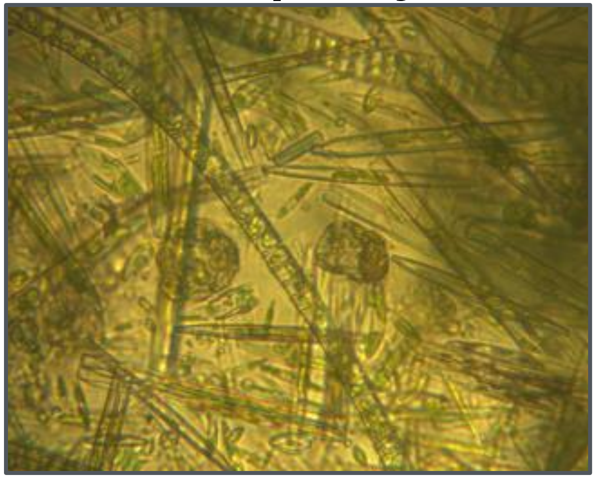
** Based on projections with non-optimized fuel intermediate yields achieved at bench scale at SNL and from the literature, not including potential energy extraction from HTL aqueous co-product (ACP), using algal turf polyculture biomass from HydroMentia with the following AFDW material composition:

8g lipid
39g protein
34g carbohydrate
19g other organics
100g basis (AFDW)

3 – Technical Accomplishments/Progress/Results (cont’d)

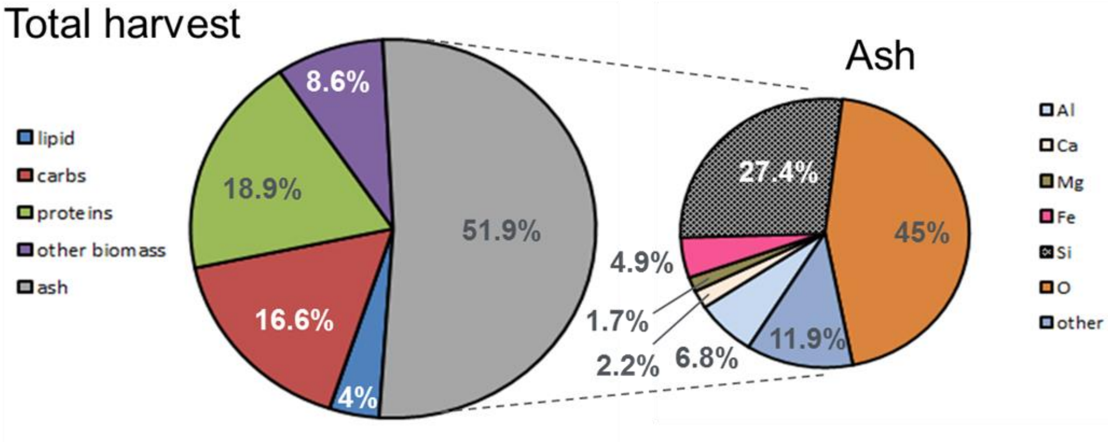
Algal turf biomass characterization (raw harvested material)

From systems and operations non-optimized for biomass quality



HydroMentia Sample

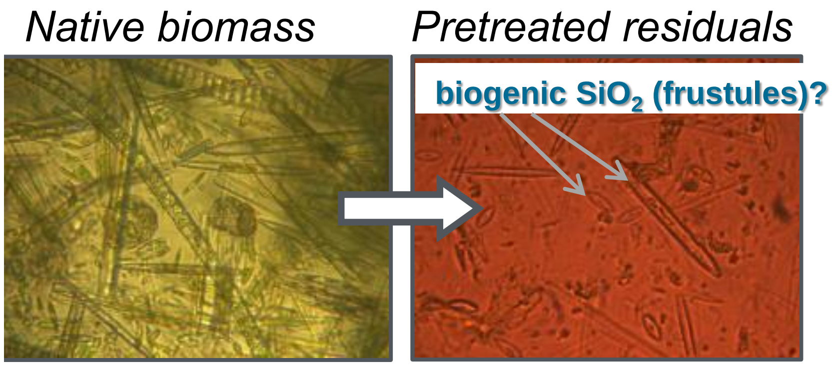
- Composed of multiple phylogenetic groups: Dominant clades include chlorophyta, diatoms & cyanobacteria – details depending on location
- Relatively low lipid content (8% AFDW)
- Relatively high protein content (39% AFDW)
- Relatively high carbohydrate content (34% AFDW)
- Can have relatively high ash content (50+% raw harvest) *Biogenic + Exogenous Ash*
- Ash reduced from 52% to ~20% w/ rinsing
- Untapped opportunities to improve and optimize harvested material quality

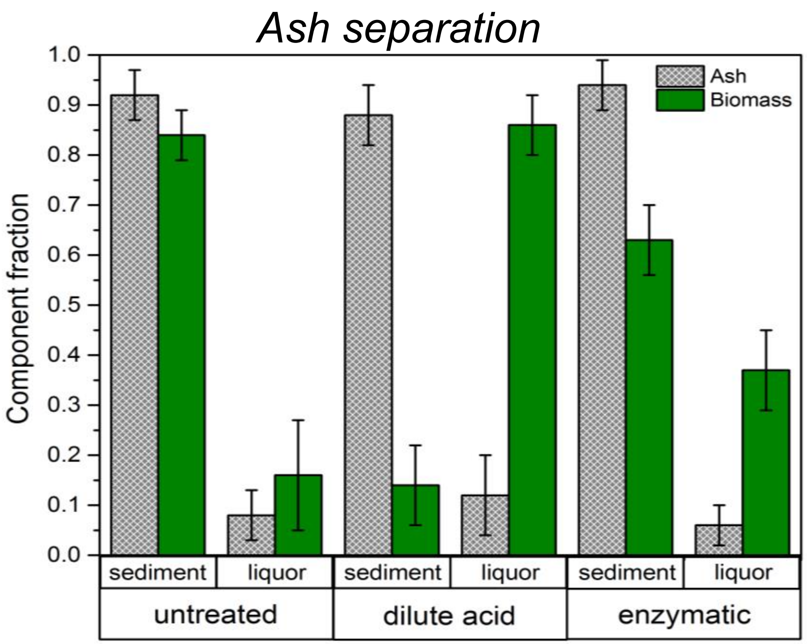


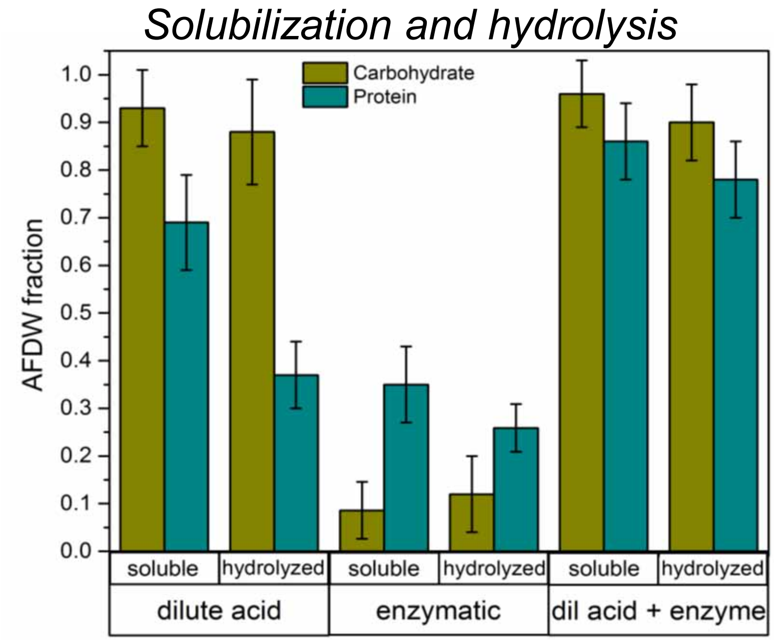
3 – Technical Accomplishments/Progress/Results (cont'd)

Biochemical Pretreatment - Solubilization, hydrolysis, & ash separation

- Dilute acid effective for solubilizing the protein & carb fractions + carb hydrolysis
- Relatively low-cost enzymatic treatment necessary for protein hydrolysis
- Dilute acid and enzymatic treatments are each effective for separating ash
- Simple rinsing reduces exogenous ash



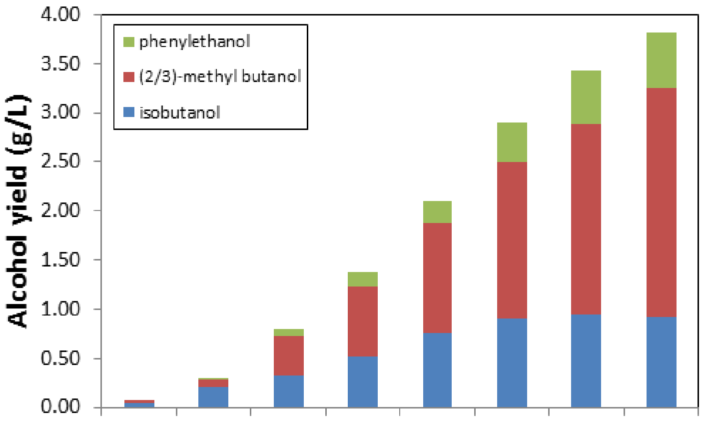


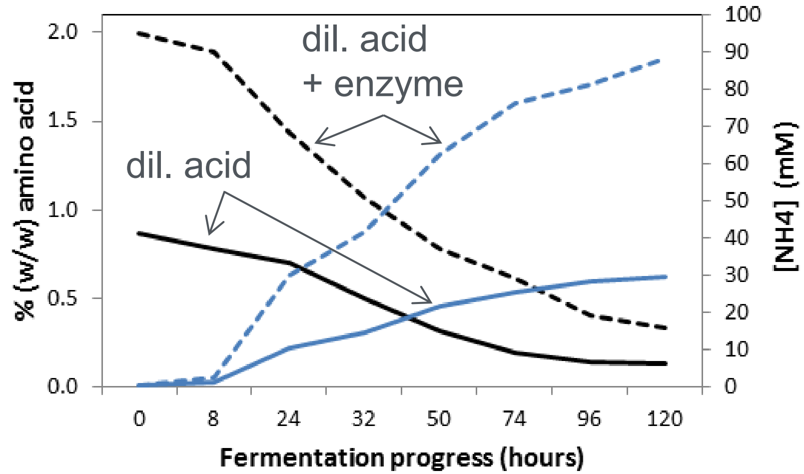


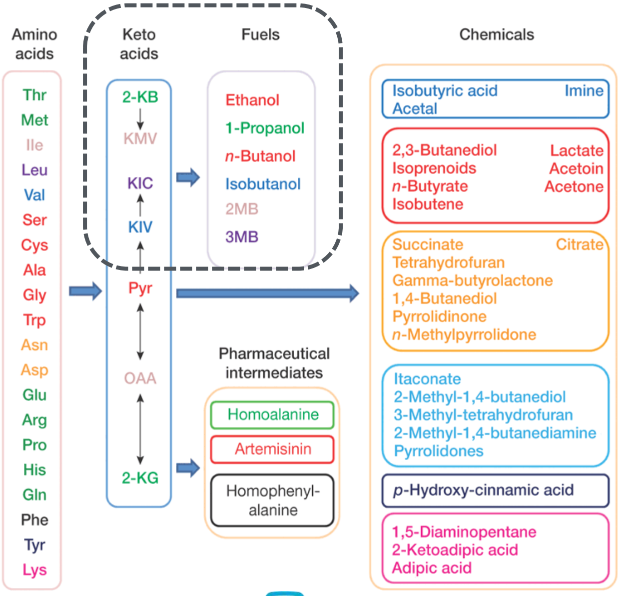
3 – Technical Accomplishments/Progress/Results (cont'd)

Biochemical conversion: Sugar & Protein Fermentation

- 70% of theoretical protein conversion achieved at bench scale
- 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)







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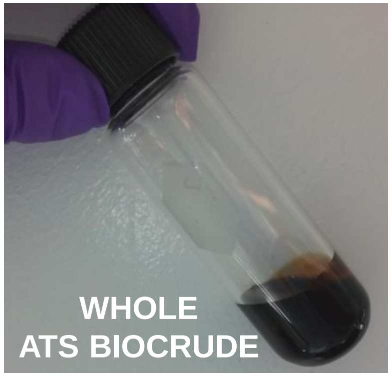
3 – Technical Accomplishments/Progress/Results (cont'd)

Thermochemical conversion – results of non-optimized bench tests

Improved biocrude yields obtained for polyculture algal turf vs. monoculture

- HTL oil yield of whole polyculture algal turf is **44% , with N content of 4.5%**
- HTL oil yield of monoculture (*nannochloropsis*) for same process conditions yields 35%, despite less ash - other monocultures are to be investigated
- Literature values of monocultures with continuous HTL systems obtain >50% yields implying the likelihood of much improved performance for polyculture algae
- Whole algal turf polyculture produced the least char
- HHV of 38.7 MJ/kg and 39.4 MJ/Kg for HTL oil from whole algae & residue, respectively
- HTL of biochemically preprocessed residue yields 22% biocrude, ***N content of 0.89 %***

	Whole Algal Turf	Algal Turf Residue*	Whole *Nannoch.*
GAS	14%	18%	13%
BIOCRUDE	44%	22%	35%
AQUEOUS	25%	32%	30%
SOLIDS	17%	28%	22%



	Nitrogen partitioning in HTL Fractions from Algal Turf Residue	Nitrogen partitioning in HTL Fractions from Whole Alga Turf
GAS	40%	42%
BIOCRUDE	13%	17%
AQUEOUS	19%	26%
SOLIDS	28%	15%

** Algal Turf Residue refers to the material remaining after fermentation of carbs and proteins*

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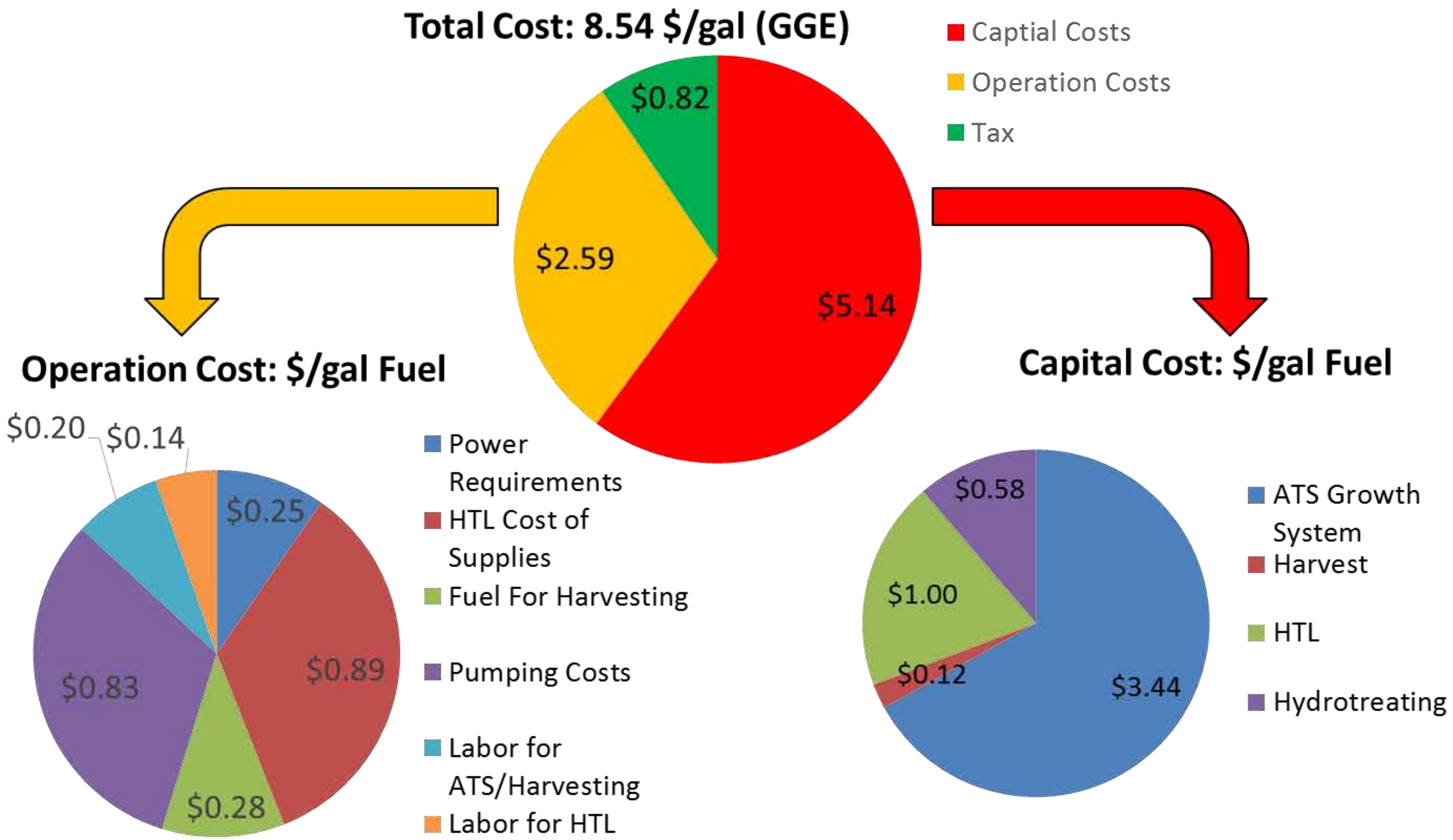
3 – Technical Accomplishments/Progress/Results (cont'd)

Preliminary TEA Results for Algal Turf + Whole Biomass HTL*

Assuming high (unimproved) ash content (50%) harvested biomass @20% solids to HTL

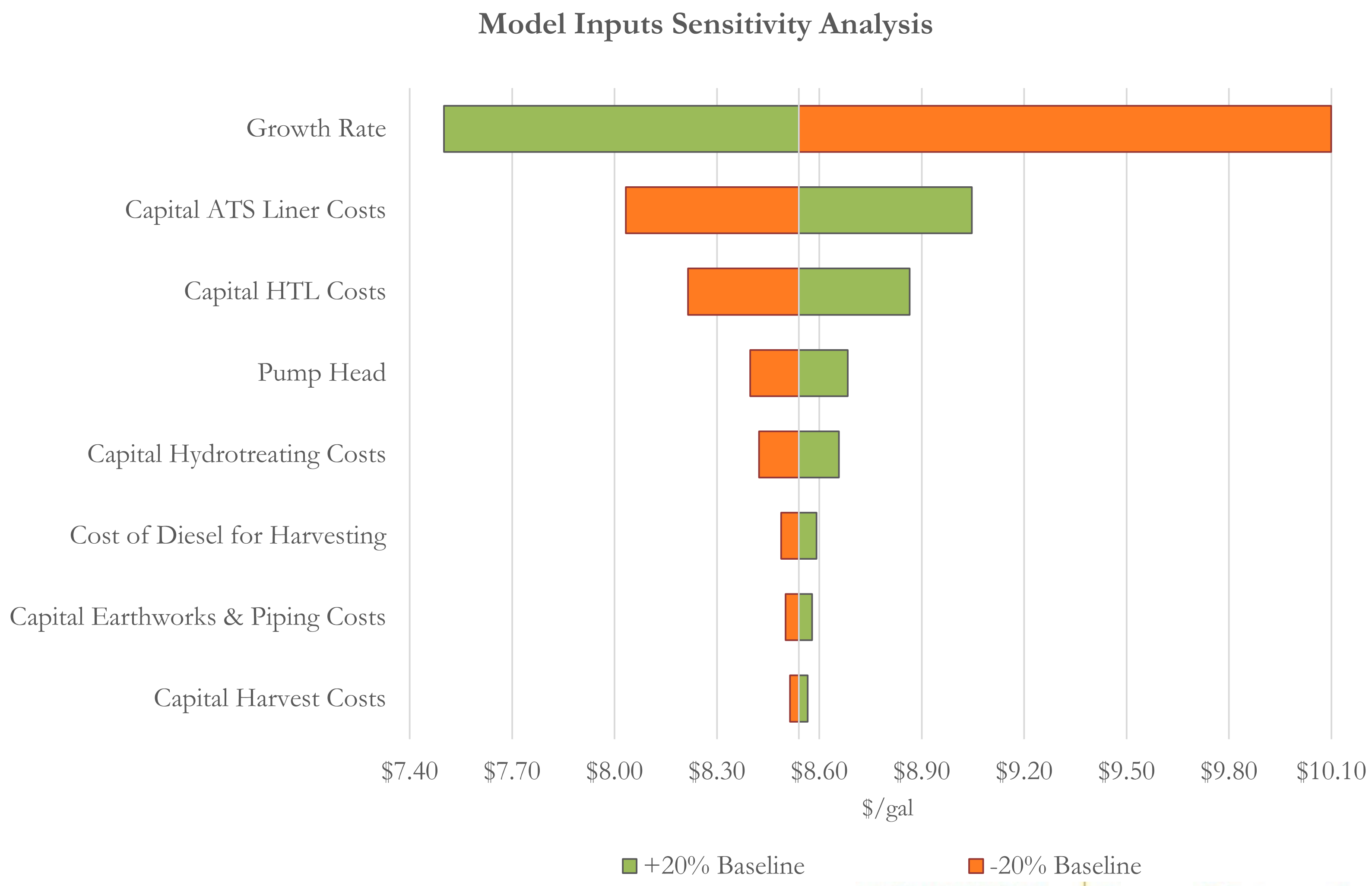


- *HTL Processing & Upgrading To Renewable Diesel Using 2014 PNNL AHTL Report Results … Revised TEA Underway for Tandem Biochem + HTL & Whole Algal HTL w/ SNL Data*

3 – Technical Accomplishments/Progress/Results (cont'd)

Preliminary TEA Sensitivity Results for Algal Turf + HTL Processing

Assuming high (unimproved) ash content (50%) harvested biomass (20% solids) to HTL



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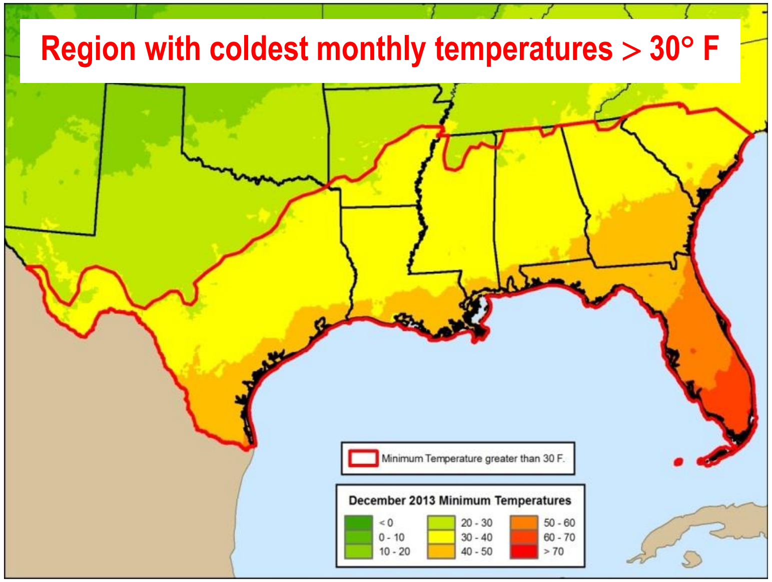
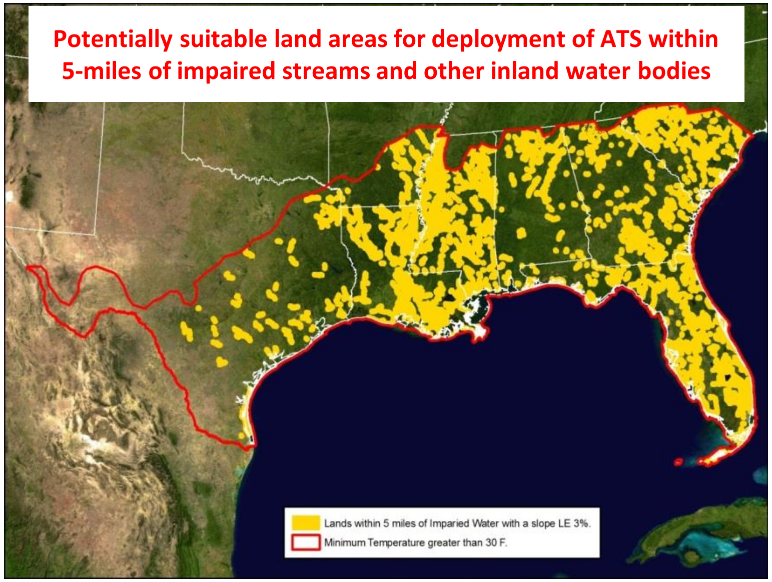
3 – Technical Accomplishments/ Progress/Results (cont'd)





Assessment of Scale-Up Potential

Based on initial screening of potentially suitable land area for siting Algal Turf cultivation closely adjacent to impaired surface waters in the eight state Southeastern region, with dual-use role of biomass feedstock production and water quality improvement.

Screening suggests >1 billion GGE/yr potential

Refined assessment in progress

State	Ag Acres within 5 miles of Impaired Waters	Shrubland Acres within 5 miles of Impaired Waters	Total Ag & Shrubland Acres within 5 miles of Impared Waters
Alabama	2,312,215	388,264	2,700,479
Arkansas	1,705,378	78,175	1,783,553
Florida	6,621,383	876,168	7,497,551
Georgia	3,004,481	445,032	3,449,513
Louisiana	9,865,027	639,112	10,504,139
Mississippi	9,702,977	1,609,786	11,312,763
South Carolina	3,041,534	481,329	3,522,863
Texas	3,797,384	1,078,400	4,875,784
Total Acres	**40,050,379**	**5,596,266**	**45,646,645**

Data sources used:

Temperature Data from PRISM Climate Group, Oregon State Univ.
http://www.prism.oregonstate.edu/

Impaired Streams and Water bodies from the EPA ATTAINS Program
http://water.epa.gov/scitech/datait/tools/waters/data/downloads.cfm

Digital Elevation Model (GTOPO30) from the USGS
https://lta.cr.usgs.gov/GTOPO30

4 – Relevance

- Polyculture algal turf for biofuels is promising alternative for meeting BETO MYPP Algal Program Goals:
  - Practical and scalable cultivation & harvesting systems and operations;
  - Leverages industry commercialization of algal turf for water treatment;
  - Potentially capable of high, stable, and resilient biomass productivity;
  - Potentially avoids cost & logistics of providing supplemental CO_2 & nutrients;
  - Dual-use opportunity for water cleaning (N & P removal) credits;
  - Largely unexplored opportunities to improve ATS productivity & quality.
- Biochemical and/or HTL processing promising for converting low lipid content biomass to fuels and coproducts, including nutrient recycling;
- Initial TEA feasibility w/ whole algal biomass HTL processing looks promising, with TEA in progress for tandem biochemical + HTL processing;
- Preliminary GIS land and impaired water source screening assessment suggests promise for single-pass ATS operations capable of >1B GGE … refined resource assessment in progress.

4 – Relevance - Hub

- Integrated polyculture R&D efforts and the BETO AOP process allows flexibility to adapt and adjust focus based on findings;
- Polyculture Hub activities have been designed to address a subset of these key challenges through **collaboration and integration** of expertise and capabilities towards established goals;
- Interface with industry on needs and system and process improvements (HydroMentia, others) + close communication and collaboration with BETO ATP^3 testbed for monoculture comparison;
- **Expected Outcomes:**
  - Polyculture options for achieving relatively high biomass productivity, stability, and resilience relative to monoculture;
  - Polyculture biomass production target: $\geq$**20 g/m²/day (AFDW)** annualized daily productivity.

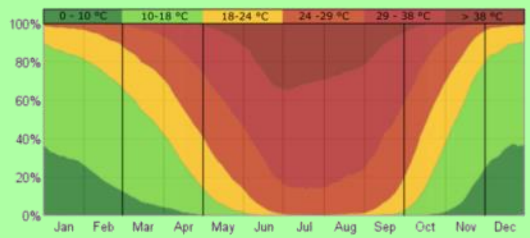
5 – Future Work - SNL

- Polyculture algal turf productivity & quality improvement – dynamic interdependencies: engineered system & biology;
- Probiotic polyculture performance enhancement and possible seeding of ATS with selected consortia;
- Meso-scale polyculture cultivation testing/monitoring;
- Refinement and optimization of biochemical & HTL processing and conversion of polyculture biomass;
- Testing and evaluation of larger-scale biochem-HTL polyculture processing (with LBNL-ABPDU and PNNL);
- Comparative performance testing of polyculture vs. monoculture (with ATP^3);
- Initiation of LCA and refinement of TEA and GIS feasibility.

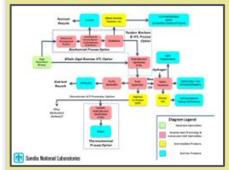
5 – Future Work - Hub

INL

- Productive polycultures at cool temperatures
- High-throughput to field validation



SNL

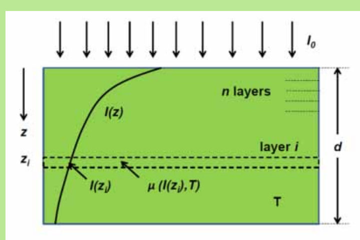


- Polyculture algal turf biomass productivity & quality improvement
- Biochemical & HTL processing and conversion of polyculture biomass
- Probiotic performance enhancement of polyculture
- Comparative performance testing of polyculture vs. monoculture
- Meso-scale pond testing/monitoring

HUB

PNNL

- Evaluate polycultures in climate-simulation ponds
- Predictive modeling of polycultures



ORNL

- Stable polycultures resistant to pond crashes
- Meso-scale pond testing
- Predictive modelling of long term grazer:algae population dynamics

Summary

Overview: *Benthic polyculture algal turf biomass production, with biochemical and/or thermochemcial (HTL) processing to fuel intermediates, offers an alternative path to meet BETO's Algal Program MYPP goals and milestones.*

Approach: *Maximize yields, minimize costs, and identify viable path for integrated scale-up of polyculture algal biomass production and conversion using high-efficiency biochemical and/or HTL utilization of all biomass components to optimize production of liquid fuels.*

Technical Accomplishments/Progress/Results: Characterized algal turf biomass from several sources; Achieved *promising bioconversion yield of algal turf proteins and carbohydrates to mixed alcohols & HTL conversion of residue yielding reduced N-content biocrude at bench scale; Achieved >40% bench scale HTL conversion of whole algal turf biomass; Initial TEA and scale-up feasibility promising.*

Relevance: *Biochemical and/or HTL conversion of low-lipid, higher ash polyculture algal turf biomass produced without need for supplemental CO_2 and nutrients, and/or with nutrient recycling, has promise as an alternative path to affordable, scalable, and sustainable biofuels.*

Future work: *Increased polyculture algal biomass productivity and quality (reduced ash), larger scale demonstration of linked biochemical / HTL conversion operations, pro-biotic enhancement, dynamic system modeling, LCA, TEA, and GIS feasibility assessment.*

Thank you! - Questions?

Ron Pate - SNL/NM

505-844-3043 **rcpate@sandia.gov**

Contributors:

Ryan Davis - SNL/CA

Anthe George - SNL/CA

Stephen Horvath - SNL/NM

Todd Lane - SNL/CA

Len Malczynski - SNL/NM

Ben Wu - SNL/CA

Deborah Newby - INL

Walter Adey - Smithsonian Institution

Dean Calahan - Smithsonian Institution

Mark Zivojnovich - HydroMentia, Inc.

Justin Hoffman - Utah State University

Jason Quinn - Utah State University

Sandia National Laboratories

Smithsonian National Museum of Natural History

HydroMentia WATER TREATMENT TECHNOLOGIES

UtahStateUniversity

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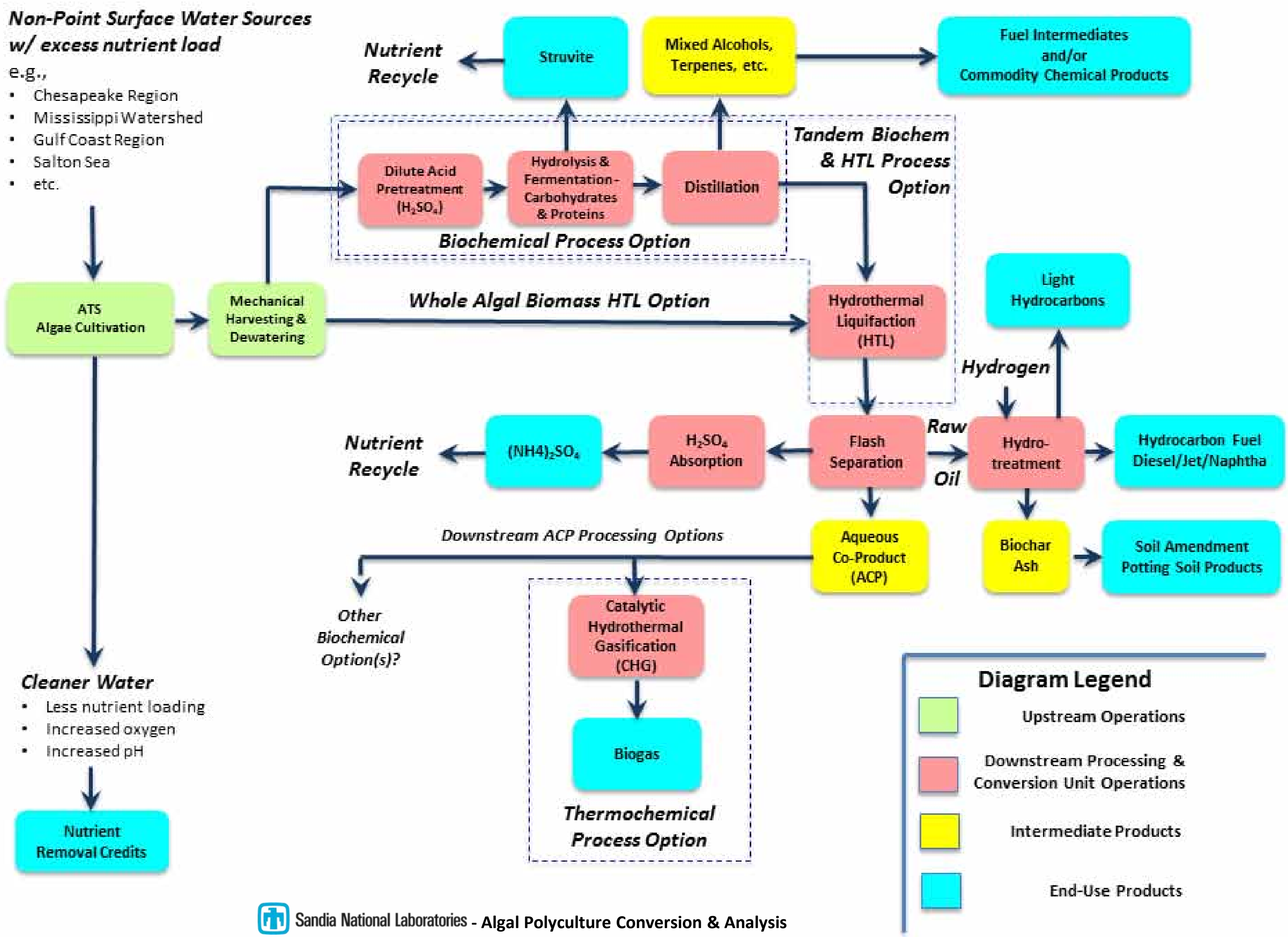
Responses to Previous Reviewers' Comments

- Project started after last BETO Peer Review

Additional Slides

High-Level Concept for Polyculture "Algal Turf to Fuels"



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Projected fuel yields (GGE) as function of biomass productivity*

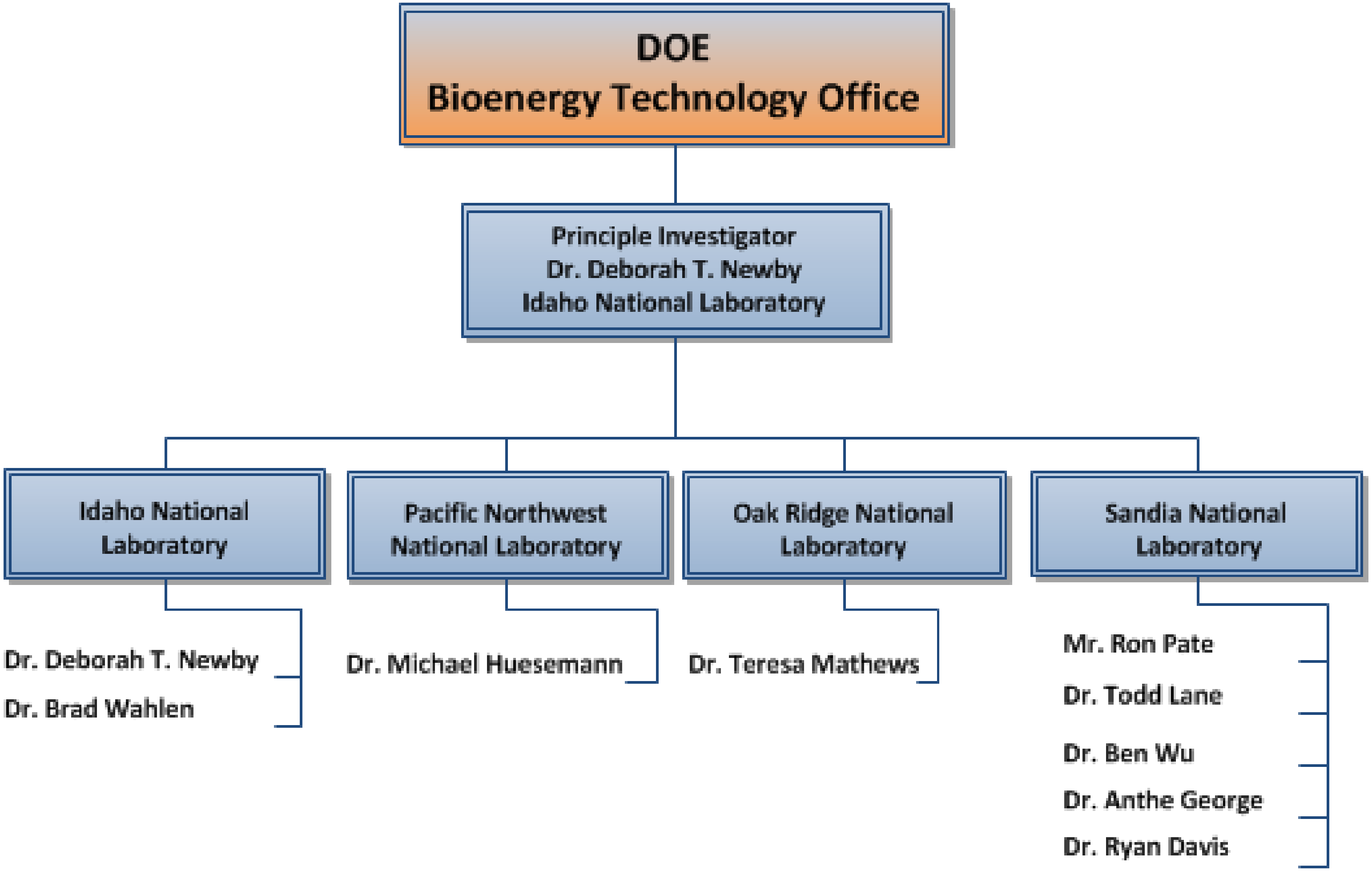
Still to be Included is Value of Product vs. Cost of Production Tradeoff

* Based on process yield results from non-optimized and non-integrated bench scale testing using wet harvested algal turf biomass supplied by HydroMentia and using assumed HTL biocrude upgrading conversion yield factors from 2014 PNNL AHTL Report

Fuel Production per Processing Pathway		Polyculture Algal Biomass Annual Average Daily Productivity [g m^{-2} d^{-1}] (AFDW)			
		15	**20**	**25**	**30**
Annual Biomass Production [kg/acre] (AFDW)		**22166**	**29555**	**36943**	**44332**
Tandem Biochemical & HTL Processing & Conversion					
Annual Fuel Production by Type [GGE/acre]	**Ethanol:**	702	937	1171	1405
	Isobutanol:	709	945	1182	1418
	Naphtha:	135	180	225	270
	Diesel:	701	935	1169	1403
Total Annual Fuel [GGE/acre]		**2248**	**2997**	**3746**	**4495**
Whole Algal Biomass HTL Processing & Conversion					
Annual Fuel Production by Type [GGE/acre]	**Naphtha:**	487	649	811	973
	Diesel:	2529	3373	4216	5059
Total Annual Fuel [GGE/acre]		**3016**	**4022**	**5027**	**6032**

Collaboration in Algal Polyculture Hub Starting FY15

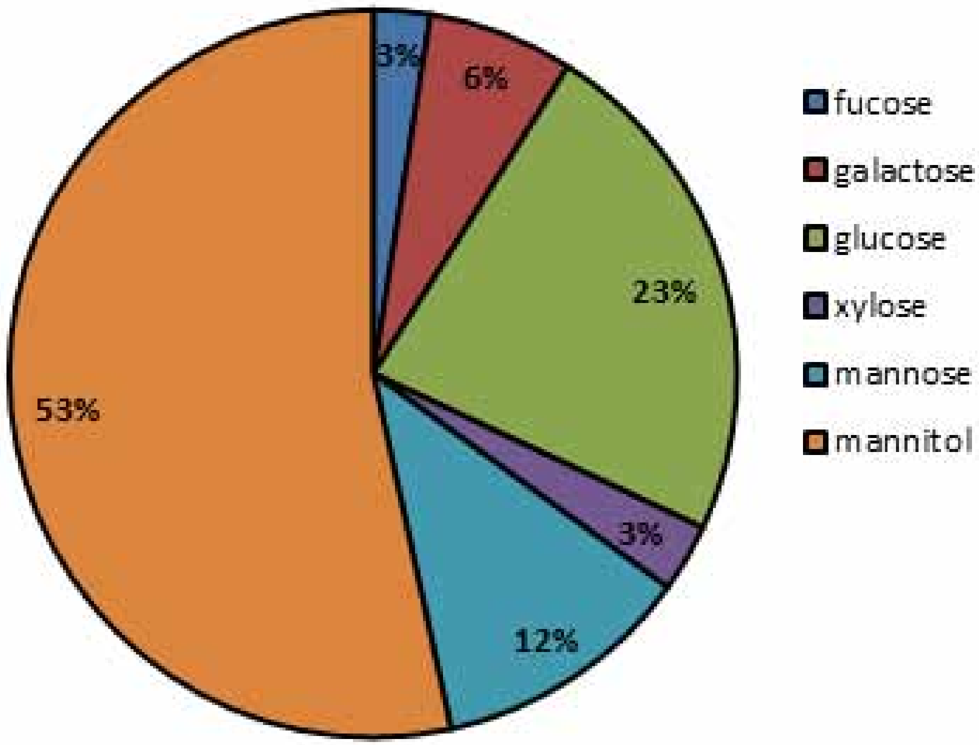
Initiated in FY14 as stand-alone SNL AOP polyculture project



Publications, Patents, Presentations, Awards, and Commercialization

- SNL Patent Application (SD#131107) – "Tandem Bio- and Thermo-chemical Conversion of Mixed Algal Biomass"
  Ryan W Davis, Anthe George, Todd W Lane, Ronald C Pate, Ben C Wu.
- Presentations at 2014 ABBB Symposium and 2014 ABO Summit.
- Joint Hub publication in preparation: Review manuscript to be submitted to BETO that establishes a baseline for the state of the art for algal polyculture overyielding and resilience (FY15 Q2).
- Publications and presentations in preparation for reporting on updated project results achieved in FY15.
- Collaboration on Algal Turf Scrubber® cultivation & harvesting with Walter Adey (Smithsonian Institution) and HydroMentia
- Collaboration discussions with ATP^3 re/ testing of polyculture vs. monoculture , LBNL-ABPDU and PNNL re/ larger scale polyculture biomass biochemical and HTL processing, and others in industry re/ commercialization.

Hydrolyzed Carbohydrate Profile*



**** Based on algal turf samples from HydroMentia***

Note: The carbohydrate fraction was ~34.5% of the non-ash biomass in the samples analyzed

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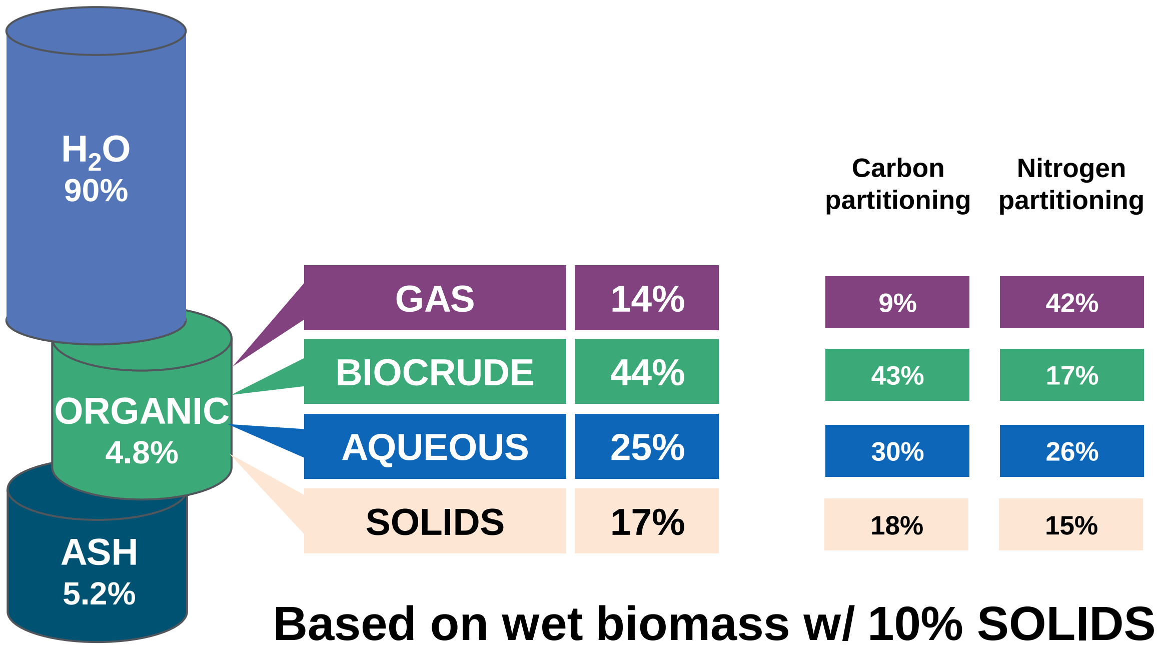
Thermochemical conversion of raw harvested algal turf:

Bench scale HTL giving > 40% biocrude yields with N content ~ 5%

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



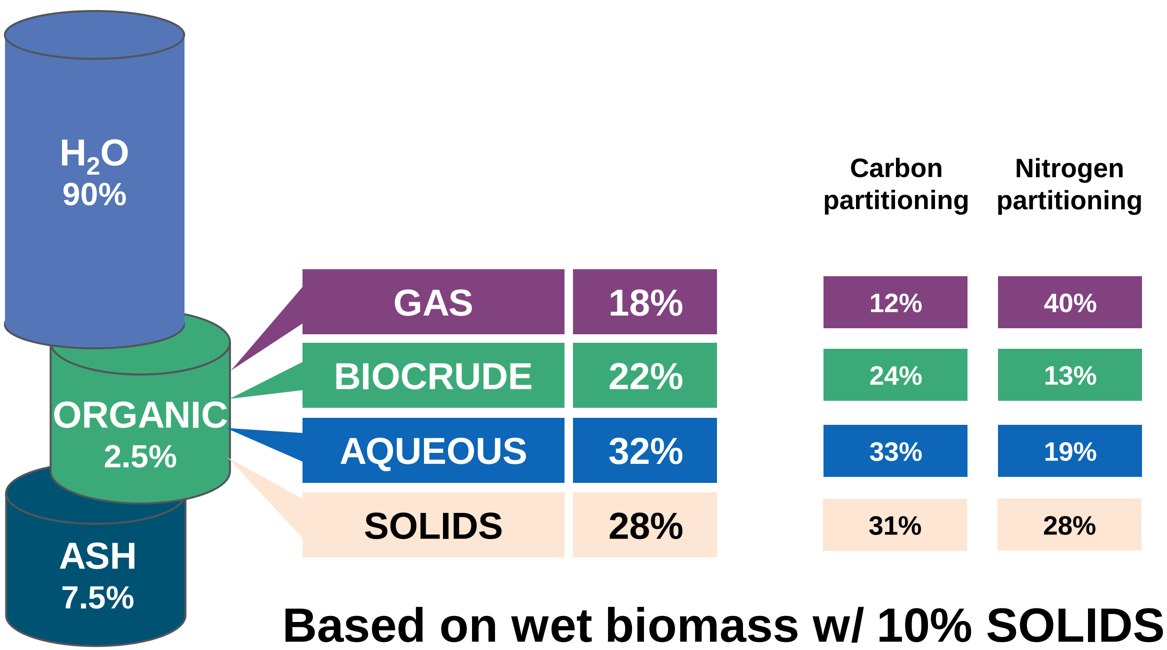
Biocrude N content: 4.5%

Based on wet biomass w/ 10% SOLIDS

Thermochemical conversion of biochemically processed algal turf:

Bench scale HTL processing of pre-processed residue … Reduces N by > 80%

- 24% biocrude from residue w/ reduced N content <1% - process unoptimized
- C in aqueous co-product and solids can potentially be recovered to increase yield
- Higher content ash likely changing heat/mass transfer profiles and affecting yield
- High heating value of 38.7 MJ/kg (versus 46 MJ/kg for typical upgraded HTL oil and 45 MJ/kg for gasoline)



Biocrude N content: 0.89%

Based on wet biomass w/ 10% SOLIDS

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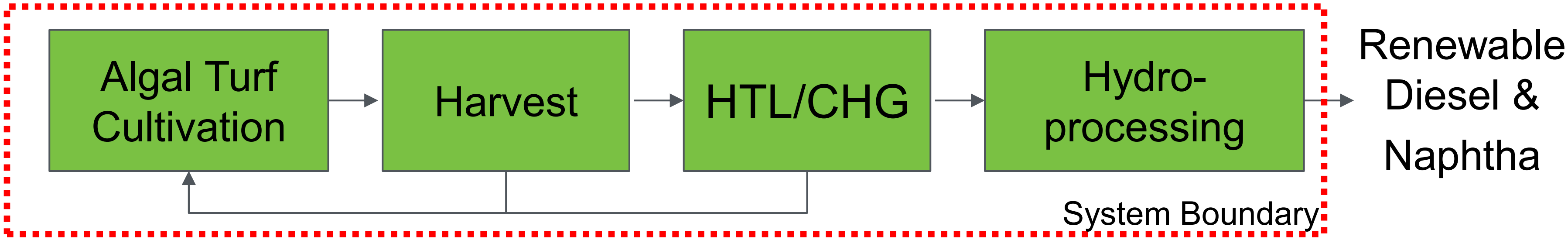
Preliminary TEA Assumptions - Non-optimized ash content



- **Economic Assumptions[1]**

Preliminary TEA Feasibility Assessment Unit Ops and Assumptions

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

[1] Consistent with the ANL-NREL-PNNL Algal Biofuels Harmonized Baseline Study: Technical Report ANL/ESD/12-4, NREL/TP-5100-55431, PNNL-21437, June 2012 and Process Design Case Studies: a) Jones, et al., "Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading", PNNL-23227, March 2014; b) Davis, et al. "Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products", NREL/TP-5100-62368, September 2014.

Preliminary TEA Assumptions - Non-optimized ash content

ATS Growth[1]	
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[1]	
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}

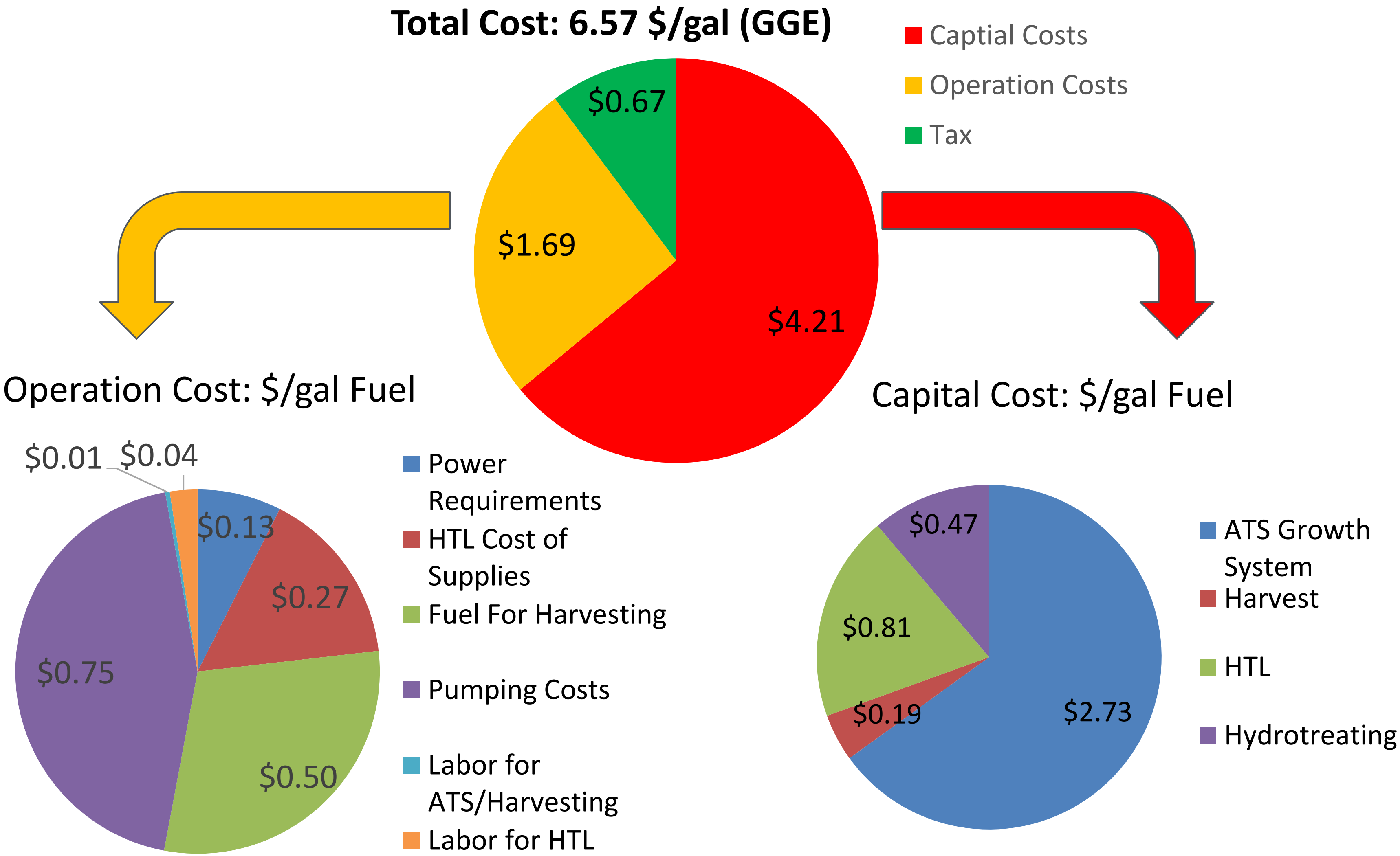
HTL/CHG Processing[2]	
NG Energy	3.7 M-MJ d^{-1}
Electrical Energy	120 MWh d^{-1}
Capital Cost	$183 M
Oil Yield	47%
Aqueous Yield	40%
Ash Content	50%
Gas	3%
Hydrotreating[2]	
Fuel Yield	78%
Capital Costs	$69 M
Processing Capacity	153 kgal d^{-1}
Diesel Yield	83%
Naphtha Yield	16%

[1] Cultivation and harvesting assessment customized to ATS, but using scale-up assumptions consistent with the ANL-NREL-PNNL Algal Biofuels Harmonized Baseline Study: Technical Report ANL/ESD/12-4, NREL/TP-5100-55431, PNNL-21437, June 2012.

[2] Performance based on projections presented in: Jones, et al., "Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading", PNNL-23227, March 2014.

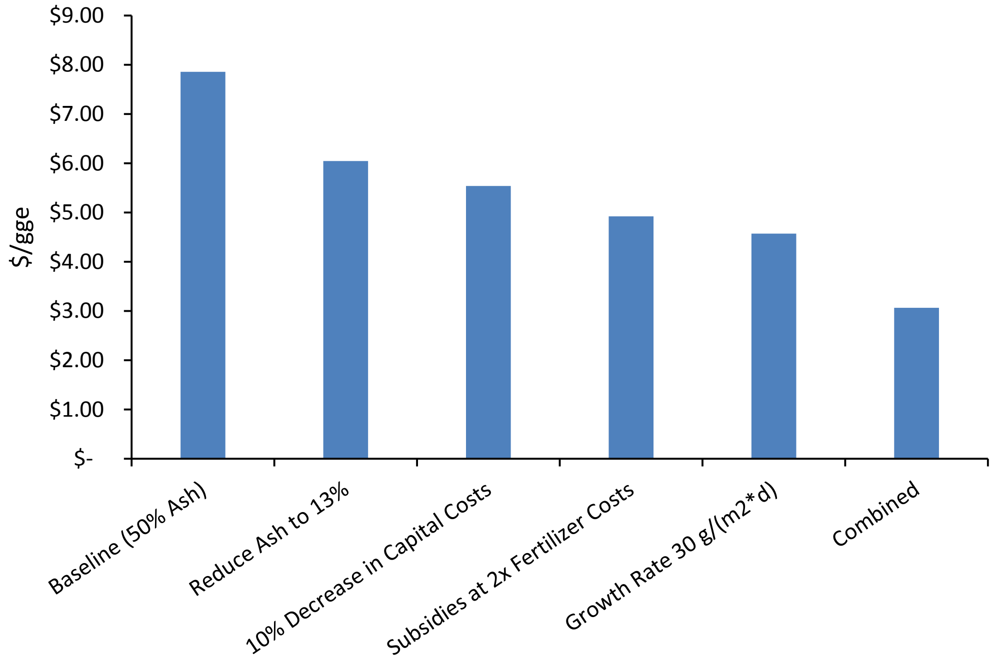
Preliminary TEA Results for HTL Processing

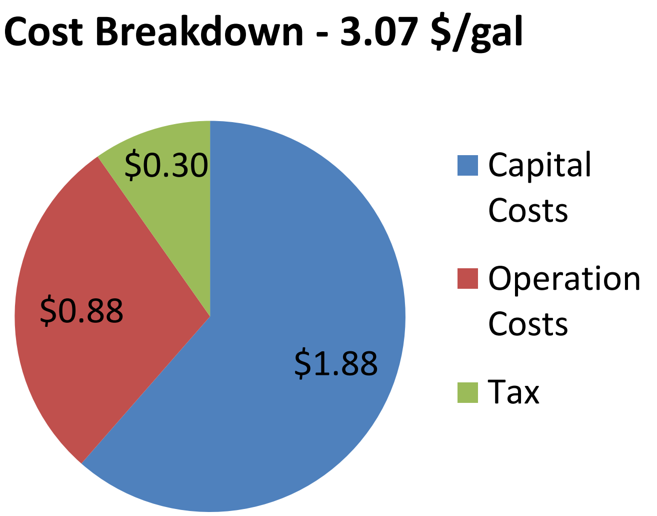
Assuming lower ash content (13%) harvested biomass (20% solids) to HTL



Example Scenario for Reducing Fuel Cost to ~ $3/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 annual growth rate** to 30 g/m^2/day (AFDW)
- **Decrease Capital Costs** by 10%
- Subsidies at 2x Fertilizer Costs (**Leverage water clean-up credits**)
- Results in estimated cost of $3.07/gal





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: 10-20+ g/m^2/day (AFDW) annual av. with non-optimized systems & operations
- No added nutrients or external CO_2
  - Using single-pass mode using water with excess N,P,CO2
- Harvest/dewatering – simple, low-energy
- Biomass focus - low neutral lipids
- Similarities with open field agriculture

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

Key Points

Algal Turf to Fuels – Promising polyculture algae solution to key challenges:

- Can avoid crashes … Cultivation resiliency with polyculture
- Can avoid expensive, energy-intense harvesting & dewatering
- Can avoid costly CO_2 supply &/or co-location w/ industrial sources
- Can avoid commercial fertilizer costs

- Turf algae pioneered in 1980s (Walter Adey) and commercialized at multi-acre scales for water treatment (HydroMentia)
- Robust algae production of 20-30 tons ac^{-1} yr^{-1} AFDW annual average demonstrated over years of pilot and commercial scale systems operations for water treatment; Non-optimized for biomass production

SNL project emphasis:

- Characterization of algal turf biomass quality – feedback for improvement
- Biochem &/or HTL processing and conversion of total (wet) biomass
  - Optimize product yields vs. costs
  - Recycle major nutrients (N & P)
  - Reduce nitrogen content in biomass residue & subsequent HTL biocrude product
- Feasibility assessment for affordable scale-up

Advantages of algal polyculture turf for biofuels

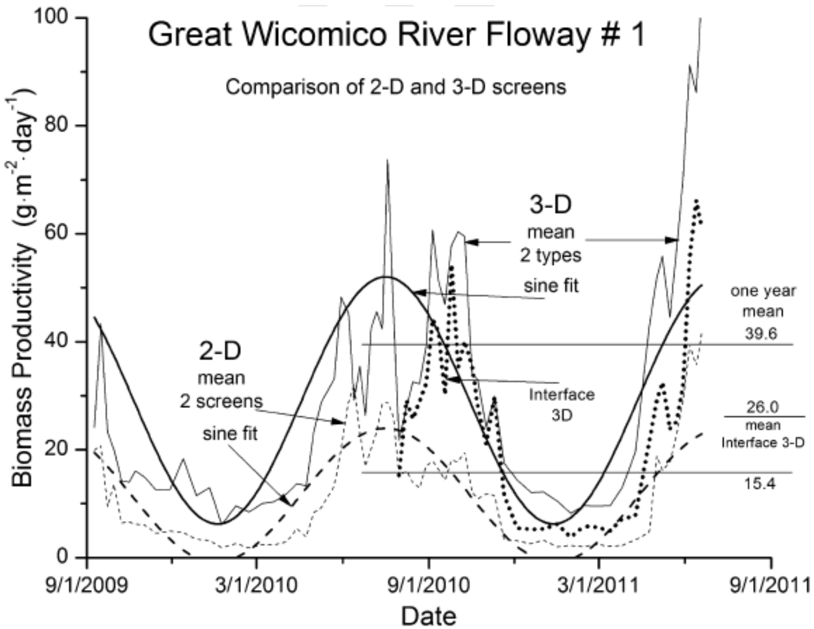
- Relatively simple cultivation system configuration - more like open field ag
  - Utilizes pulsed, shallow, turbulent flow with excellent solar insolation exposure and gaseous exchange with atmosphere
  - Stable, diversified cultivation … resilient and resistant to crashes
  - Years of commercial experience w/ multi-acre systems for water cleaning
- One-pass operation (typically used for water cleaning)
  - Annual average daily AFDW biomass production of 10 -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 annual average productivity
  - Multi-pass recycle system operation can expand deployment opportunities, but …
    - Requires supply of supplemental nutrients and CO_2
    - Imposes added CAPEX and OPEX
- 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/ agricultural operations
  - Immediately provides 6% to >15% solids content wet biomass

Challenges of algal polyculture turf for biofuels

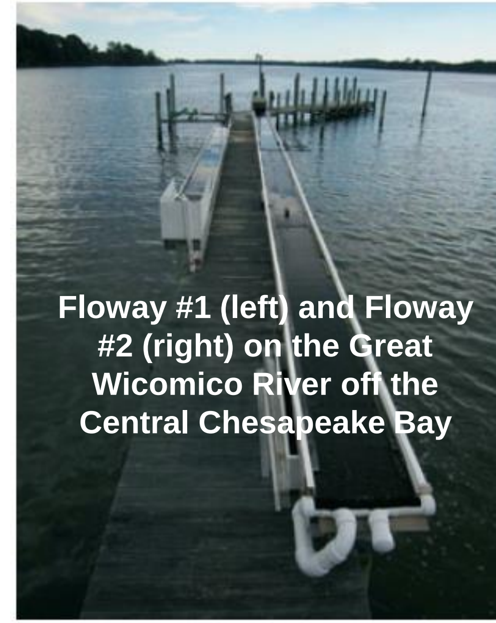
- Low neutral lipid content (< 10%)
  - Relatively high in protein and carbohydrates
- High ash content (~ 50+%) in raw harvested material

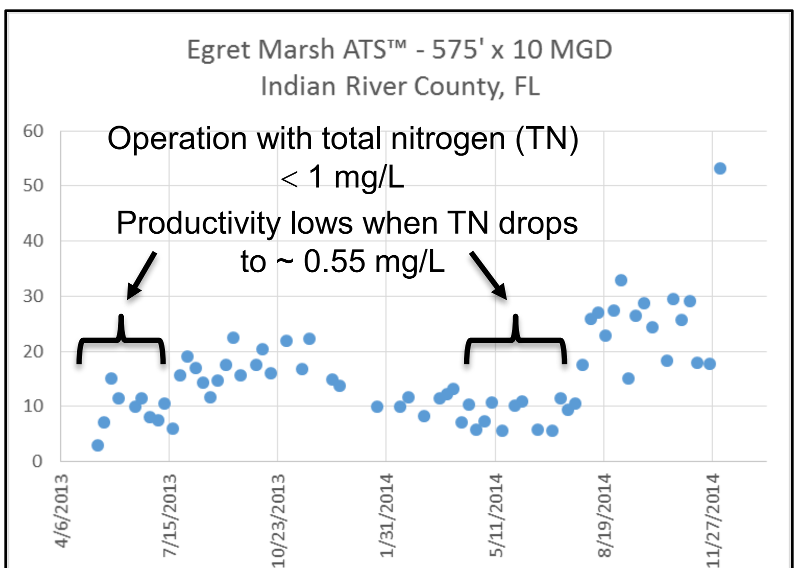
  ... ***with current systems not optimized for reduced ash***
  - Ash is combination of biogenic and exogenous environmental material
  - Improvement possible with cultivation and harvesting systems & ops
  - Simple rinsing has reduced harvested material ash content from 50+% to < 25%
  - Dilute acid pre-treatment & separation provides ash reduction for biochem processing
- Heterogeneous polyculture biomass characteristics
  - Dynamically change with season and water source chemistry
  - Provides robust and resilient culture relatively 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%, but yields are lower
- Preliminary TEA feasibility assessment looks promising.

Algal Turf Productivity in Water Treatment Systems



Biomass productivity on Floway #1, comparing 2-D (dashed lines), 3-D (solid lines) and Interface (bold dotted line) growth substrate (screens). The smooth curves are sine functions fit to the two data sets. Note the one-year mean production marked for different screen types (Adey, et al. J. Phycol. 49, 489–501, 2013).



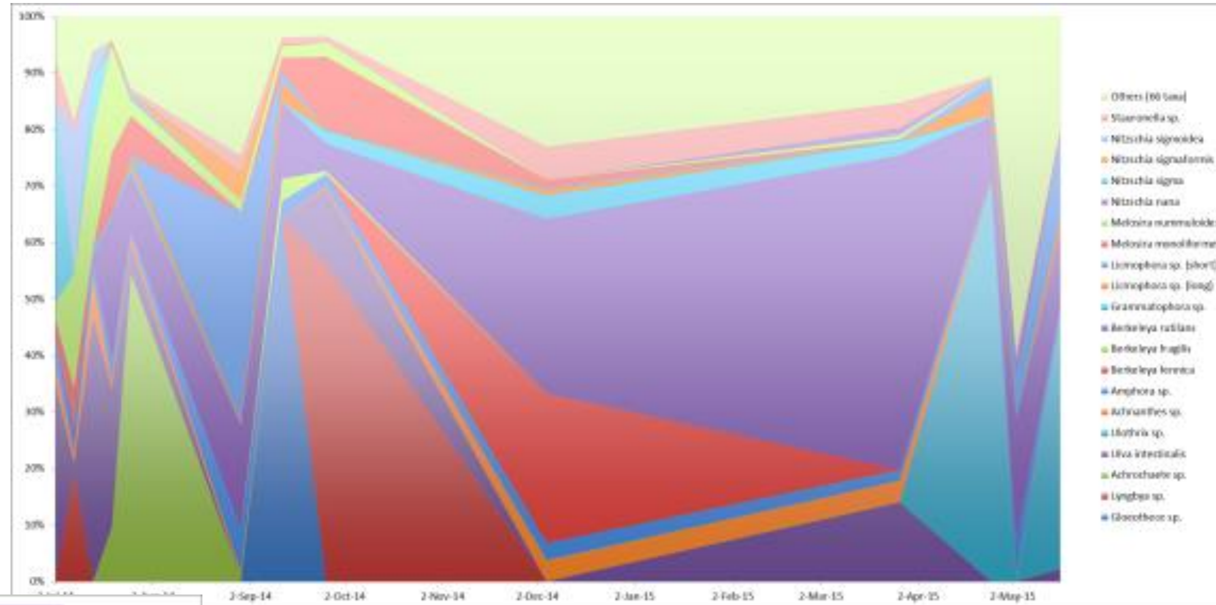


Productivity of Egret Marsh Commercial Scale ATS

Representative data from HydroMentia.

Sample of Benthic Algal Polyculture Turf

Dynamic System Diversity over Multi-Year Period



Normalized plots of dominant 15-20 species found in algal turf biomass 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.

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Examples of Algal Turf Polyculture Cultivation & Harvesting

Photos courtesy of Mark Zivojnovich, HydroMentia and Walter Adey, Smithsonian Institution