Nutrient Bioextraction and Bioenergy Recovery from Ocean Outfalls of Treatment Works

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MOCA Partnership Mini-Symposium on Ocean Acidification Remediation Projects and Policy Directions
Legislative Council Room, Augusta, Maine: 10am - 3:15pm.

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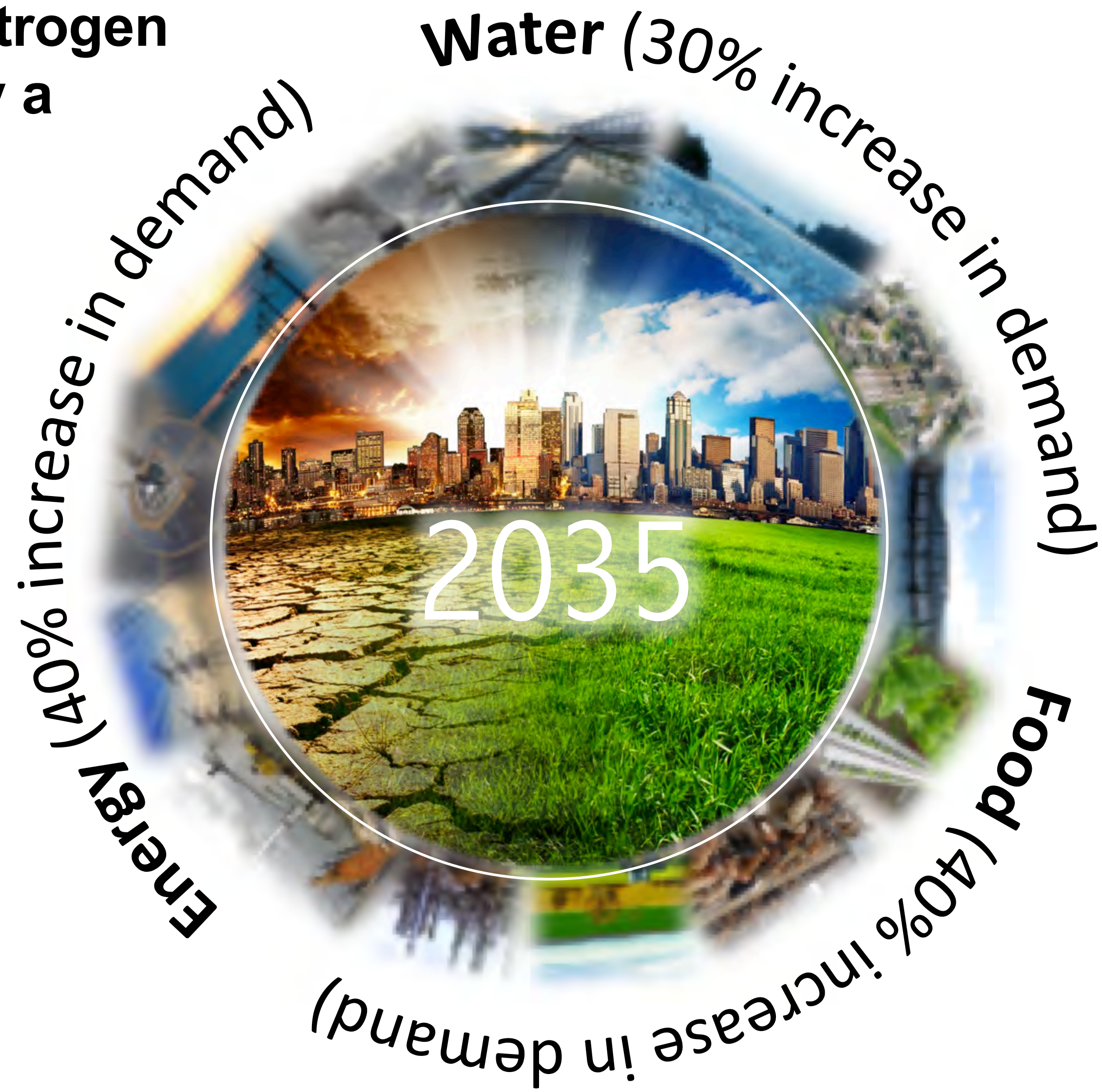
Shane W Rogers

Abstract Number: OR-19-04
Session title: OR-19-IMTA and Biomitigation (minisymp)

As global populations soar, we face unparalleled challenges of food, water, and energy security and sustainability.

Improved management of the nitrogen and phosphorus cycles will play a central role in this challenge.

Increasing population
Urbanization & Modernization
Rightful Goal of Poverty Alleviation
Changing global climate
Eutrophication



Consider:

- 15M tons NH_3 produced in the US in 1999 using Haber process (from atmospheric N)
  - Consumed 3% of the total US natural gas production in 1999
  - >90% of the NH_3 produced was for the fertilizer industry
- ~140M tons NH_3 fertilizer are produced globally, >99% by the Haber process

NH_3 produced has had profound impact on our global societies:

- Supports bioenergy feedstock, feed, and food that sustains 60% of global populace
- Population explosion of the last 150 years would not otherwise have been possible
- ~ 80% of N in modern human tissues is likely to have originated from Haber process

…and sustainability of our global environment:

- Nutrient runoff from terrestrial production of food, feed, and bioenergy feedstock degrades water quality and damages freshwater and coastal water ecosystems
- These ecosystems are further stressed by increased temperature and acidification caused by greenhouse gases released by agriculture and combustion of fossil fuels for energy and fertilizer N production.

Global use of nitrogen fertilizers produced by the Haber process is increasing at a rate of approximately 15M metric tonnes per year in response to the need to improve food security in developing regions of the world and support growing global populations.

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Wastewater effluents:

- Major source of nutrient inputs to coastal environments
- Most biotechnologies focus on $NH_4^+ \rightarrow N_2$ *(energy intense)*
- Sustainable / energy efficient nutrient recovery strategies are needed

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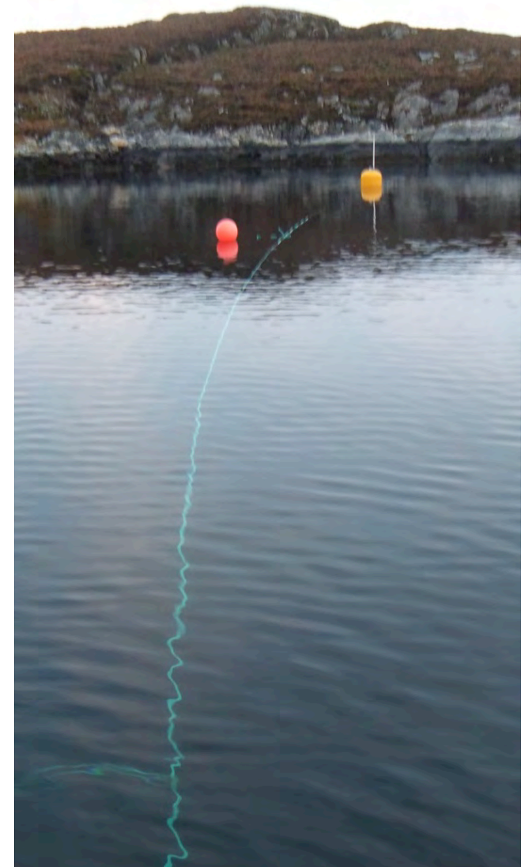
Research Goals

- Development of nutrient trading with productive aquaculture as a viable approach to management of the nitrogen cycle in respect to anthropogenic sources of coastal pollution
- Development of biomass feedstock that does not compete for land for food production and that can be supplemented with otherwise wasted nutrients
- Acceleration of the establishment of viable macroalgae aquaculture industry in the US through technology development and greater integration across sectors



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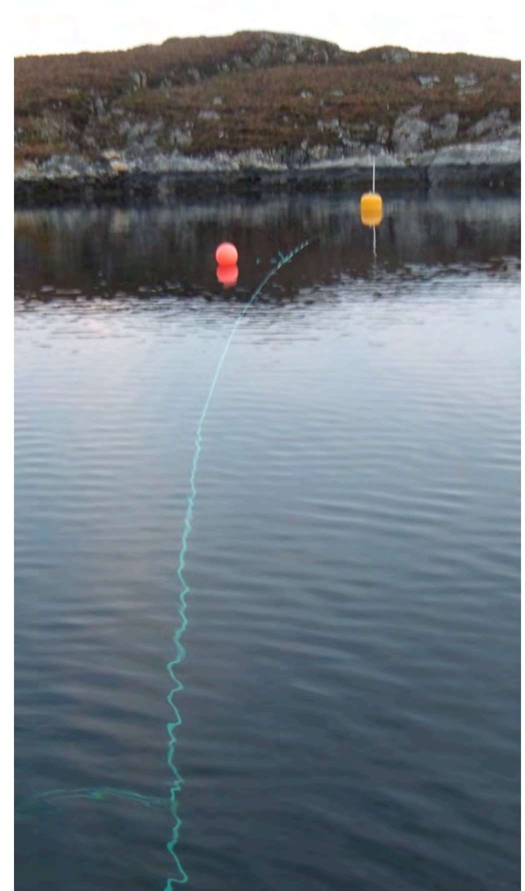
Research Objectives

- Determine the nutrient bioextractive potential of *Saccharina latissima* towards application in wastewater treatment plant ocean outfalls
- Determine production area requirements to meet nutrient bioextraction goals for wastewater treatment plants of varying scale and bioprocesses technologies
- Characterize anaerobic digestion potential of the produced kelp and energy recovery as affected by particle size and salinity



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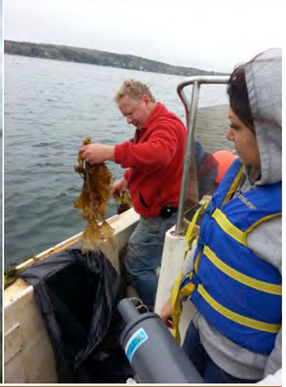
Kelp cultivation trials

- *S. latissima* farmed in Boothbay Harbor by Ocean Approved, LLC and the Boothbay Harbor Sanitary District (BHSD) to determine growth rates
- Kelp harvested from Boothbay Harbor in May, 2014.
- Kelp shipped to Clarkson overnight, rinsed with distilled water, and stored frozen until use

Location	Fresh Biomass (ton FW/ha·year)	Dry Biomass (ton DW/ha·year)	Reference
Boothbay Harbor, Atlantic Coast, Maine	45	4.6	This study
Exposed site, Atlantic Coast, Spain	40 ± 3.2	4.7±0.4	Peteiro & Freire, 2013
Sheltered site, Atlantic Coast, Spain	30 ± 2.8	3.5±0.3	Peteiro & Freire, 2013
Sheltered site, West Coast of Sweden	25 (23,28)	5.5 (5.1, 6.2)	Pechsiri et al., 2016
Salmon farm, North Atlantic, Norway	75 (53,88)	11.2 (8.0, 12.9)	Broch et al., 2013







Kelp cultivation trials

Biomass characteristics of *S. latissima* cultivated in Boothbay Harbor, Maine, Spring, 2014

Biomass Characteristics*		Tissue Element Contents, mg / g DW					
TS	0.102 g-DW / g-FW	Carbon	305	Aluminum	2.56	Nickel	0.0061
VS	0.742 g-VS / g-DW	Nitrogen	19.0	Arsenic	0.023	Lead	0.0227
COD	116 mg / kg DW	Phosphorus	1.84	Barium	0.031	Selenium	0.0012
GHC	9.8 MJ / kg DW	Potassium	23.0	Cadmium	0.001	Silicon	0.121
$BMP_{2\text{-ppt}}$	180 mL / g VS	Calcium	19.2	Cobalt	0.001	Strontium	0.0412
$BMP_{17\text{-ppt}}$	110 mL / g VS	Iron	5.89	Chromium	0.007	Titanium	0.119
		Magnesium	8.39	Copper	0.035	Vanadium	0.0119
		Sodium	3.45	Manganese	0.058		
		Sulfur	14.6	Molybdenum	0.001		

**TS = total solids; VS = volatile solids; COD = chemical oxygen demand; GHC = gross heat of combustion; BMP = biochemical methane potential at a salinity of 2-ppt or 17-ppt*

Annual net nitrogen removal rate: 88 kg /ha • yr

** Based on 45 ton FW / ha • yr @ 10.2% dry matter*

$$\text{Kelp Farm Size (ha)} = \frac{\text{16 hectares}}{\text{(mg/L N removed)} \bullet \text{(mgd plant flowrate)}}$$

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Wastewater Effluent Goals

Nutrient effluent goals (following Water Environment Federation, 2010)

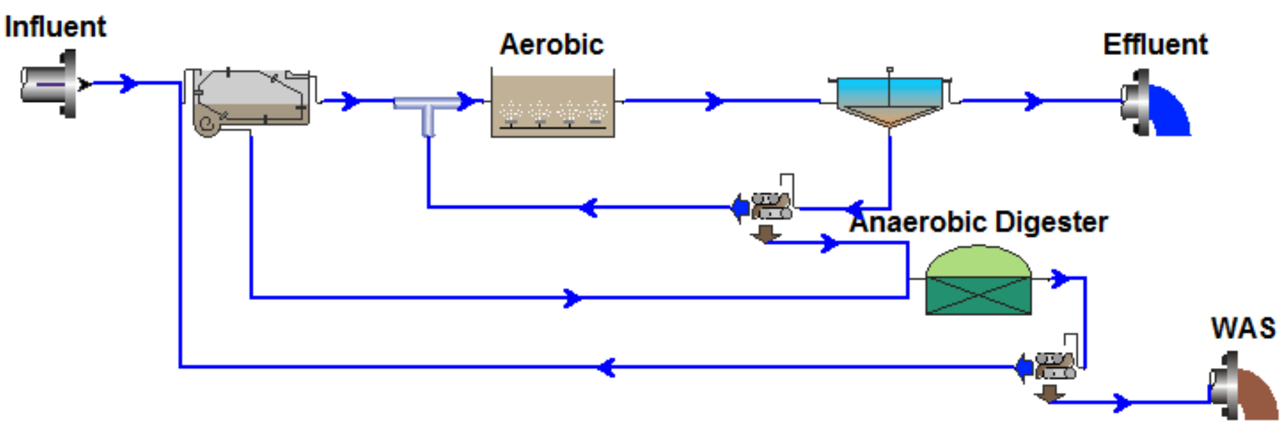
Level	TN	TP	Comment
1	8.00	1.00	Nominal nutrient removal achievable with conventional technologies
2	3.00	0.10	Enhanced removal: requires additional treatment to achieve limits
3	1.00	0.01	Very low limits: requires best practices and enhanced treatment. May or may not be feasible for some plants, especially requiring both limits simultaneously.

System Integration: Secondary Treatment

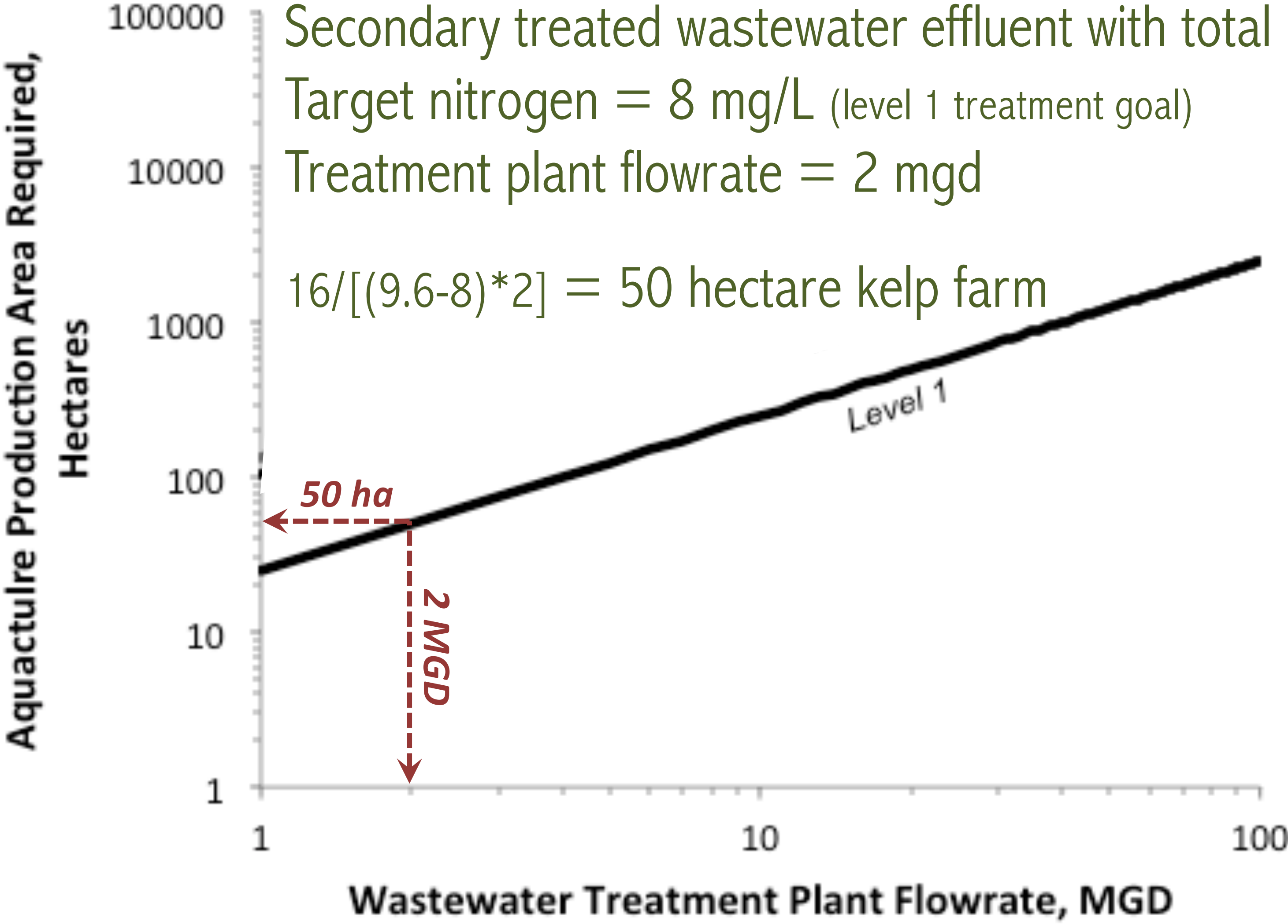
Modeled effluent characteristics for an activated sludge treatment assuming midline influent characteristics and bioprocess kinetics

Parameter	Influent §	Effluent
pH	7.00	6.98
Alkalinity, *mg/L*	100.00	82.00
Dissolved Oxygen, *mg/L*	2.00	2.00
Biochemical Oxygen Demand, *mg/L*	190.00	24.30
Total Suspended Solids, *mg/L*	210.00	14.00
Volatile Suspended Solids, *mg/L*	160.00	9.40
Total Nitrogen, *mg/L*	40.00	**9.60**
Total Phosphorus, *mg/L*	7.00	4.40

§ Midline characteristics (Metcalf & Eddy, Wastewater Engineering Treatment & Reuse, 2003, Fourth Edition)

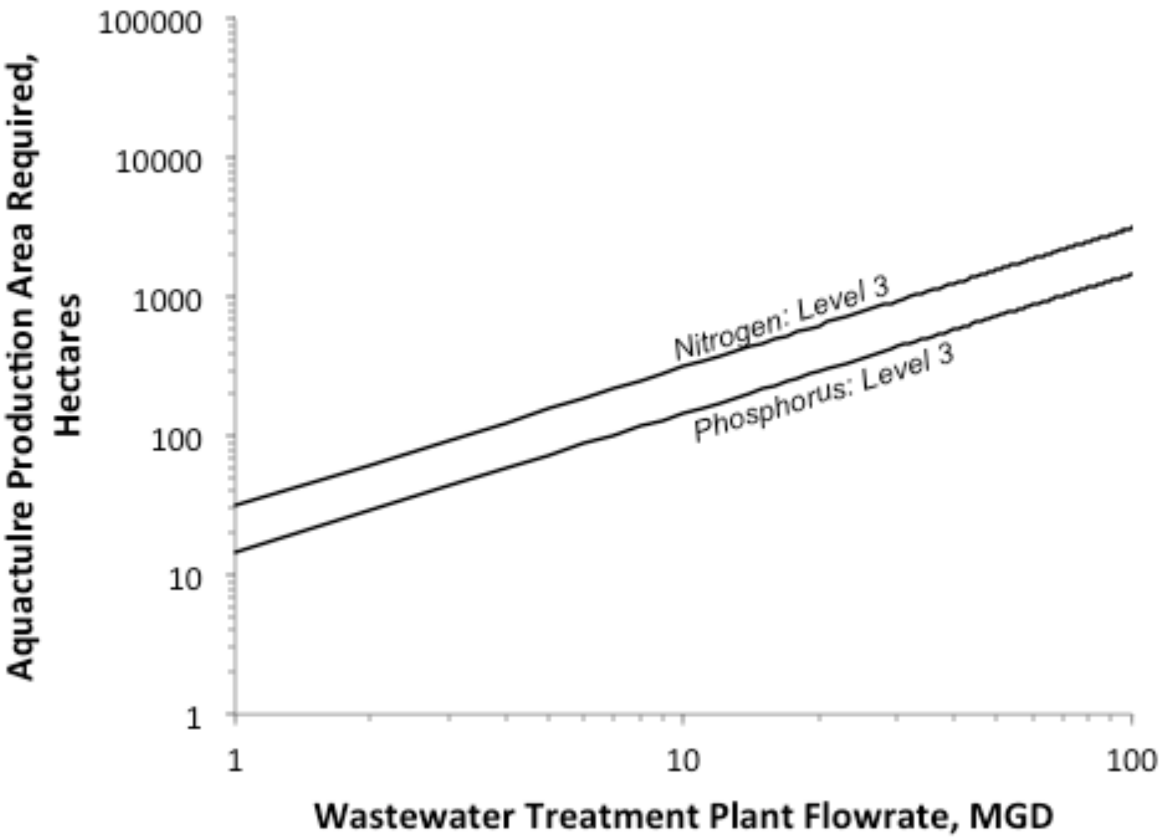


System Integration: Secondary Treatment + *S. latissima* Cultivation



Estimated production area requirements for *S. latissima* aquaculture to achieve nitrogen removal goals following secondary treatment by activated sludge in WWTPs of varying size.

System Integration: Tertiary Treatment + *S. latissima* Cultivation



Estimated production area requirements for *S. latissima* aquaculture to achieve level 3 nutrient removal goals following tertiary treatment (various processes) to meet level 2 nutrient effluent goals, in WWTPs of varying size.

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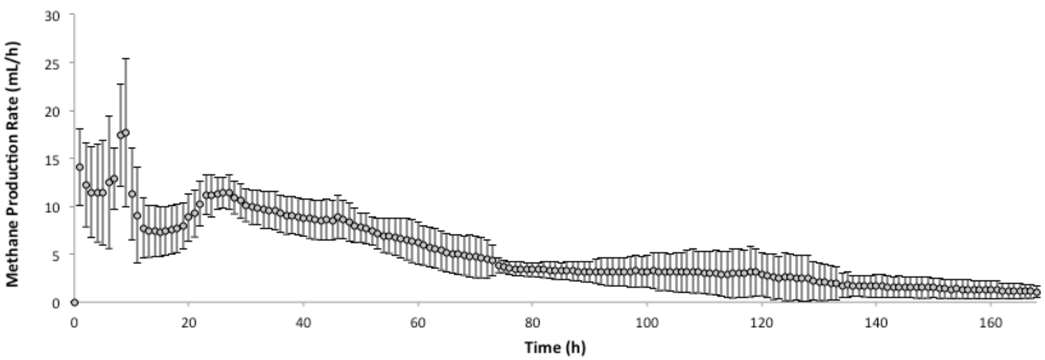
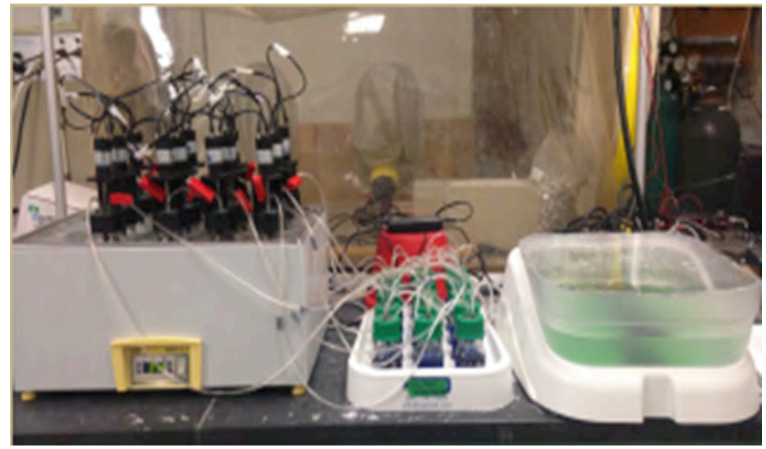
Biomethane Potential





Species	Category	BMP (mL/g VS)	Reference
Saccharina latissima	Brown algae	180 ± 17	This study
Saccharina latissima	Brown algae	440*	Pechsiri et al., 2016
Overall macroalgae		140 - 400	Murphy et al., 2013
Saccharina latissima	Brown algae	260 - 280	Chynoweth et al., 1993b
Macrocystis	Brown algae	390 - 410	
Gracilaria	Red algae	280 - 400	
Sargassum	Brown algae	260 - 380	
Ulva lactuca	Green algae	162 - 271	

* 180 mL/g VS was used in subsequent calculations as a conservative estimate

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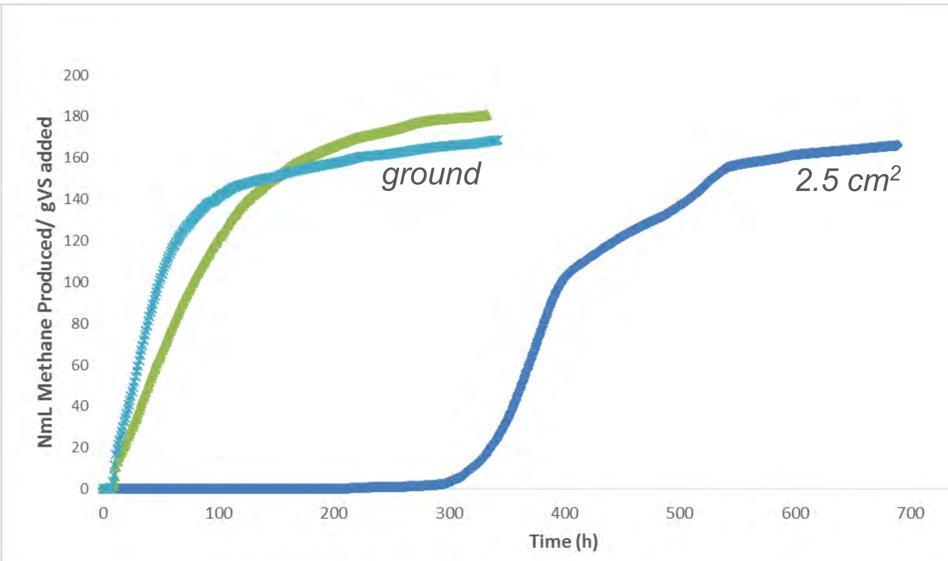
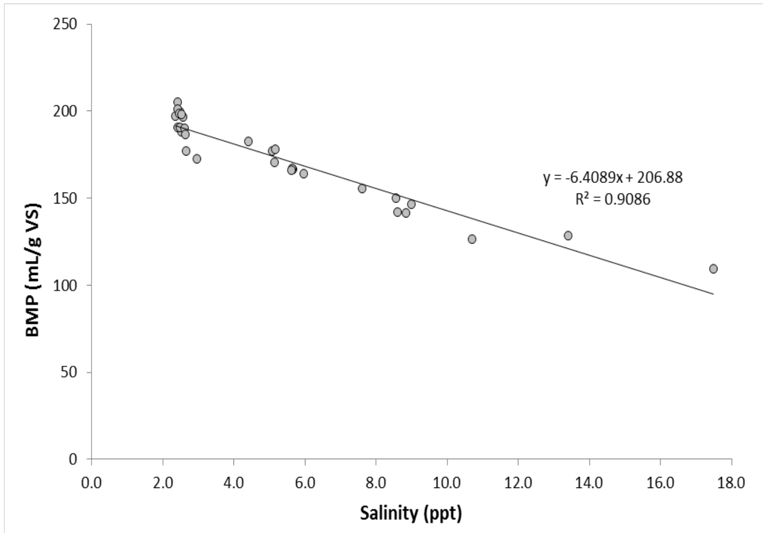
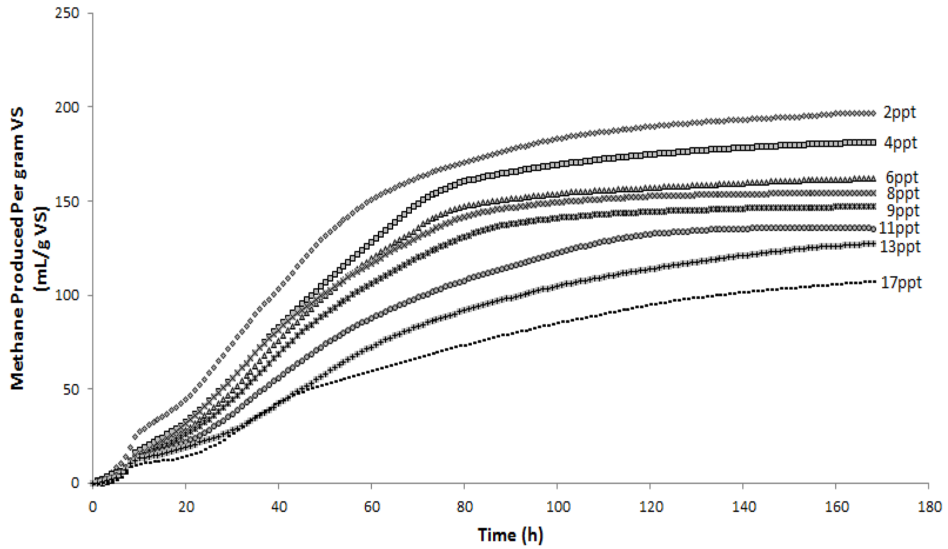
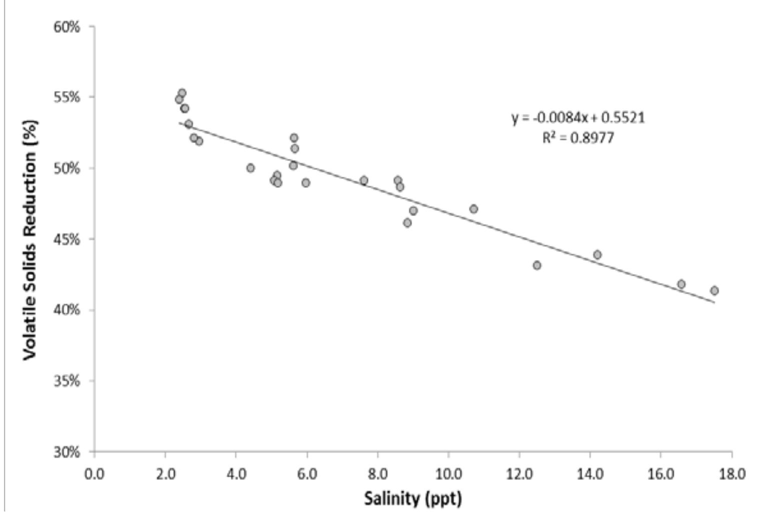
Biomethane Potential: Effects of Particle Size and Salinity









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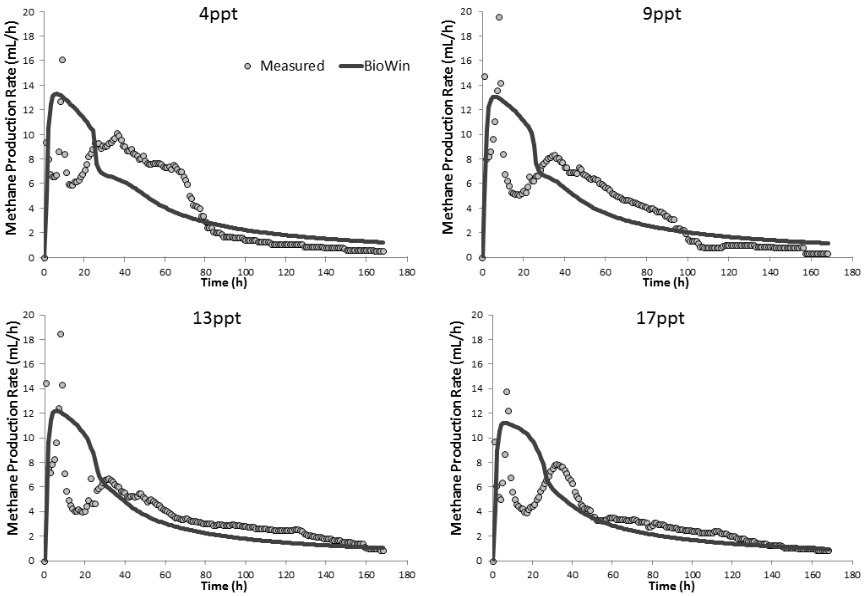
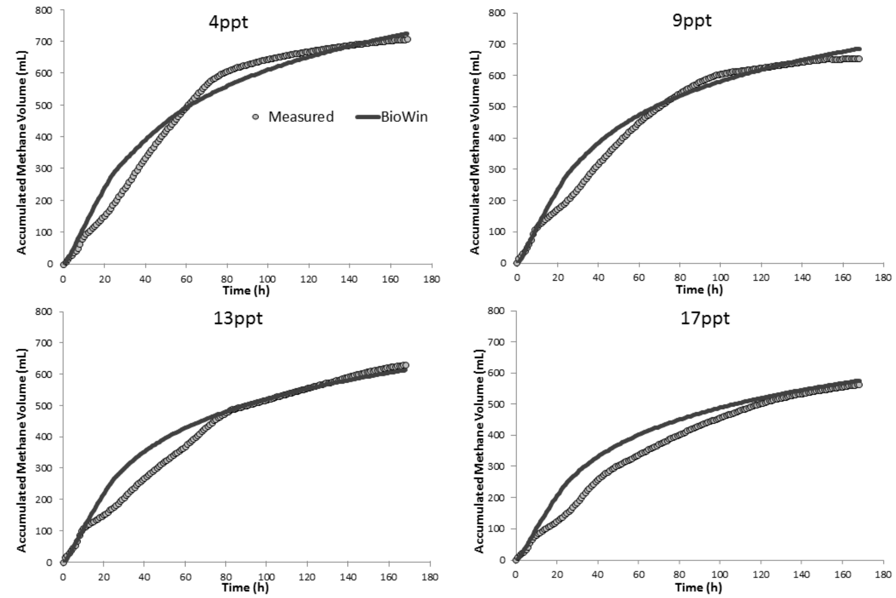
Biomethane Potential: Best Fit Rate Coefficients





Salinity (ppt)	Anaerobic Hydrolysis factor	Hydrolysis rate (d^{-1})	Anaerobic decay rate (d^{-1})	Fermentation rate (d^{-1})	Acetoclastic max spec. growth rate (d^{-1})	H_2 utilizing growth rate (d^{-1})
2	1.8	0.7	0.13	1.6	0.27	1.4
4	1.8	0.7	0.13	1.6	0.14	1.4
9	1.8	0.7	0.13	1.4	0.12	1.4
13	1.8	0.65	0.13	1.3	0.09	1.3
17	1.8	0.65	0.12	1.1	0.06	1.1
24	1.8	0.52	0.08	0.9	0.01	0.4
27	1.8	0.45	0.06	0.7	0.01	0.37

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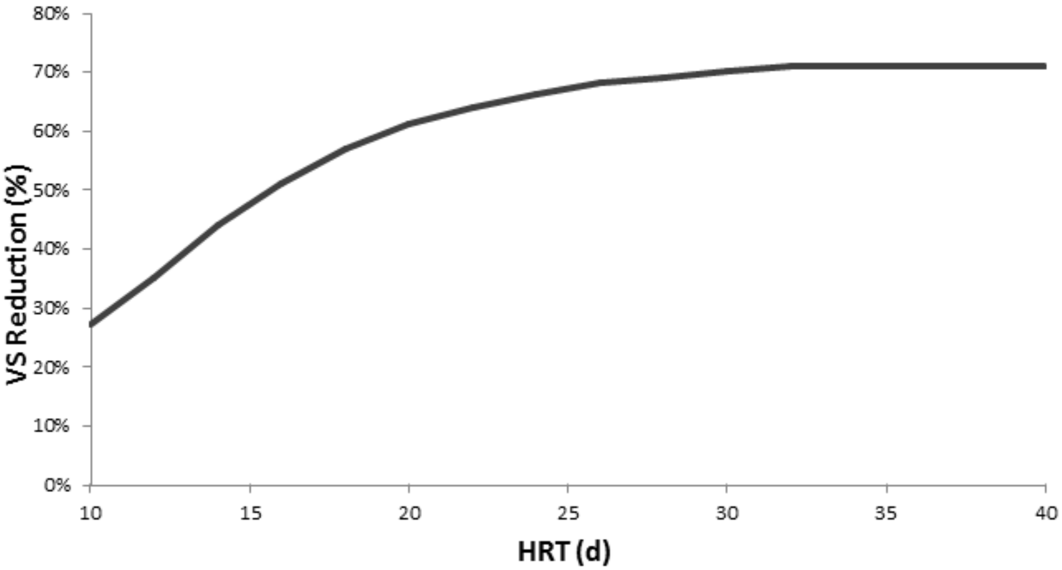
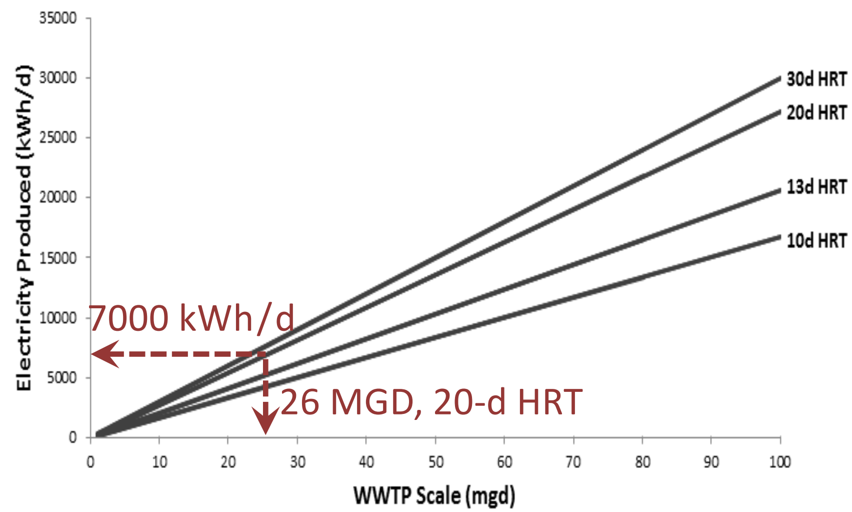
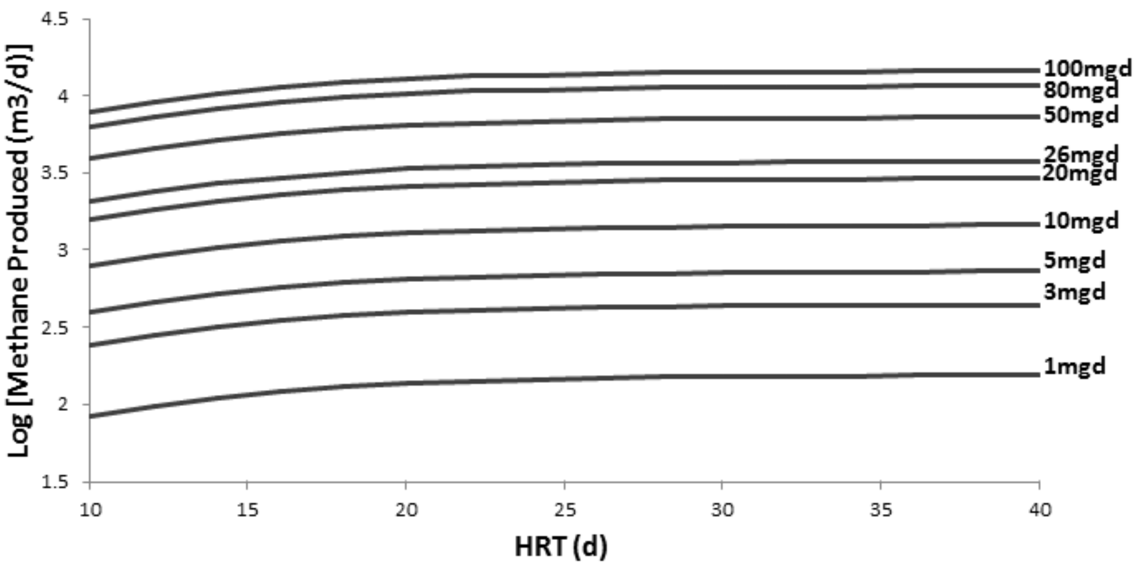
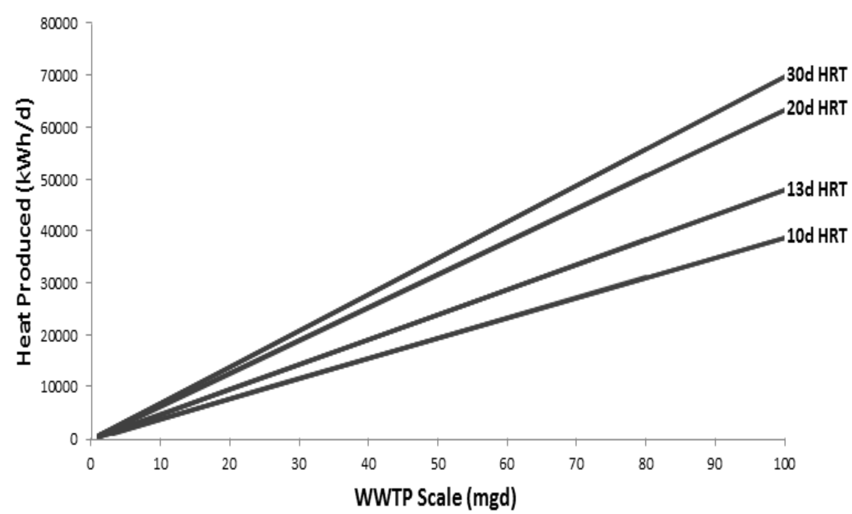
Biomethane Potential: Full-scale anaerobic digestion simulations

Based on 45 ton FW/ha·year









Discussion and Conclusions

- *S. latissima* was explored for potential nutrient bioextraction and recovery from plumes of ocean outfalls of WWTPs.
  - 45 tons FW/ha
  - Biomass production characteristics may be greater when grown in nutrient-rich plumes
  - 88 kg-N/ha • yr
  - Composition may be affected by period of harvest
  - 16 ha / [(mg/L N removed)(mgd)]
- Macroalgae aquaculture for nutrient recovery and biomass production may be a viable alternative, especially for smaller wastewater treatment plants and those seeking very low levels of net nutrients discharge in conjunction with tertiary treatment processes
- Biomethane potential of *S. latissima* was 180 mL CH_4/g VS
  - Strongly influenced by salinity
  - Pretreatment may be necessary for effective anaerobic digestion.
  - Alternative anaerobic digester seeds (potential for greater biomethane production)
  - Harvesting period may play a role

Continuing Work

- Exploration of effects of growth in plumes of wastewater discharges on kelp production rates and biomass composition.
  - Positive effects of nutrients enrichment on growth and composition may be offset by negative effects of increased micropollutants, turbidity, DOM, etc.
  - Biomass characteristics may be influenced by growth and harvesting periods
  - WWTP effluent quality and composition of nutrients will change with seasons
- Analysis of the technology as a component of wastewater treatment practice will help understand economic benefits and trade-offs relative to tertiary treatment. Mixture of goods that may emerge from *S. latissima* (e.g., proteins, alginates, succinic acid, phenols...) should be explored.
- Life cycle assessment of the proposed process as an alternative to nutrient removal by engineered operations and processes

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Acknowledgements:

Graduate Students:

Yujiao Yang and Nona Jesmanitafti, Clarkson University

For Field Trials:

Chris Higgins, Boothbay Harbor Sanitary District, Boothbay Harbor, Maine
Paul Dobbins, Ocean Approved, LLC, Portland, Maine

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