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Biological Systems and Engineering

Seaweed Valorization through Anaerobic Digestion

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Valorization of Biomass through Anaerobic Digestion

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- **Anaerobic Digestion** is an exothermal four-step breakdown of a wide range of biomass (carbs, protein, fat) into C_1/C_2 molecules, reversing photosynthesis (= **a mechanical cow**)
- Methanogenesis, the last of the four steps, requires *mcr* activity only found in Archae, and releases methane as value product into the gas phase, lowering the thermodynamic cost of separation
- AD is rate limited by Archaea growth rates (doubling times) to 20d HRT
- Seaweed is largely an inconvenient, high-ash, high-salt substrate with challenging logistics and moderate conversion performance as feed, and hence as AD substrate, while competing with abundant terrestrial biomass that is now left unused to decompose, with easier to accessibility
- Various LCA models have shown irrecoverable CI scores (+120 - +150 g CO_{2eq} / MJ)
- Key value drivers for CNG are ecosystem services, i.e. methane and pollution avoidance or carbon sequestration, resulting in renewable fuel production (i.e. LCFS, REDD2), and not merely the commodity revenue
  - ➢ Price is a function of amount, form, location, use, time and environmental attributes
- Conversion rates of 60-80% leave biomass digestate as burden and boon

AD is a four-step degradation with known stoichiometry and known inhibitions (temperature, pressure, salinity, ammonia)

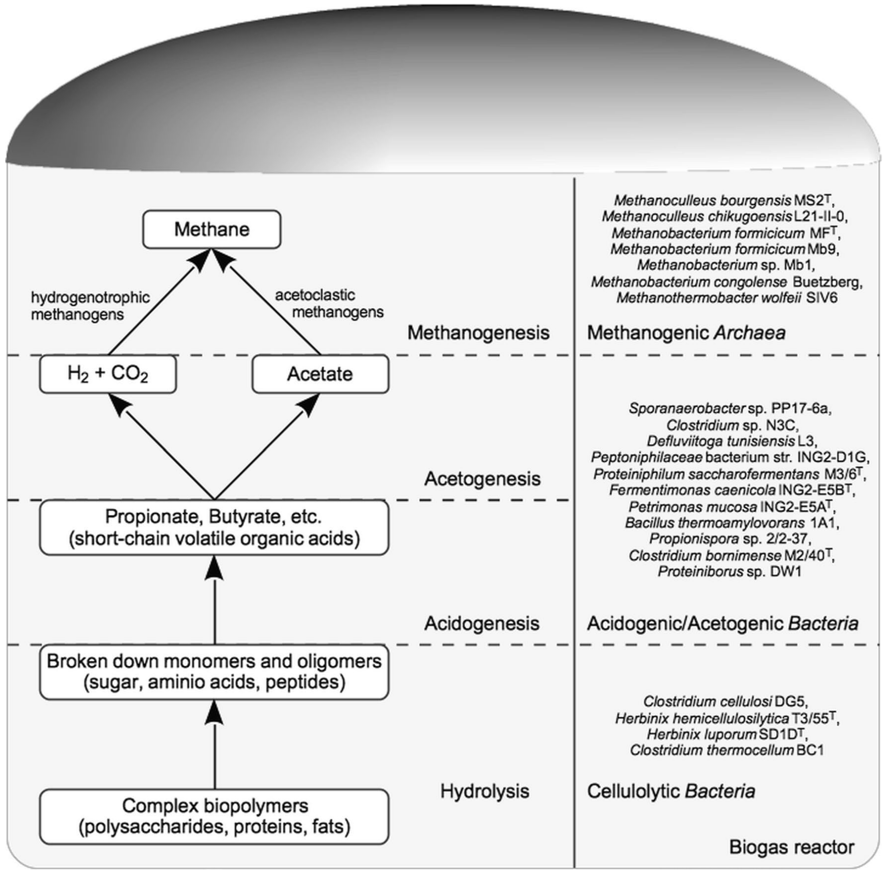

Fig. 3 Overview of the four phases of the conversion of biomass into biogas and allocation of the analyzed microbial strains to the different conversion steps. Functional roles of the organisms were determined considering relevant KEGG pathways, namely the propionic acid, ethanol, formic acid, butyric acid, and lactic acid fermentation

Buswell & Boyle (1940)

$$C_cH_hO_oN_nS_s + \tfrac{1}{4}(4c-h+2o+3n+2s)\ \mathbf{H_2O} \longrightarrow$$

$$\tfrac{1}{8}(4c-h+2o+3n+2s)\ \mathbf{CO_2} + \tfrac{1}{8}(4c+h-2o-3n-2s)\ \mathbf{CH_4} + n\ \mathbf{NH_3} + s\ \mathbf{H_2S}$$

Examples:
Carb: 790 l Biogas/kg VS
Prot: 700 l Biogas/kg VS
Fat: 1250 l Biogas/kg VS

mcr

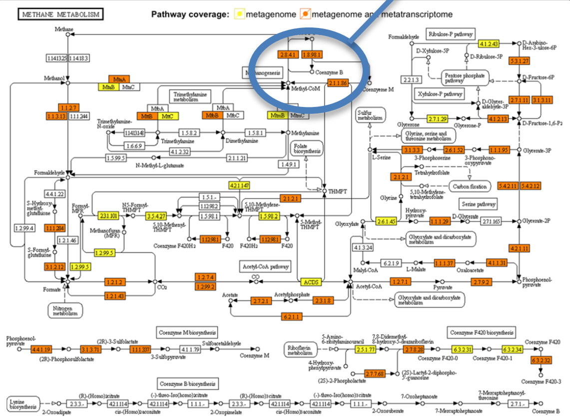

Fig. 1 Methane metabolism pathway analysis. Genes reconstructed in our assembly that are involved in the methane metabolism [PATH:ko00680, (http://www.genome.jp/kegg-bin/show_pathway?ko00680)], are highlighted: genes with only metagenomic support are in yellow and genes with metatranscriptomic support as well, suggesting active gene expression, are in orange. Methane is synthesized from CO_2, methanol or acetate. KEGG pathway map courtesy of Kanehisa Laboratories

- **M**ethyl-**C**o-enzyme M **R**eductase
- Vitamin B12 Analog
- Ni-center
- Only known pathway to get from CO_2 and H_2 to CH_4

Ideal feedstock characteristics for AD conversion differ significantly from cellulosic ethanol feedstock criteria

- High specific biogas yield per organic dry matter content
- High fresh matter biomass yield per acre (more than 30t FM/ac)
- **Dry matter content between 20% and 35%**
  - ✓ **Malolactic fermentable**
- **Low lignin content (less than 5-6%)**
  - ✓ Easy hydrolyzation without the use of external enzyme addition
- Low protein content, **high fat content**
  - ✓ Favorable C:N ratio
- Wide, local, existing availability
  - ✓ Dual purpose crop that has demand in energy, food and fuel
- Perennial, low water use, drought resistant, low/no till requirement
- **Easy harvesting protocol** with field shredder or mower
- **Low cost or preferably revenue at digester gate**
- Sugar beet, corn/sorghum silage, energy cane, camelina, bana/napier grass

The US has massive amounts of underutilized biomass substrates, including sorghum, soybean straw, corn stover and manure with easy access

Source	Stream Size [t/y]	metric t CH4/year	mmBTU	GGE	Scenario
Crop Residues	353,925,900	70,001,884	3,745,178,652	32,852,444,316	70% collected; return digestate
Corn Residues	**155,027,688**	37,243,852	1,992,587,509	17,478,837,798	70% collected; return digestate
Soybean Residues	**101,744,614**	18,802,405	1,005,949,570	8,824,119,032	70% collected; return digestate
Wheat Straw	**50,291,939**	5,709,141	305,445,395	2,679,345,573	70% collected; return digestate
Ethanol Stillage	**40,272,569**	6,113,376	327,072,410	2,869,056,224	All DDGS
Biodiesel Glycerin	2,797,300	775,412	41,485,386	363,906,899	All glycerin
Organic MSW Fraction	**78,517,185**	3,938,864	210,733,622	1,848,540,546	BioCycle 2011 w/ 35% organic
Energy Crops	394,853,895	62,234,057	3,329,591,282	29,206,941,074	Max Yield with BTS2 acreage
Miscanthus	128,195	10,179	544,579	4,777,007	Max Yield with BTS2 acreage
Sorghum	**388,718,580**	61,875,905	3,310,429,721	29,038,857,206	Max Yield with BTS2 acreage
Energy Cane	6,007,120	347,974	18,616,982	163,306,861	Max Yield with BTS2 acreage
Landfill		8,422,744	450,626,168	3,952,861,126	Min. 50 SCFM biogas
Waste Water Treatment		1,044,503	55,882,057	490,193,484	Min. 50 SCFM biogas
Manure	**682,441,573**	9,903,137	529,828,868	4,647,621,652	2012 Census Dairy & Feed
Dairy	**271,446,096**	3,103,305	166,030,276	1,456,405,928	2012 Census Dairy & Feed
Beef in Feedlot	**170,665,601**	2,687,889	143,805,048	1,261,447,791	2012 Census Dairy & Feed
Hogs	**171,018,889**	2,555,176	136,704,779	1,199,164,727	2012 Census Dairy & Feed
Chickens	**69,310,987**	1,556,767	83,288,766	730,603,206	2012 Census Dairy & Feed
Total		162,433,978	8,690,398,447	76,231,565,321	

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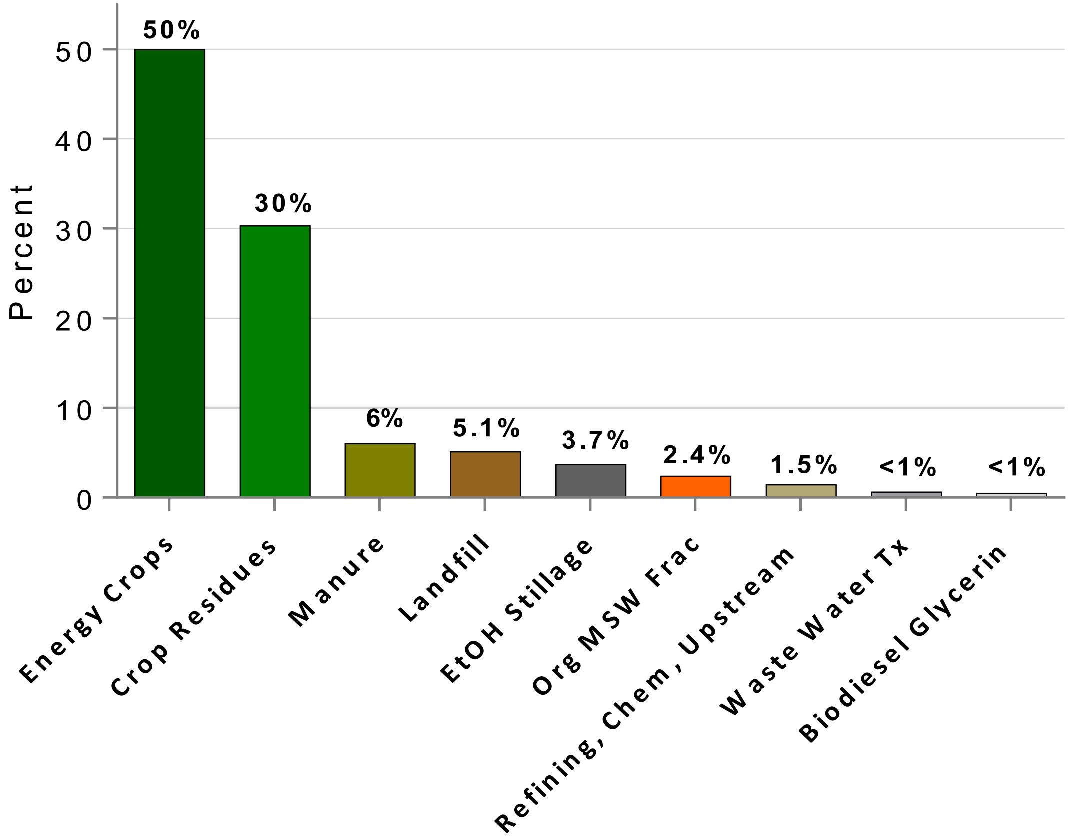
From those substrates alone, biogas could generate 51% of US fossil transportation fuel



➢ **US Potential = 8.81 Quad / 77 billion GGE**

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High yielding US biogas substrates include sorghum, corn stover

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Substrate	m_N^3 Gas/ t oDM	DM [%]	oDM [%DM]	CH_4 [%]	Lignin [%]	Yield [t/ac]	Conversion [% of theor.]
Corn Stover	**420**	90.8%	95.1%	54.6%	8.5%	4.35	35-55%
Sorghum	**555**	90.8%	91.9%	52.0%	10.3%	7.55	50-65%
Dairy Manure	**490**	1.5-3.5%	70-90%	58%			50%
Gracilaria	**450**	5-17%	20-70%	55%	0%	?	11-88%
Macrocystis	**400**	18.7%	69.5%	55%	1-5%	?	45%
Sargassum	**200-500**	5%	65-77%	58%	7-15%	?	25-57%

- **Sorghum is the highest yielding biogas energy crop**
- **Corn stover is the highest yielding crop residue**
- **Seaweed has low dry matter content and average specific conversion**

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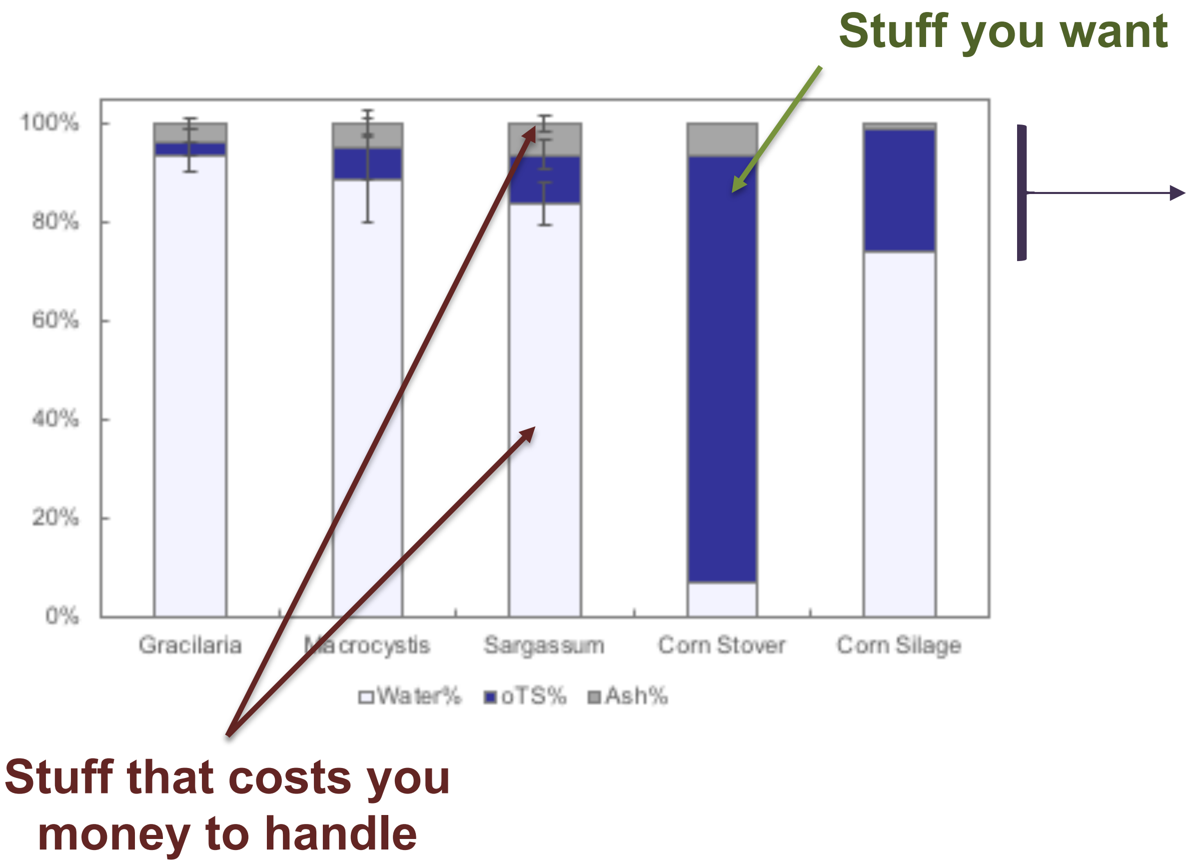
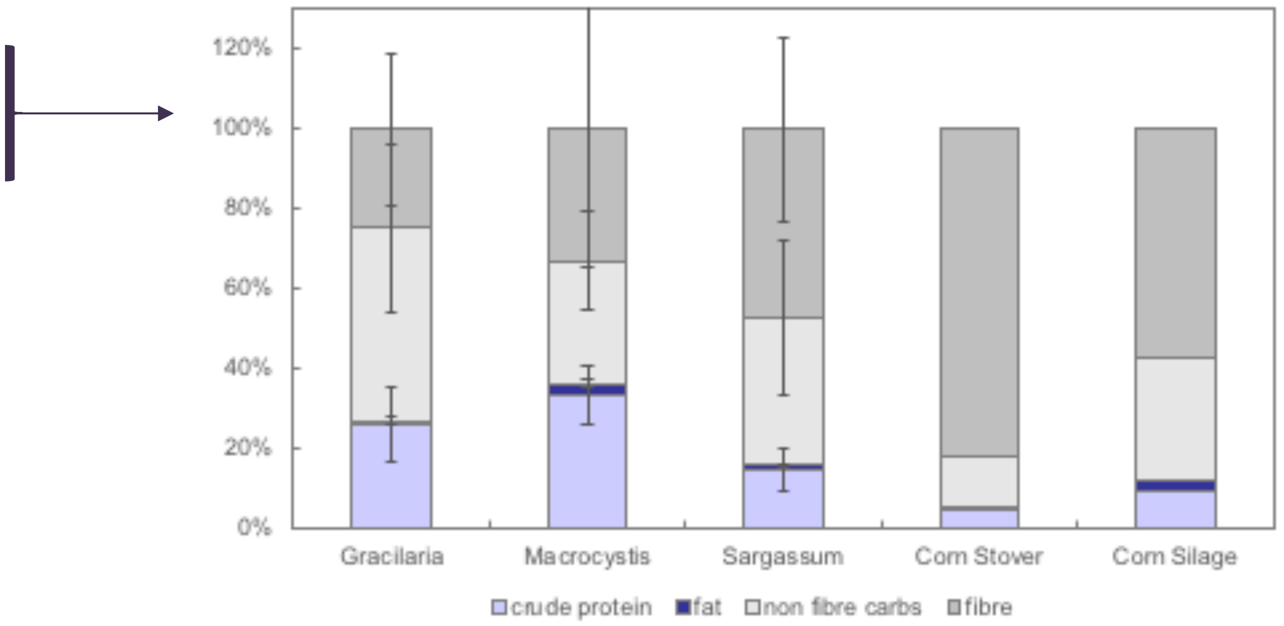
Steve Singer, Lydia Rachbauer

Conversion of biomass to biogas and methane follows composition conversion yields (Buswell), driving economics





Biomass composition of seaweed is imbalanced for feed stuff (USDA/NOAA 2011), lacking nutrients

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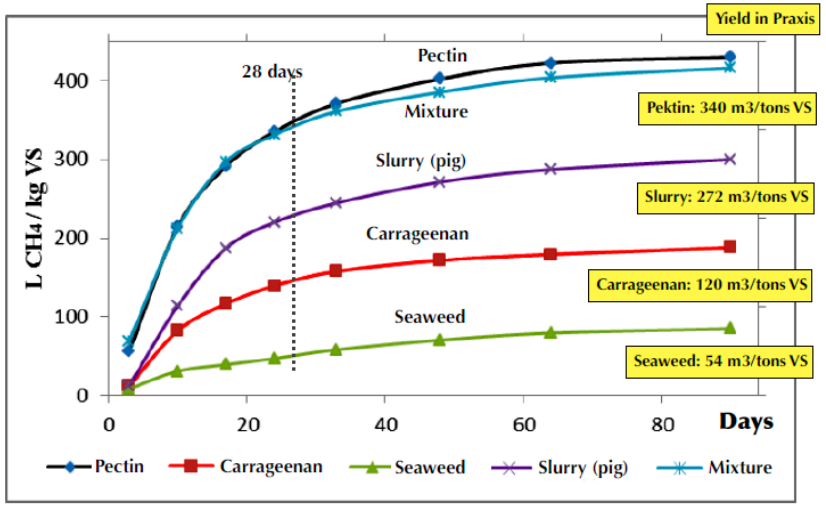
Europe has a history of (cast) seaweed with mixed outcomes

COASTAL BIOGAS

Solrød Biogas A/S
- 226,000 tpy feedstock
- 7,400 tpy seasonal seaweed
- <6% of methane
- Cadmium, salt limited

biosea CoastObs MACROFUELS TAPAS GENIALG EnAlgae PHYCOMORPH

- LCA showed CI irrecoverable above +120 g CO_{2eq}/MJ
  - Mostly lack of suitable business proposition
    - Specialty Foods, ex-EU applications
      - Hypothetical Magic Molecules



Reported methane yields are inconsistent and vary widely

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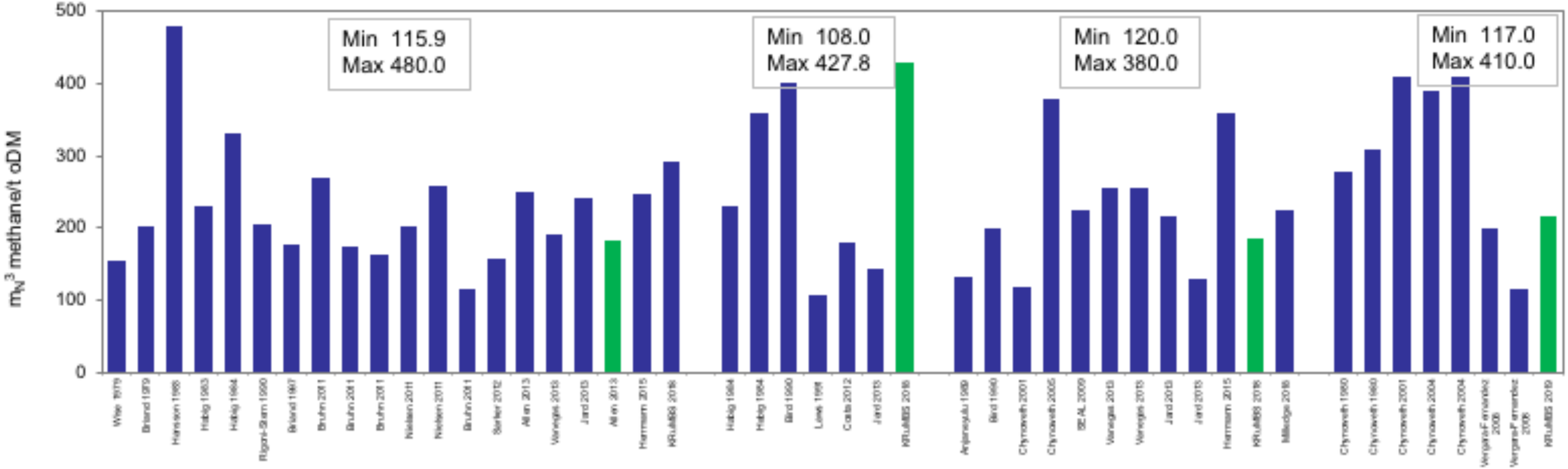
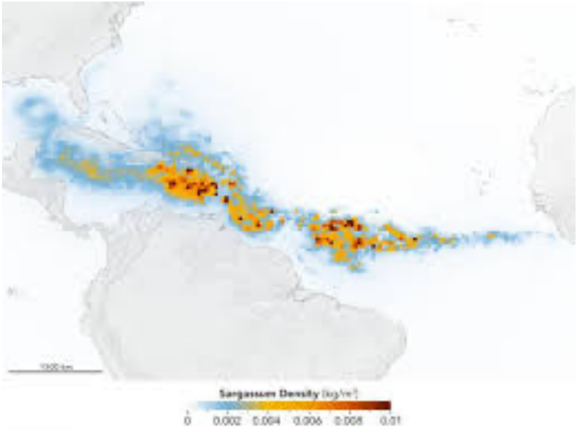


Literature Review of BMP for seaweed

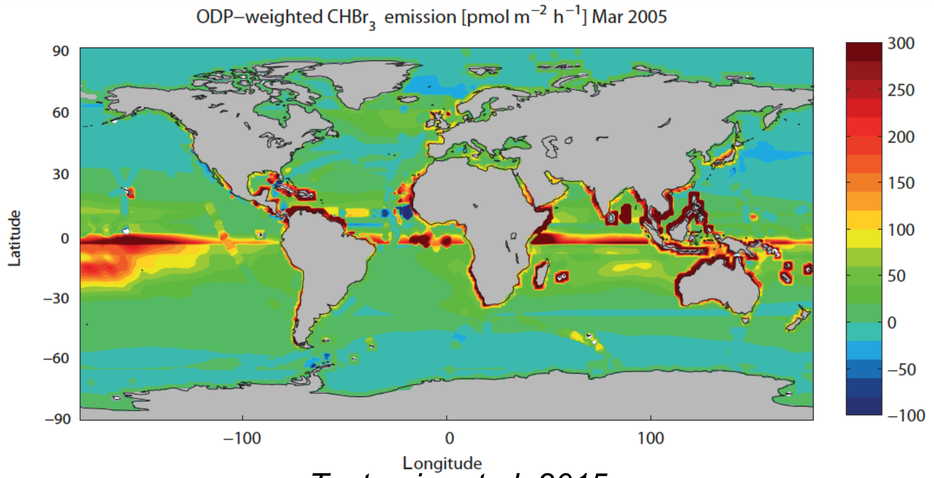
But seaweed stinks!

Coastal Suffocation



Wang et al. 2019

20 million ton annually



Tegtmeier et al. 2015

220,000 t CH_4 / year, >1,000 ppm H_2S

<u>Next Steps:</u>

- Assess overall ecological impact of Sargassum blooms
  - ➢ Tourism, native marine ecology, fishing, atmosphere
- Collection method at scale
- Scale continuous AD process at low-temp / high-salinity
- Develop monetization through ecosystem services

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