Recent Advances in Seaweed Aquaculture for Nutrient Bioextraction & Ecosystem Services: Lessons Learned from the US MARINER Program, ARPAe (DOE)

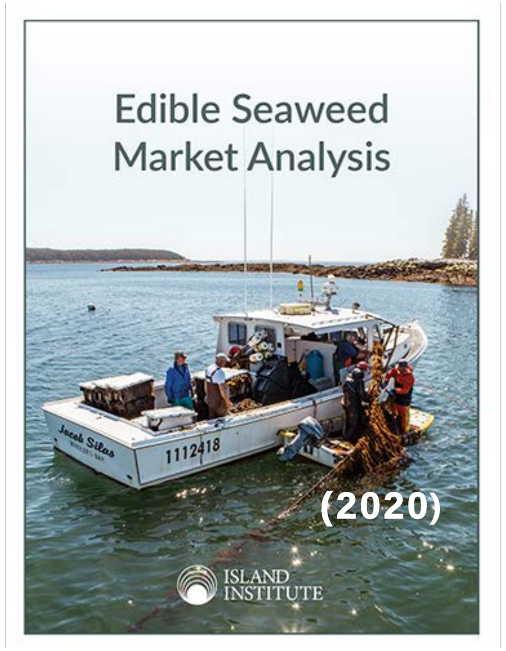
Charles Yarish*[1,2]

J.K. Kim[1,3], G. Kraemer[4], S. Lindell[2], M. Stekoll[5], M. Marty-Rivera[1], D. Bailey[2], Y. Li[1], M. Aydlet[2], C.A. Goudey[6], D. Manganelli[6], K. Barbery[7] & B. Smith[7]

[1]University of Connecticut
charles.yarish@uconn.edu

[2]Woods Hole Oceanographic Institution
[3]Incheon National University, Korea
[4]Purchase College, Purchase, NY
[5]University of Alaska, Juneau, AK,
[6]C.A. Goudey & Associates, Newburyport, MA
[7]GreenWave, New Haven, CT

USA ESTIMATED SEAWEED MARKET (2022)



SOURCE	ESTIMATED DRY POUNDS
Net Imports	**1,600,000**
Domestic Aquaculture	**106,390 - 130,000**
Domestic Wild	**30,000 – 1,600,000**
Total	**1,736,390 – 1,765,000**

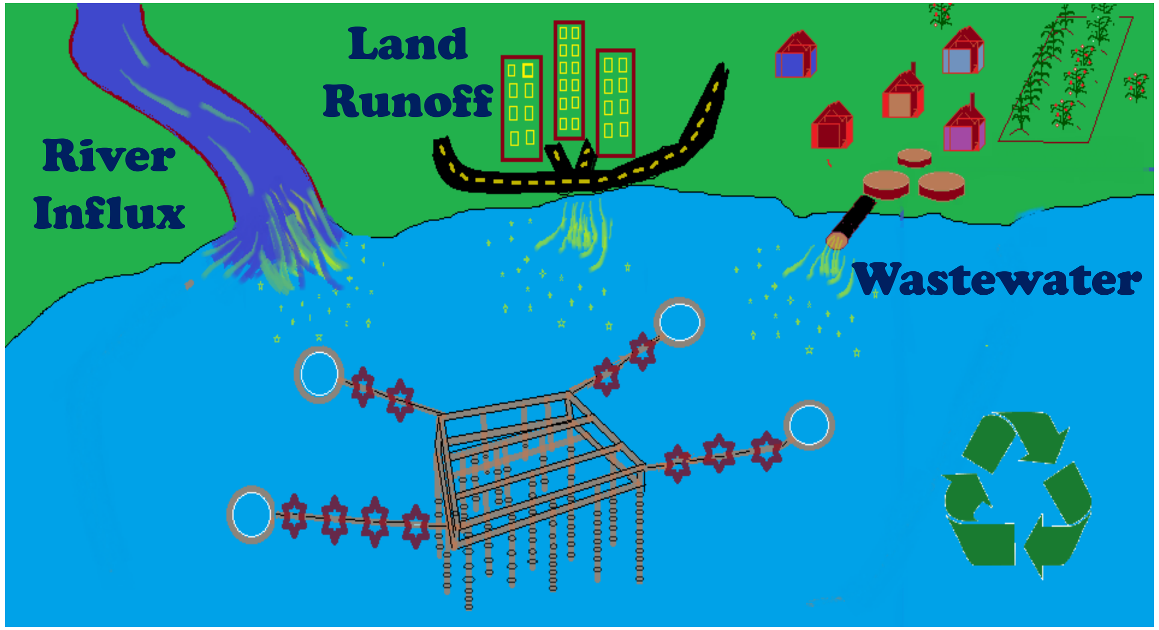
Source (US)	**Estimated Wet Pounds**	**Equivalent Dry Pounds**
Aquaculture	1,063,900-1,300,000	106,390- 130,000
Wild	300,000 – 350,000	30,000 – 35,000
	16 million (2022; Seaweed Hub)	1,600,000 -(2,000,000?)
Total	**17,363,900 – 17,650,000**	**1,736,390 – 1,765,000**

~95-98% of edible seaweed products found in the U.S. are currently imported

Long Island Sound Estuary

Nutrient bioextraction in urban waters

The removal of nutrients from an aquatic ecosystem through the harvest of enhanced biological production (aquaculture of seaweed and/or shellfish)

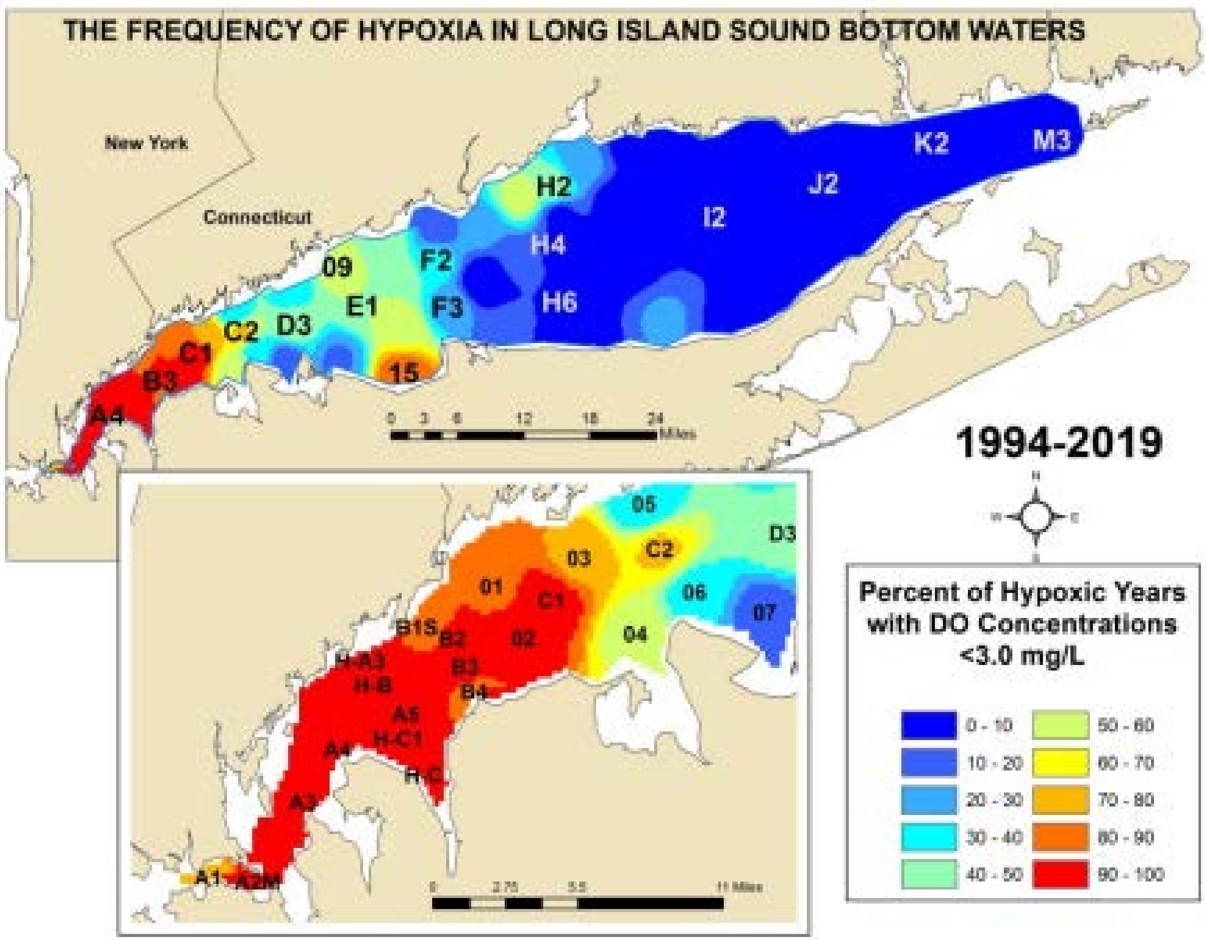


How does nutrient bioextraction work?

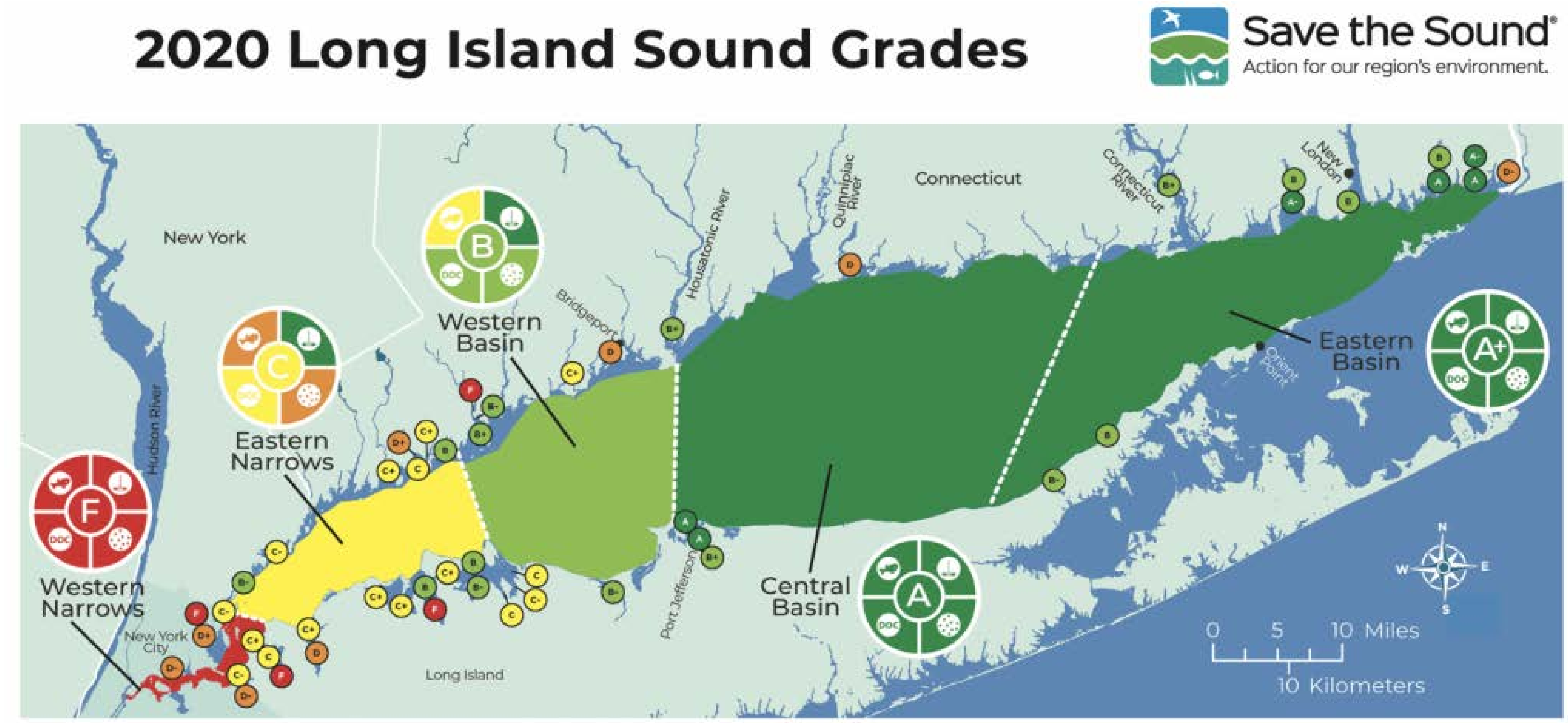
- Cultivation and harvest of macroalgae and shellfish
- Nutrients are taken up either directly (seaweed-inorganic nutrients such as nitrate and ammonium) or indirectly (shellfish, via plankton-organically bound nutrients)
- Removal of biomass removes nutrients from the ecosystem


Frequency of Hypoxia in Long Island Sound Bottom Waters

(CT DEEP and EPA Long Island Sound Study)



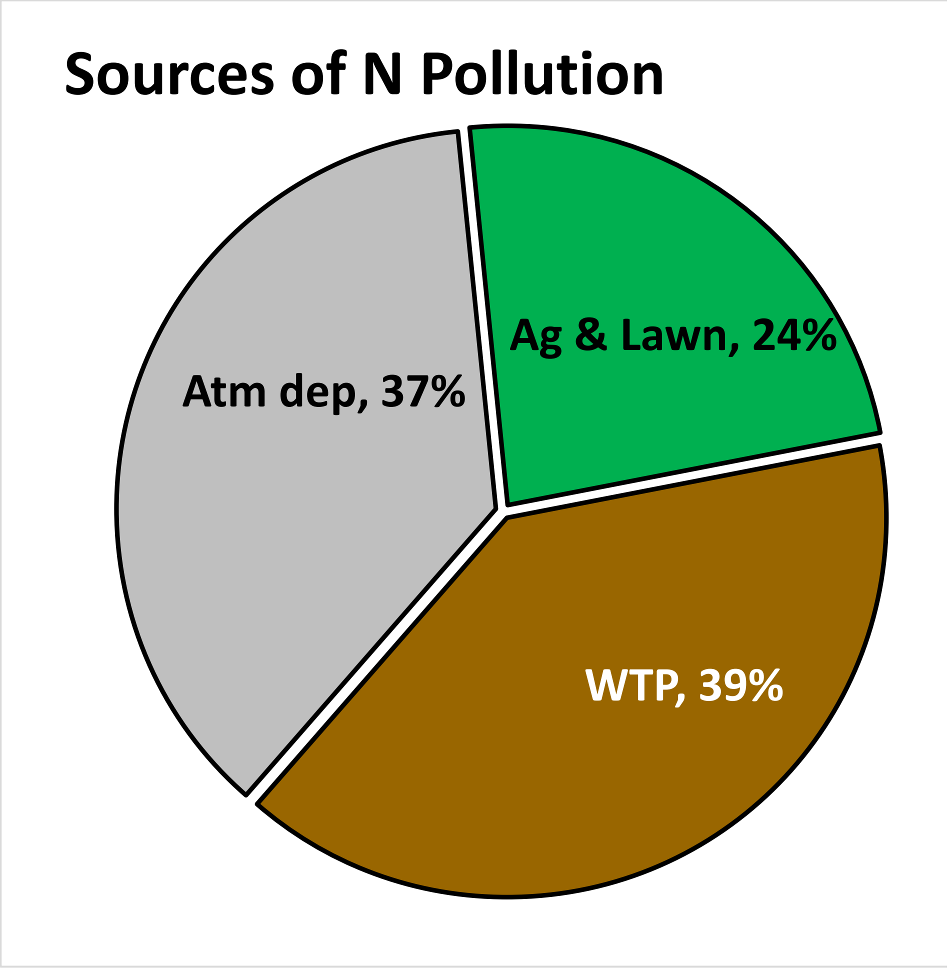
Ecosystem services approach to overcome NIMBY



Why was nutrient bioextraction being conducted in Long Island Sound & Bronx River estuary (East River)?

- Longtime focus of nitrogen management has been on point sources (i.e., wastewater treatment plant upgrades)
- Growing recognition that nonpoint source pollution is also a substantial problem that needs to be addressed
- Nutrient bioextraction may also address legacy pollution in the water column and sediments

Long Island Sound Estuary (US EPA's LISS)



Major project sponsors and participants

- U.S. EPA Long Island Sound Study's Long Island Sound Futures Fund, National Fish and Wildlife Foundation
- Connecticut Sea Grant College Program
- NOAA SBIR I and II
- U.S. Department of Agriculture, National Institute of Food and Agriculture ((NIFA)

- University of Connecticut
- Purchase College
- Bridgeport Regional Aquaculture Science and Technology Center
- Rocking the Boat
- Thimble Island Oyster Co.

Open water seaweed farms

Central LIS
Branford, CT
(Thimble Island Oyster Co.)

Bronx, NY (BRE)

Western LIS
(Fairfield, CT)

Gracilaria tikvahiae (red seaweed, a summer crop)*

- Growing season: June – Oct. (> 15 °C)
- Commercial value of *Gracilaria* ~ $1 billion annual value, FAO 2021

Rocha et al. 2019. Characterization of agar from cultivated *Gracilaria tikvahiae*:… Food Hydrocolloids 89:260-271. https://doi.org/10.1016/j.foodhyd.2018.10.048.

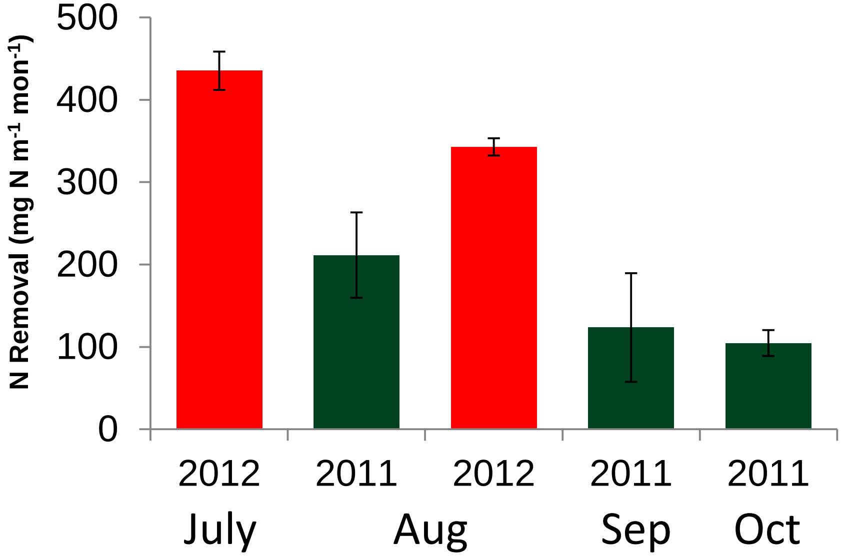
Kim et al. 2014, Aquaculture, 433:148-156.

>16.5 % per day

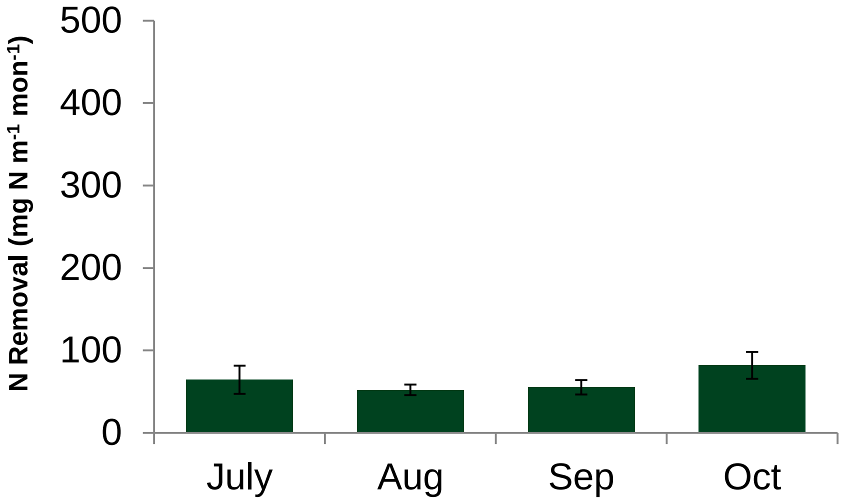
14 days: 1,700 lb

Nitrogen Removal (site and season)

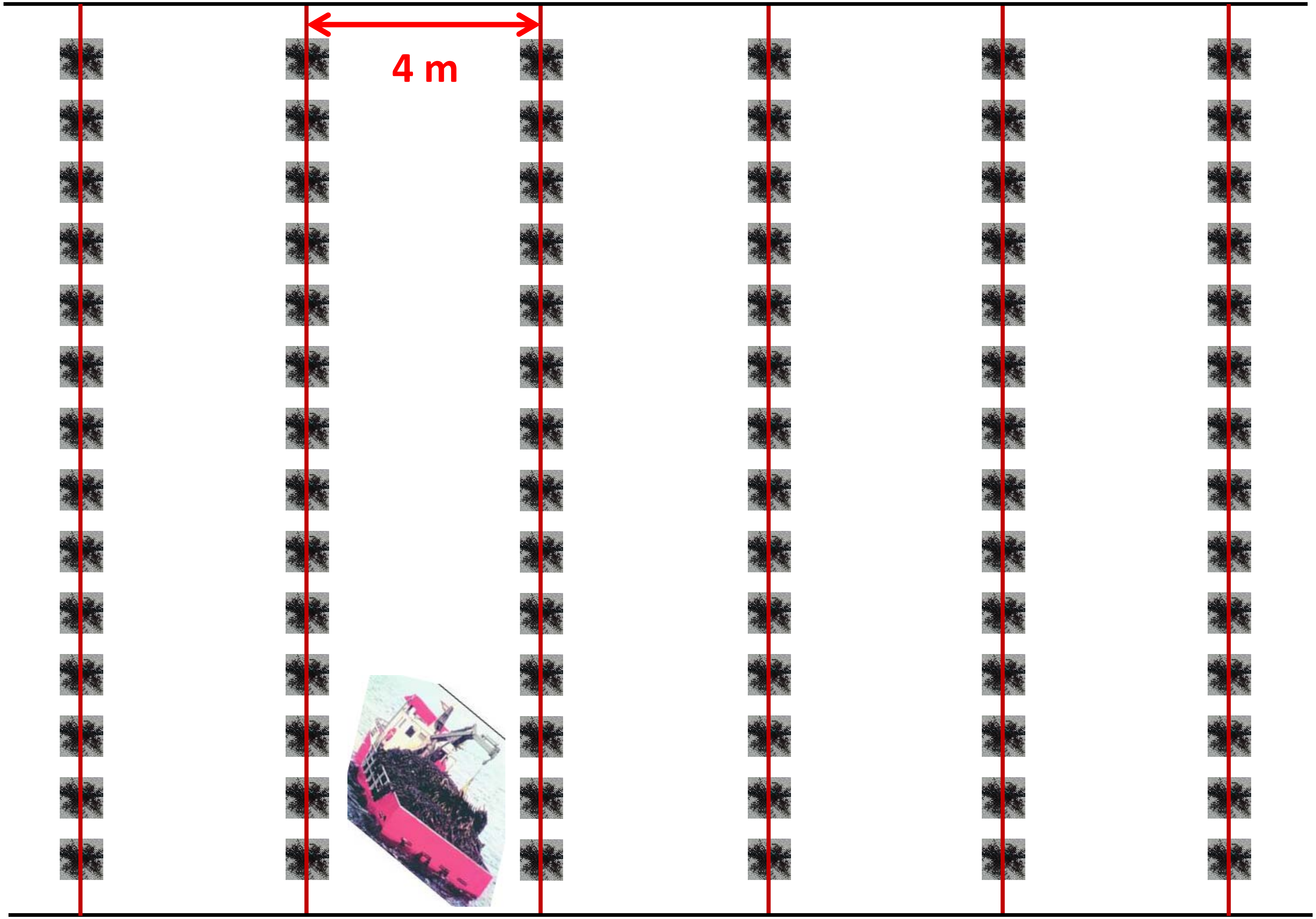
Bronx (2011 & 2012)



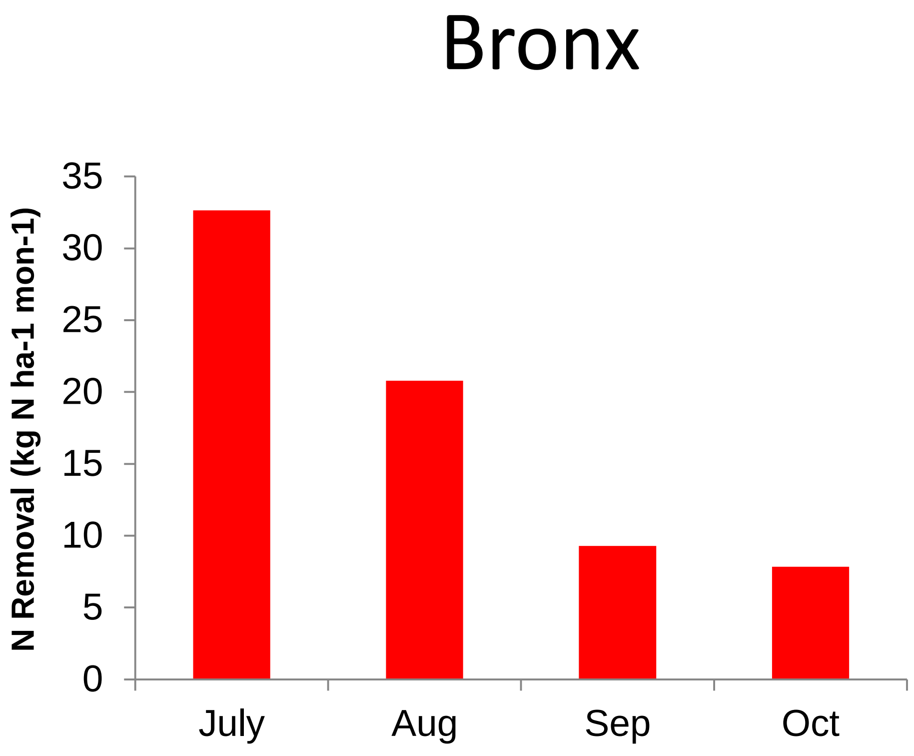
LIS (2011)

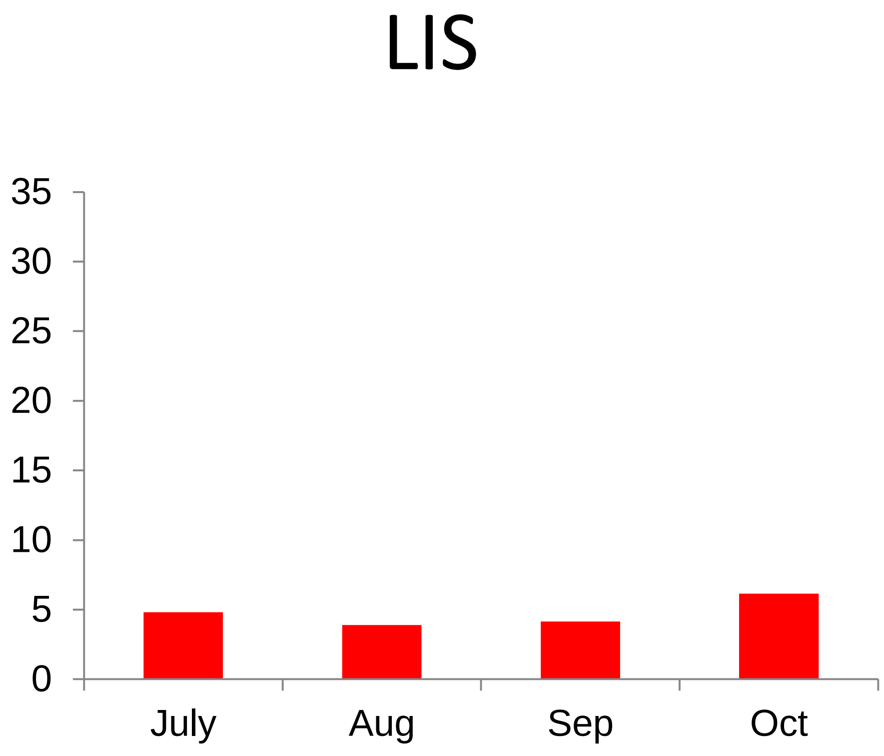


Kim et al. 2014, Aquaculture, **433:148-156**.


4 m

Nitrogen Removal (hypothetical one ha *Gracilaria* farm)





Estimated LIS Production Potential for *Gracilaria*

Suitability Level	*Hectares*	*Annual Production (wet weight, t/y)*	***Total Dry Production (t/y)***	**Total Value (assuming $669.57 per Hectare)**
Not Suitable	81,795.00	0.00	0.00	0
Suitable	61,566.10	349,510.75	52,426.61	$41,222,814
On Eastern Beds (State-managed)	8,875.40	50,385.64	7,557.85	$5,942,701
TOTAL	**70,441.49**	**399,896.39**	**59,984.46**	**$47,165,514**

Gracilaria (based upon western LIS site)
72.9 kg FW per 100 meter
4 meters between longlines
1,823 kg/ha/year

Saccharina (sugar kelp, brown seaweed, a winter crop)

- Kelp is the most widely cultivated species in the world (~$5.53 billion annual value)
- Human food and source of alginates (colloid & biomedical)
- Growing season: Nov. – May (< 15 °C)
- Nutrient bioextraction (ecosystem services)
- Biofuels

Productivity

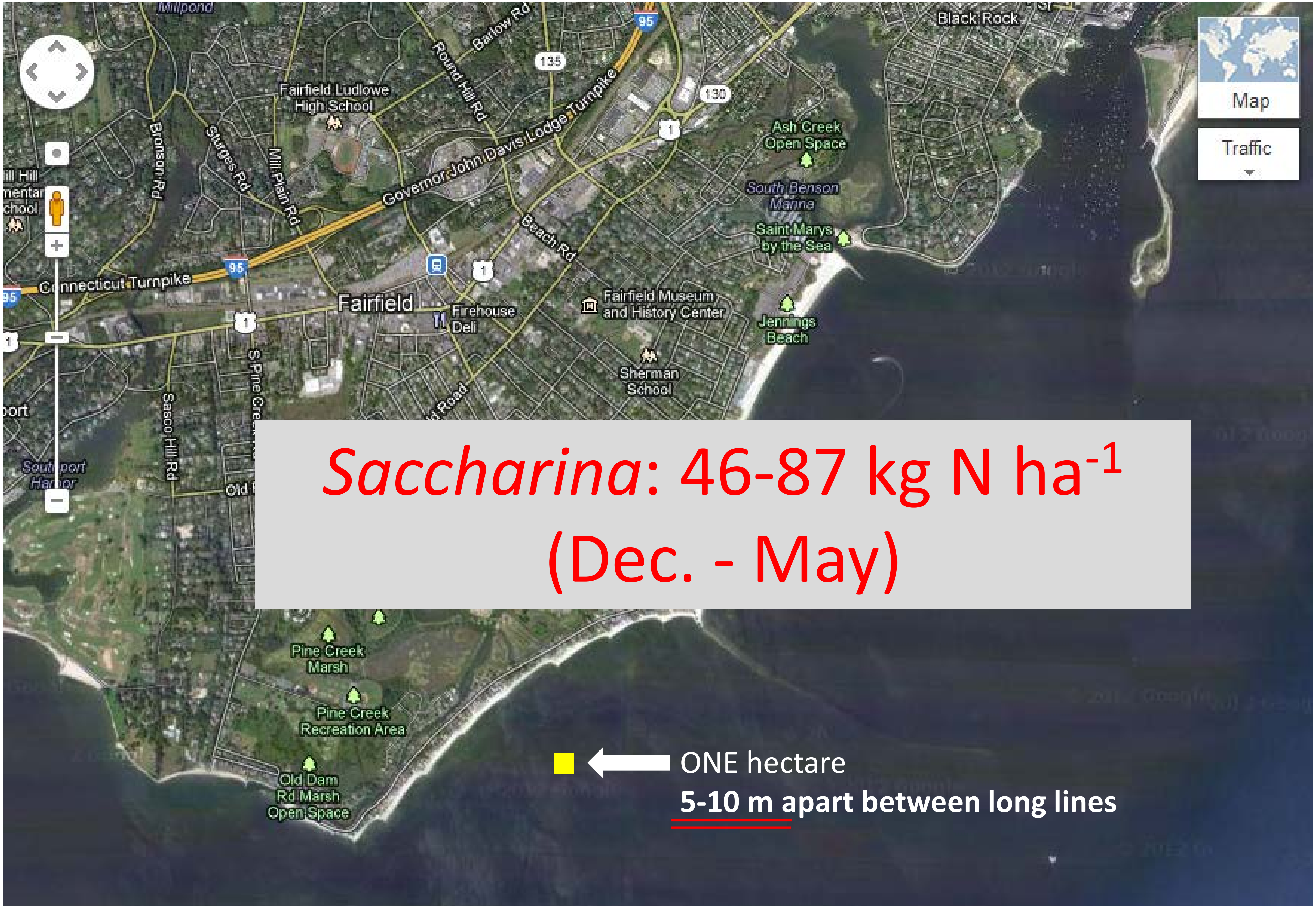
~ 1,752 kg per 100 m longline
(Dec. – May growing season)

Kim et al. 2015, Marine Ecol. Prog. Series

Productivity (sugar kelp)

*19.3 – 36.8 MT FW ha^{-1}
(Dec. – May growing season)

* Assumption: 5-10 m spacing between longlines

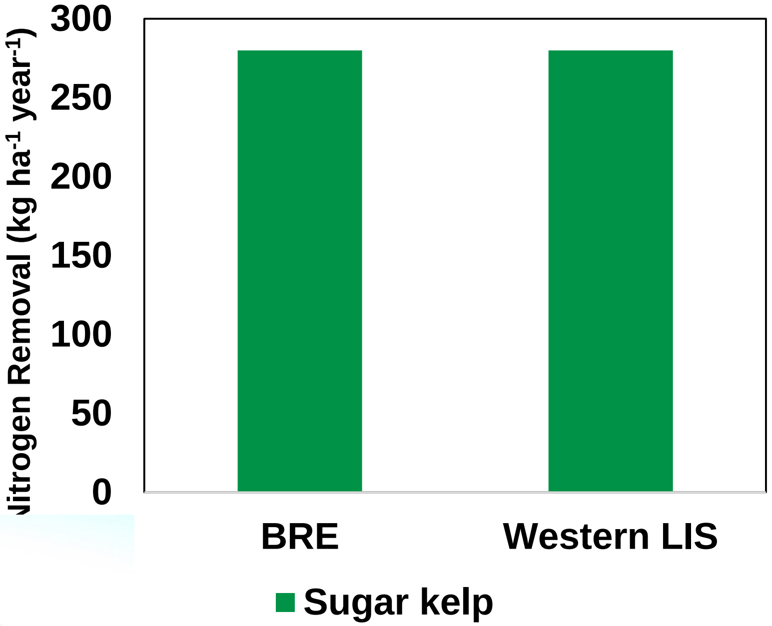


Saccharina: 46-87 kg N ha^{-1}
(Dec. - May)

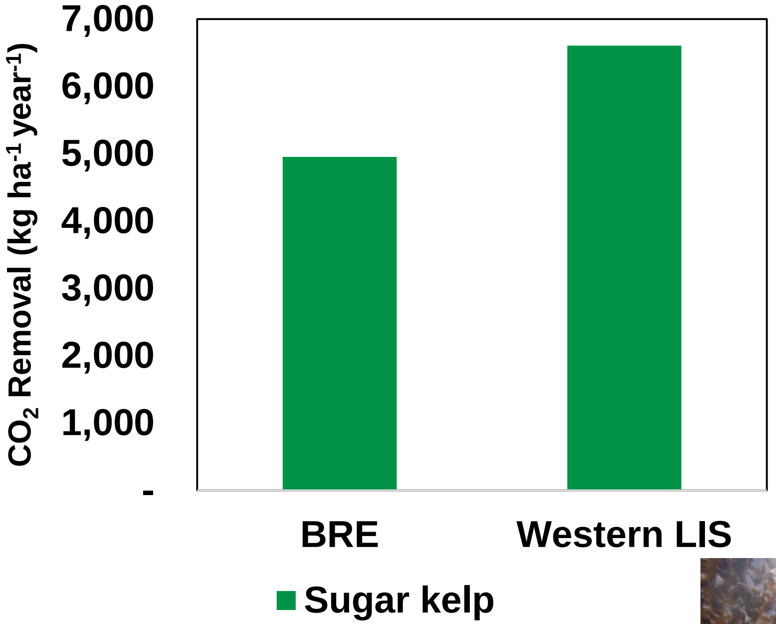
ONE hectare
5-10 m apart between long lines

Nutrient Bioextraction by Kelp

Nitrogen Removal



CO_2 Removal



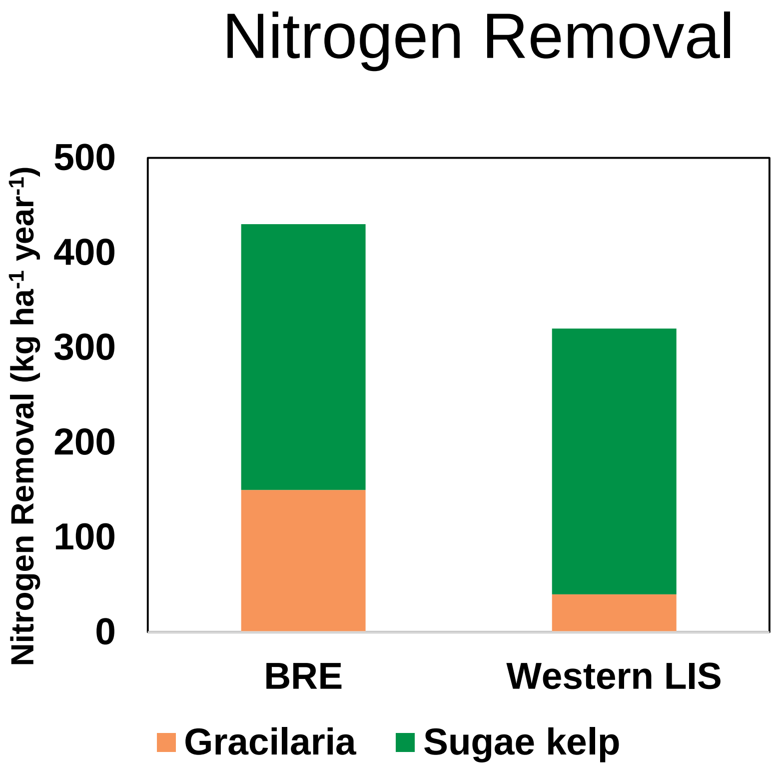
Kim et al. 2015, Marine Ecol. Prog. Series

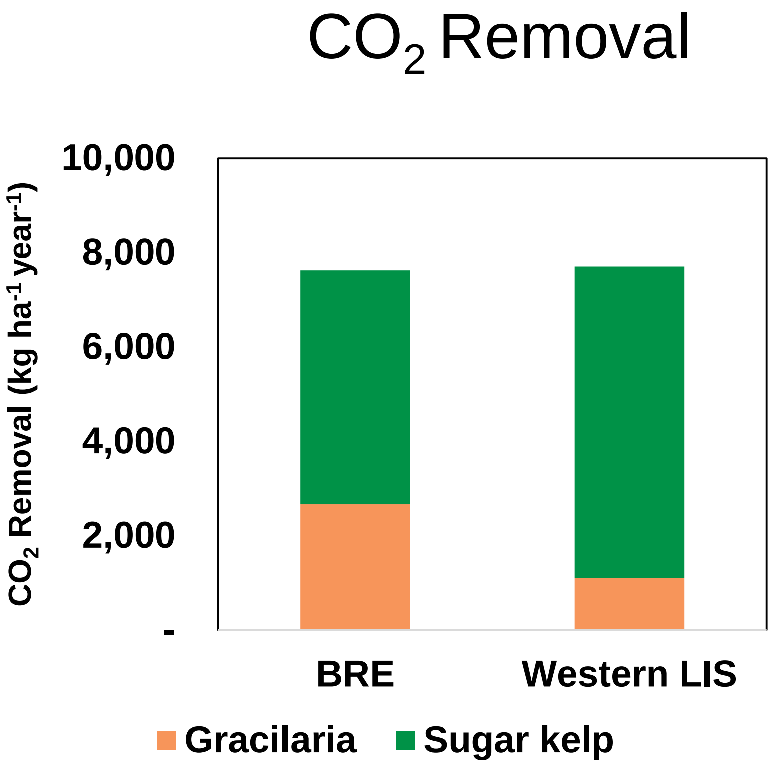
Estimated LIS Production Potential for *Saccharina*

Suitability Level	*Hectares*	*Annual Production (wet weight, t/y)*
Not Suitable	81,795.00	0.00
Suitable	61,566.10	1,188,225.73
On Eastern Beds (State-managed)	8,875.40	171,295.20
TOTAL	**70,441.49**	**1,359,520.93**

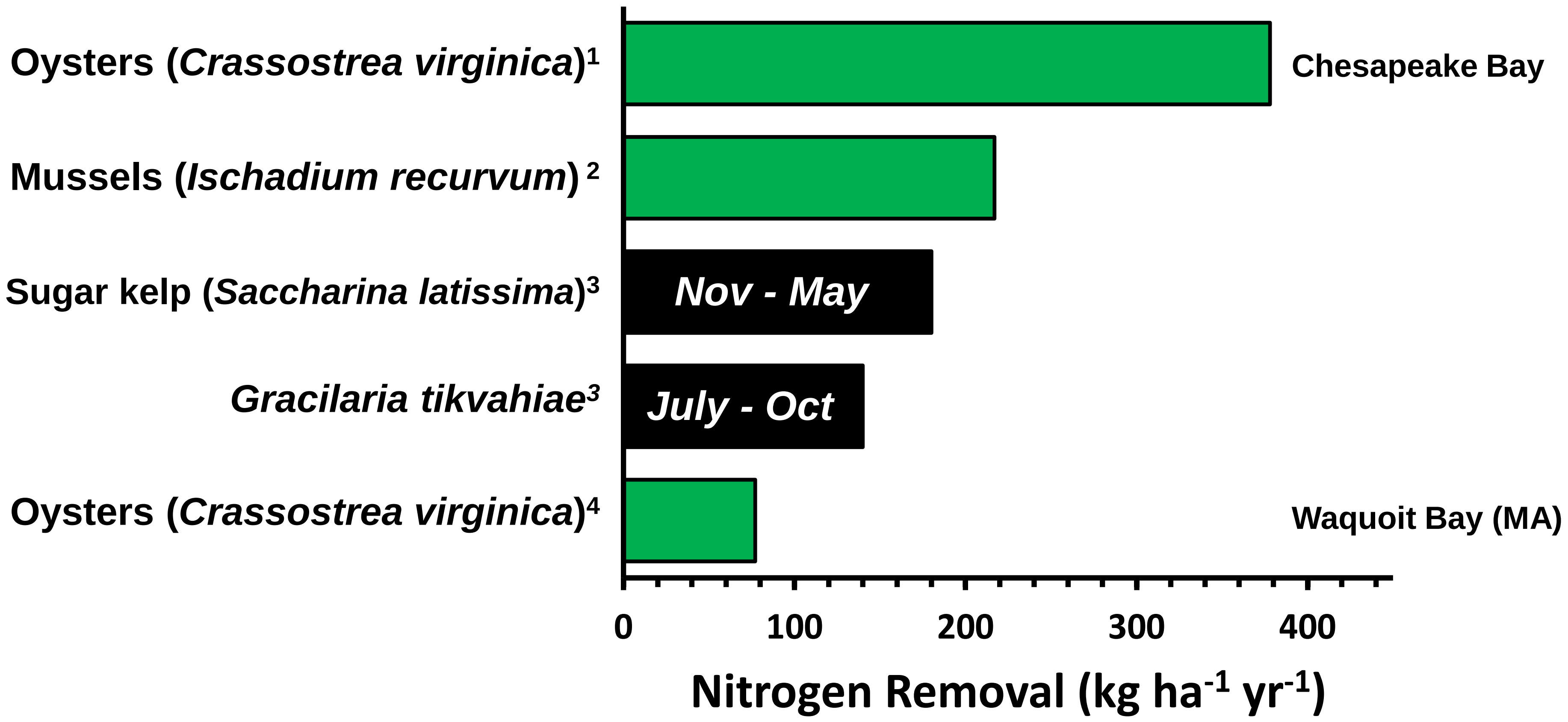
Kelp
18 kg FW per meter
10 meters between longlines
19.3 tons/ha/year

Nutrient Bioextraction by Seaweeds





Nutrient bioextraction: comparison



[1]Higgins et al. (2011)
[2]Kellog et al. (2013)
[3]Kim et al. (2014, 2015)
[4]Kite-Powell et al. (2006)

Aquaculture 433 (2014) 148–156
Contents lists available at ScienceDirect
Aquaculture
journal homepage: www.elsevier.com/locate/aqua-online

Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary

Jang K. Kim [a,*], George P. Kraemer [b], Charles Yarish [c]
[a] Department of Marine Sciences, University of Connecticut, 1 University Place, Stamford, CT 06901
[b] Department of Environmental Studies, Purchase College, 735 Anderson Hill Road, Purchase, NY 10
[c] Department of Ecology and Evolutionary Biology, University of Connecticut, 1 University Place, St

Vol. 531: 155–166, 2015
doi: 10.3354/meps11331
MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser
Published July 2

Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction

Jang K. Kim[1,*], George P. Kraemer[2], Charles Yarish[3]
[1]Department of Marine Sciences, University of Connecticut, 1 University Place, Stamford, CT 06901, USA
[2]Department of Environmental Studies, Purchase College, 735 Anderson Hill Road, Purchase, NY 10577, USA
[3]Department of Ecology and Evolutionary Biology, University of Connecticut, 1 University Place, Stamford, CT 06901, USA

ALGAE
29(3): 227-235
.org/10.4490/algae.2014.29.3.227

...of Gracilaria tikvahiae grown in urbanized ... New York City, USA: a preliminary ... alternative fish feeds

...ster[1] and Charles Yarish[3]
...hwest Fisheries Science Center, National Marine
...iversity Place, Stamford, CT 06901, USA
...icut, One University Place, Stamford, CT 06901,

...019) 260–271
ScienceDirect
...loids
.../locate/foodhyd
Food Hydrocolloids

...tivated for nutrient

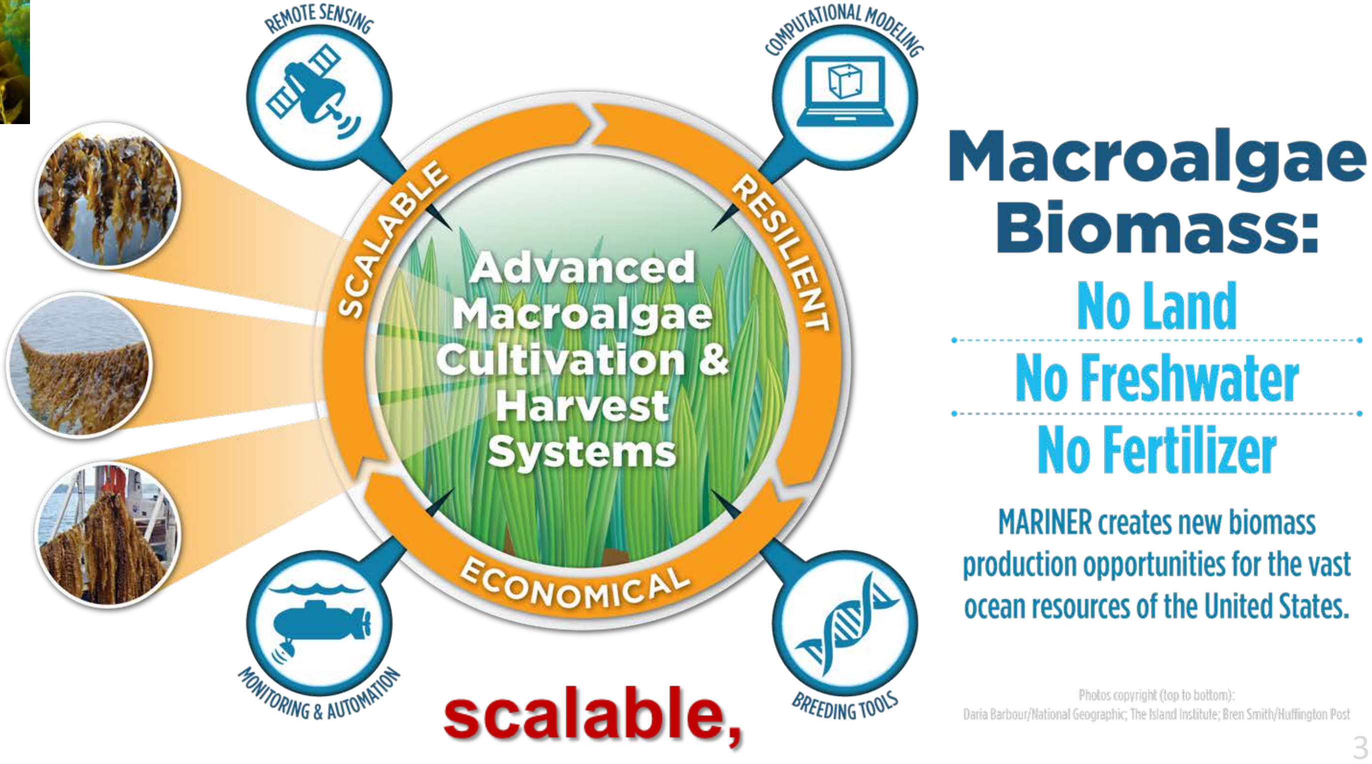
...galves[a], Jang K. Kim[c,d,e], Júlia M.C.S. Magalhães[a],
...Química, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465, Porto, Portugal
...& Evolutionary Biology and Marine Sciences, University of Connecticut-Stamford, 1 University Place, Stamford, CT, 06901, USA
...ience, School of Natural Sciences, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon, 22012, South Korea
...Sciences, Incheon National University, 119, Academy-ro, Yeonsu-gu, Incheon, 22012, South Korea

Algal Researc...
Contents lists av...
Algal...
journal homepage: www.elsevier.com/locate/algal

Evaluation of the metal content of farm grown *Gracilaria tikvahiae* and *Saccharina latissima* from Long Island Sound and New York Estuaries

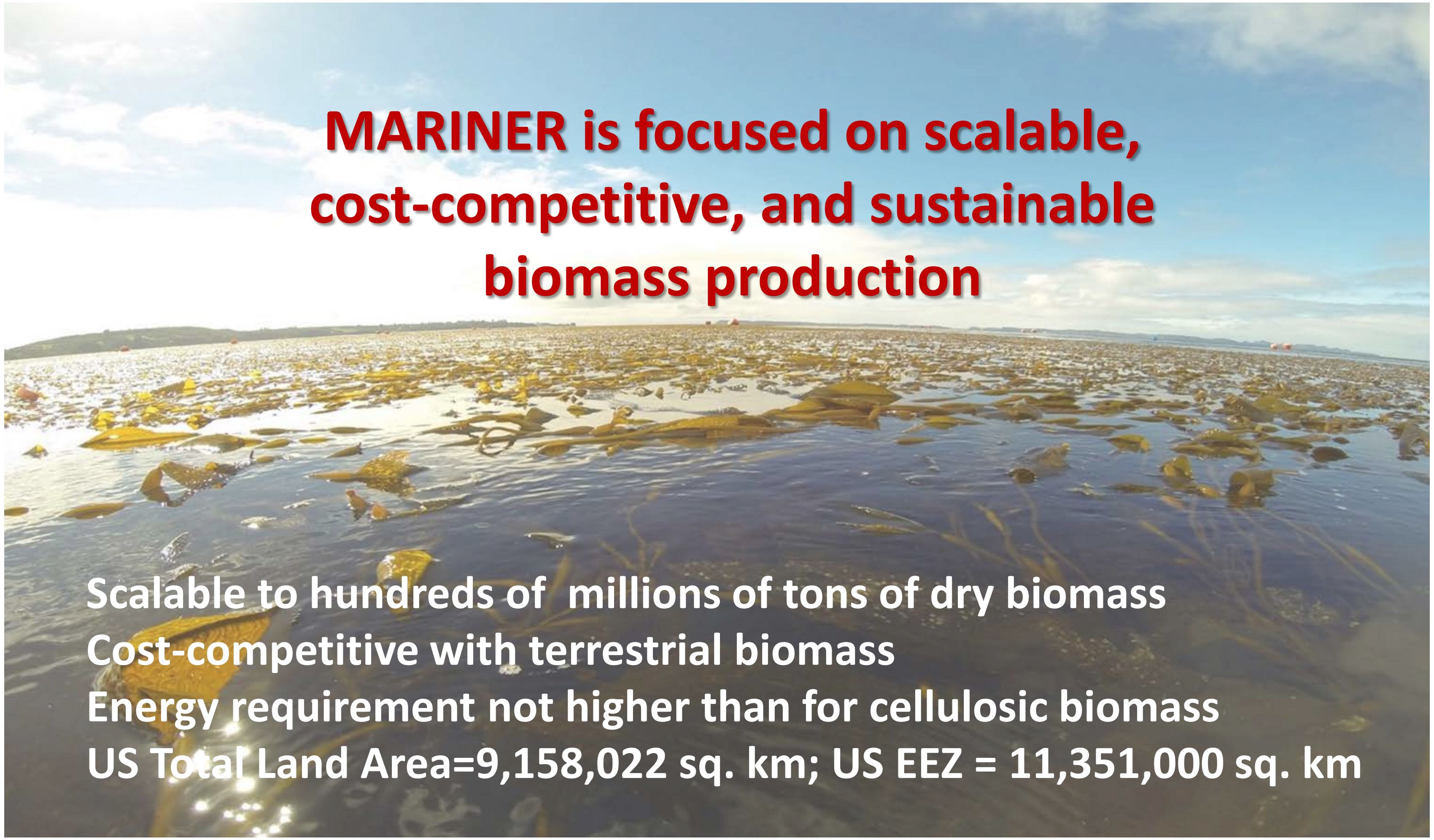
Jang K. Kim[a,b,*], George Kraemer[c,**], Charles Yarish[b]
[a] Department of Marine Science, School of Natural Sciences, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea
[b] Departments of Ecology & Evolutionary Biology and Marine Sciences, University of Connecticut-Stamford, 1 University Place, Stamford, CT 06901, USA
[c] Department of Environmental Studies, Purchase College, 735 Anderson Hill Road, Purchase, NY 10577, USA

The ARPA-E MARINER Program (MacroAlgae Research Inspiring Novel Energy Resources ~ $62 Million, 20+ projects)



scalable, cost-competitive, and sustainable biomass production

Courtesy of ARPA-E



MARINER is focused on scalable, cost-competitive, and sustainable biomass production

Scalable to hundreds of millions of tons of dry biomass
Cost-competitive with terrestrial biomass
Energy requirement not higher than for cellulosic biomass
US Total Land Area=9,158,022 sq. km; US EEZ = 11,351,000 sq. km

ARPA-E estimates the United States has suitable conditions and geography to produce at least 500 million dry metric tons of macroalgae per year. Such production could yield ~10% of the nation's annual transportation energy demand.

Courtesy of ARPA-E

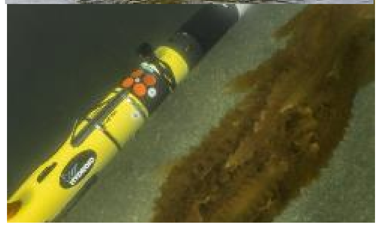
Technical Barriers for Macroalgae

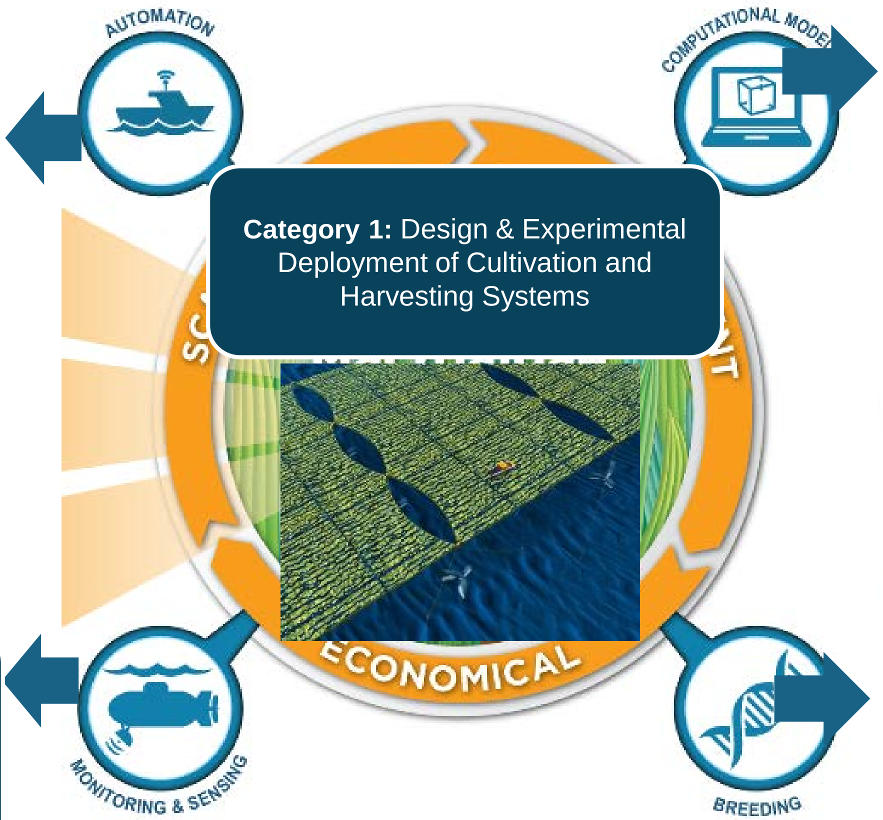
Courtesy of ARPA-E

- To be market relevant it is necessary to dramatically **increase the scale** of biomass production.
- To reach the necessary scales macroalgae farms must move offshore. This requires farm structures that can **survive open-ocean conditions**.
- This requires a **fundamental change** to the way farm structures are **designed, manufactured, and operated.**
- Macroalgae farms need to **maximize their biomass yield** to optimize the structures that are deployed.
- To reduce costs, **increased automation**, biomass **sensing**, and remote diagnosis tools are needed.

MARINER Program Structure

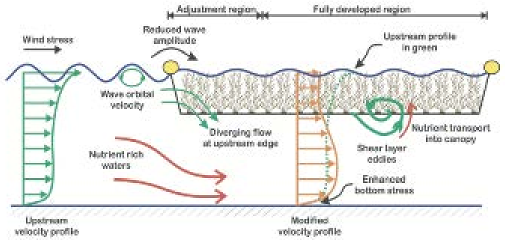
Category 2: Design & Experimental Deployment of Critical Component Technologies





Category 1: Design & Experimental Deployment of Cultivation and Harvesting Systems

Category 3: Development & Validation of Computational Modeling Tools



Category 4: Design & Deployment of Aquatic Monitoring Technology and Tools

Category 5: Research & Development of Breeding and Genetic Tools

Courtesy of ARPA-E

MARINER Tech-to-Market: Where are the Opportunities?

Human
- Whole foods
- Nutraceuticals
- Proteins*
- Hydrocolloids

Energy and Industrial Products
- Biogas via anaerobic digestion*
- Biofuel via HTL or fermentation
- Chemicals and Intermediates

Animal Health & Nutrition
- Ruminants
- Monogastrics

Ecosystem Services
- **Nutrient uptake**
- Local deacidification
- Wave attenuation
- Carbon storage
- Fertilizers*

*** Coproduct Opportunities: Prior to anaerobic digestion to biogas/ other chemicals, higher value compounds (e.g., proteins) can be extracted. Digestion residue can be used as fertilizer rich in P, K and possibly N**

Courtesy of ARPA-E

Development of Scalable Coastal and Offshore Macroalgal Farming

Project Vision

Develop replicable farm system for seaweed production that when combined with innovative seed planting and harvesting technologies results in affordable biomass production

Project Impact

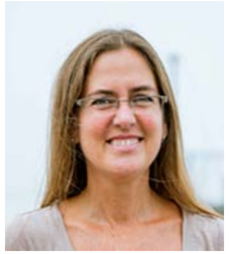
An affordable pathway to produce temperate kelps at a scale that will have meaningful impact on both near-term seaweed mariculture practices and future US energy needs

Project Team

PI - Michael Stekoll
University of Alaska
msstekoll@alaska.edu

<u>Co-PIs, Partner Organizations</u>
Scott Lindell, WHOI slindell@whoi.edu
Hauke Kite-Powell, WHOI
Bren Smith, GreenWave
Clifford Goudey, C.A. Goudey & Assoc.
Loretta Roberson, MBL
Beau Perry, Blue Evolution
Charles Yarish, University of Connecticut
David Fredriksson, US Naval Academy
Andrew Drach, Callentis Consulting Group
Julie Decker, Alaska Fisheries Development Foundation
Stefan Kraan, Aquaceuticals
+ farmers in AK







Project Team – the kelp farmers

Nick Mangini
Kodiak Island Sustainable Seaweed

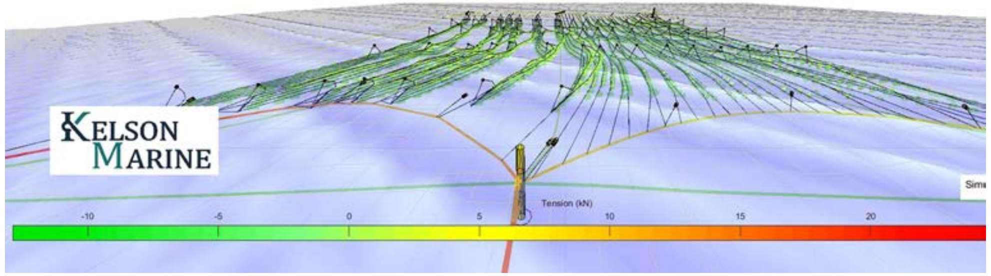
Alf Pryor
Kodiak Kelp Co.

Kim J.K., Stekoll M., and Yarish C. 2019. Opportunities, challenges and future directions of open water seaweed aquaculture in the United States. Phycologia 58 (5): 446-461; https://doi.org/10.1080/00318884.2019.1625611)

Michael Stekoll, University of Alaska

Technology Progress in Alaska

- Improved seeding techniques; away from meiospores
- Improved modeling to aid with farm design
- Modification of farm (18,300m-60,000’)
  - Doubling the length of growlines
  - Variable spacing of growlines
  - Adding flotation
  - Addition of tensioning deadeyes
- New Harvest Methods
  - Use of harvest bags
  - “Kelp Buddy”
  - Large vessel modifications



Comparison Between Years

	2019-20	2020-21	% Change
Growing Days (days)	211-236	191-217	-8.7
Farm Size			
Between Spar Buoys (ha)	0.77	1.35	+75
Anchor Footprint (ha)	5.05	7.46	+48
Amount of Growline (m)	3,323	7,622	+129
Harvest Yield (kg)	26,751	39,284	+47
Estimated Harvest Yield (kg)	26,751	55,232	+106
Yield per Meter (kg/m)	8.2	7.37	-10
Yield per Hectare			
Between Spar Buoys (kg/ha)	34,742	*40,912*	+18
Anchor Footprint (kg/ha)	5,297	*7,404*	+40

TEA Output

Growth rate, dry content have the largest impact on biomass yield and cost. Second tier factors are grow-line length and crew costs.

Path to $80/dry tonne:

- Increase wet harvest yield per meter
  - Breeding (ref. Cat 5 project)
  - Grow rope diameter
- Increase dry content
- Increase harvest efficiency

Selective Breeding Technologies for Scalable Offshore Seaweed Farming

Advanced Research Projects Agency • ENERGY

PI – Scott Lindell
Woods Hole Oceanographic Institution

Project Vision

Develop tools to identify and breed superior sugar kelp cultivars, improving productivity 10 to 20% per generation.

Project Impact

Tools and methodologies created and tested will be broadly applicable to rapid improvement of seaweed breeding and cultivation in the U.S.

C.A. Goudey & Associates

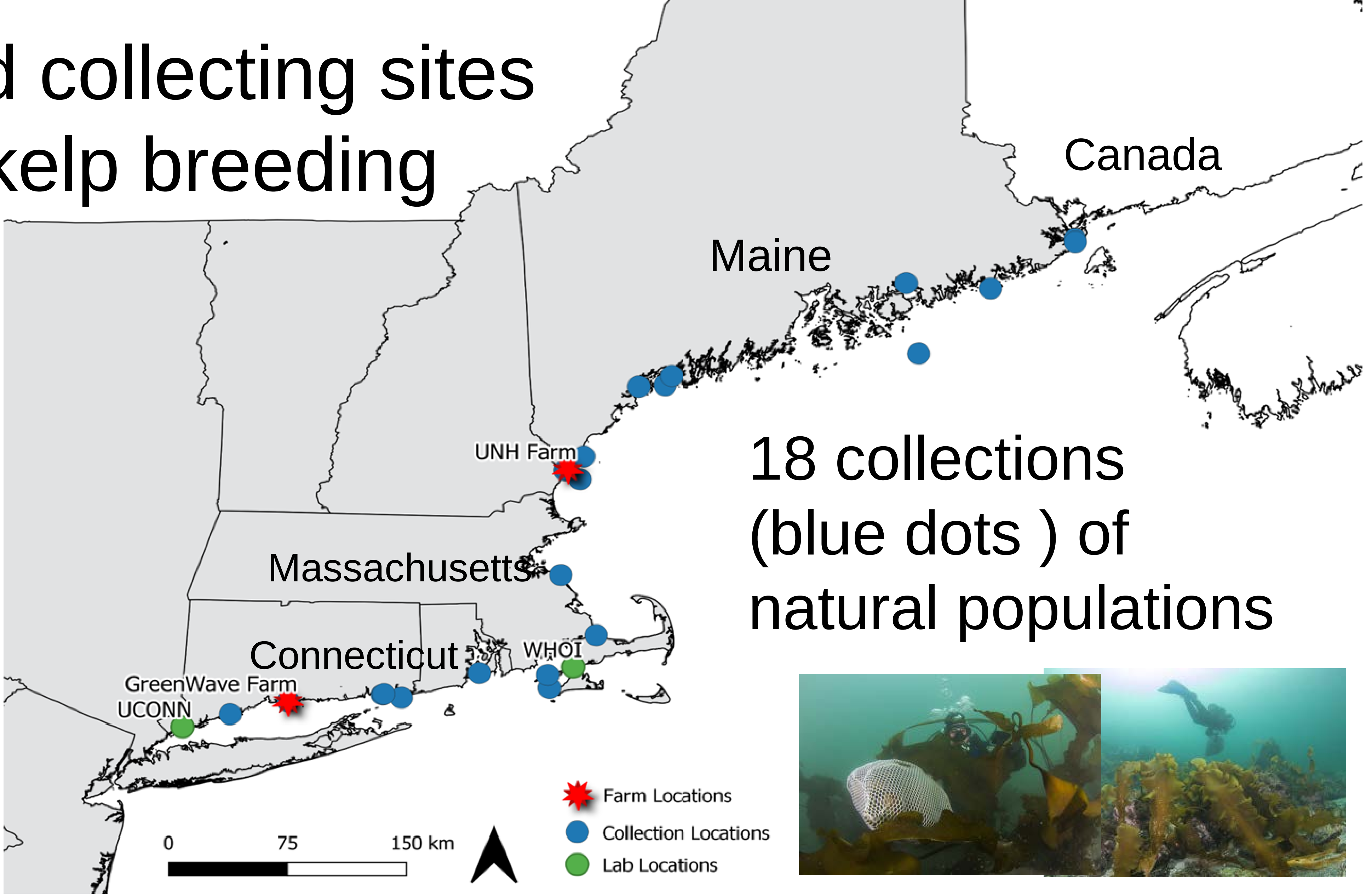
Marine Biological Laboratory Woods Hole

University of Alaska
USDA/ Cornell University
HudsonAlpha, NOAA Fisheries NEFSC

UCONN

GreenWave

Wild collecting sites for kelp breeding



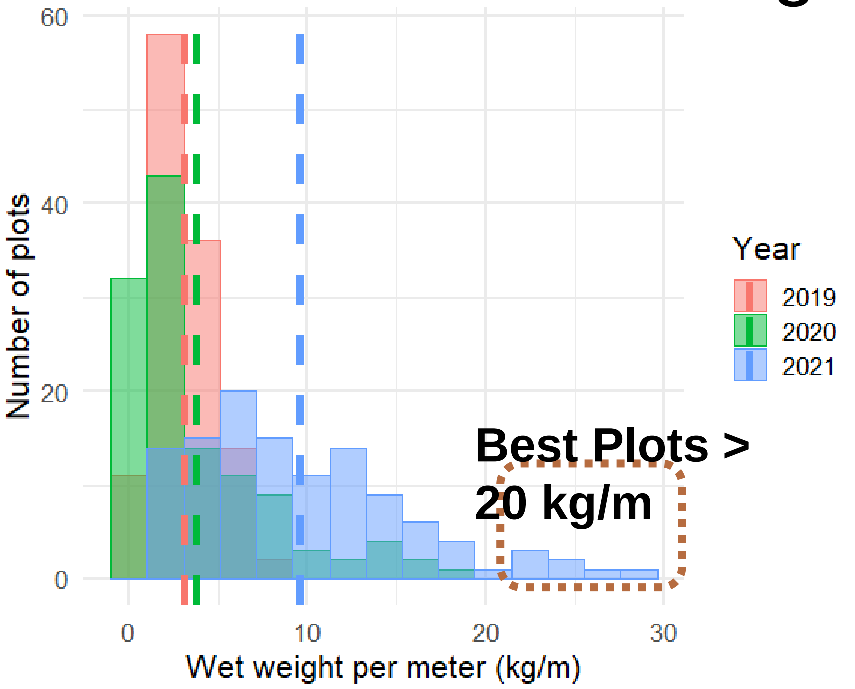
18 collections (blue dots) of natural populations

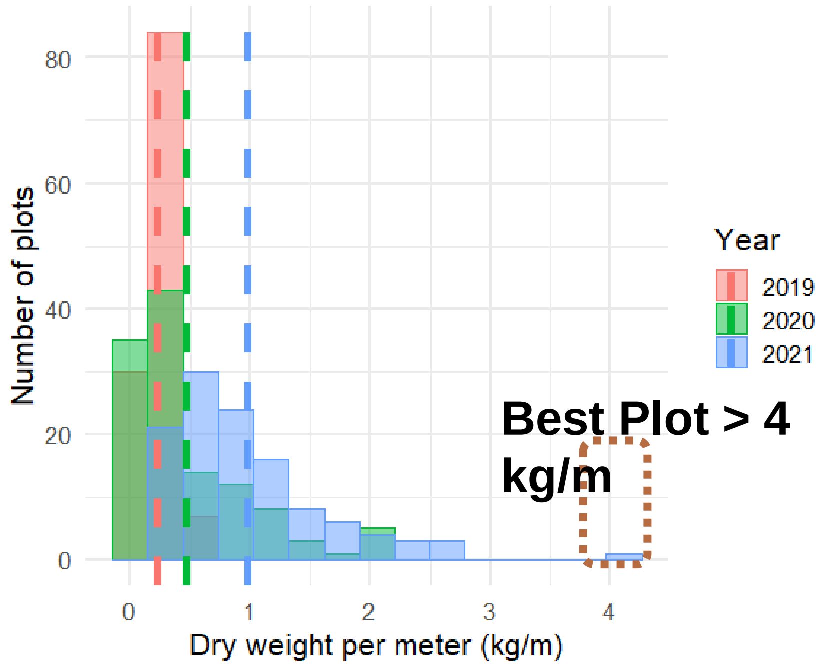
Mao, X., Augyte, S., Huang, M., …(2020). Population genetics of sugar kelp in the Northwest Atlantic region using genome-wide markers. Front. Mar. Sci., 21 August 2020 | https://doi.org/10.3389/fmars.2020.00694 .

Multi-seasons farm testing

- 2018-2019 random crosses to cover diversity
- 2019-2020 random crosses to cover diversity
- **2020-2021 crosses made based on the prediction from the genomic selection model**
- >300 Crosses were made for the Gulf of Maine farm (GOM) located in Newcastle, New Hampshire. All crosses were made from isolates derived from GOM.
- >80 Crosses were made for the Southern New England farm (SNE) located in Connecticut and derived from SNE.
- The GOM performed better than SNE

Yield Traits: Wet Weight and Dry Weight (kg/m)





> 2 X Commercial Average

Top Ranked Plot

28 kg/m wet wt.

4 kg/m dry wt.

Harvesting at UNH

Phenotyping-Tissues

- **CHN** Analyses

- **Sugar** Analyses (Total Sugars, Fucose, Mannitol, Glucose, Xylose, Mannose, Arabinose, Galactose, Rhamnose, Glucuronic Acid, Galacturonic Acid, Mannuronic Acid, Guluronic Acid)

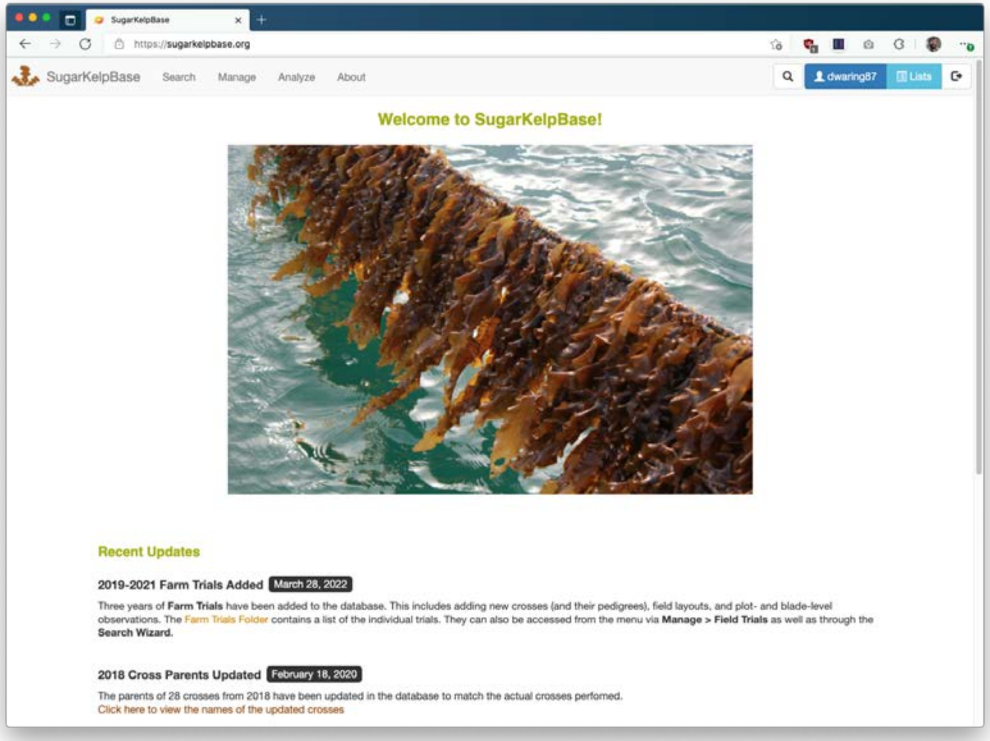
- **Proximate** Analysis (Moisture, Protein, Fat, Fiber, Ash)

- **Ash** Analyses

-

- **Elements** (B, Na, Mg, Al, P, S, K, Ca, Fe, Mn, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, Cd)

Database construction



SugarKelpBase
https://sugarkelpbase.org

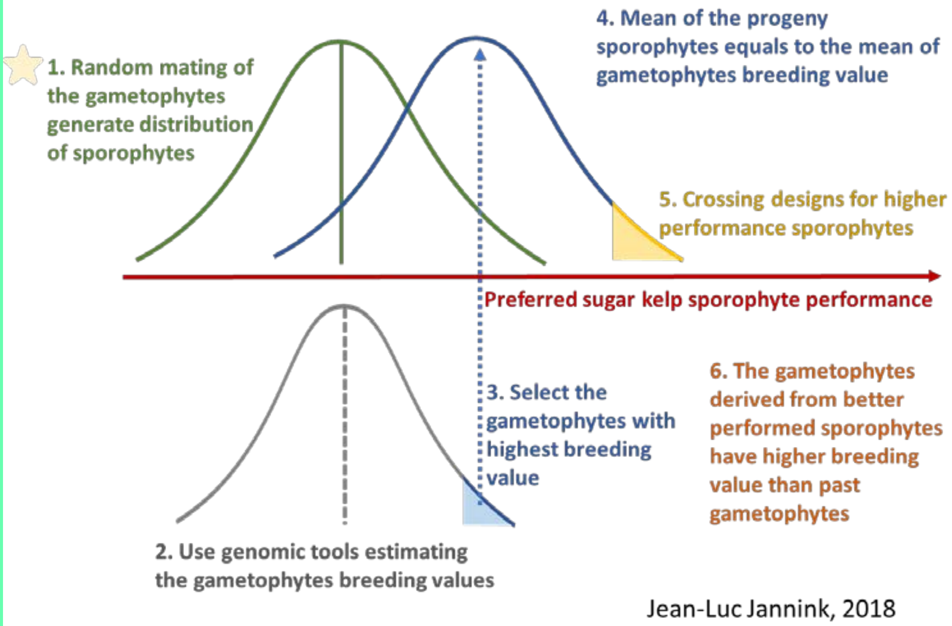
A comprehensive breeding database and website powered by Breedbase

Contains information about:

- Germplasm
- Locations
- Farm trials
- Founder population collections
- Gametophyte maintenance
- Phenotypic characteristics

Future work on the genomic tools

- Improve the genomic prediction model
- Increasing the gametophytes collections
- Improved database, genotypic and phenotypic data
- High yield strains
- GWAS
- Marker development



Seaweed Bio-refinery

Courtesy: J. Forster

Bio-active compounds

Human food – fresh or dried

Hydrocolloids mannitol, other carbohydrates

Minerals

Protein, fats, other nutrients

Animal and aquaculture feeds

Biochemical feed-stocks (Bio-plastics)

Fermentation to Bio-fuel

Biomass > feed

Soil conditioner

Waste



What’s Next in Coastal Management?
Bioextraction technologies

In nutrient rich coastal waters (LIS) we can use extractive organic aquaculture of shellfish and extractive inorganic aquaculture of seaweed to provide invaluable ecosystem services and produce unique suite of commodities!

Acknowledgements

- **U.S. Dept. of Energy ARPA-E (Contracts: DE-AR0000912; DE-AR0000911; and DE-AR000915)**
- Connecticut, Maine & MASS Sea Grant College Programs
- NOAA SBIR I and II (Ocean Approved)
- U.S. EPA Long Island Sound Study's Long Island Sound Futures Fund, National Fish and Wildlife Foundation
- Maine Aquaculture Innovation Center
- U.S. Department of Agriculture, National Institute of Food and Agriculture (NIFA)