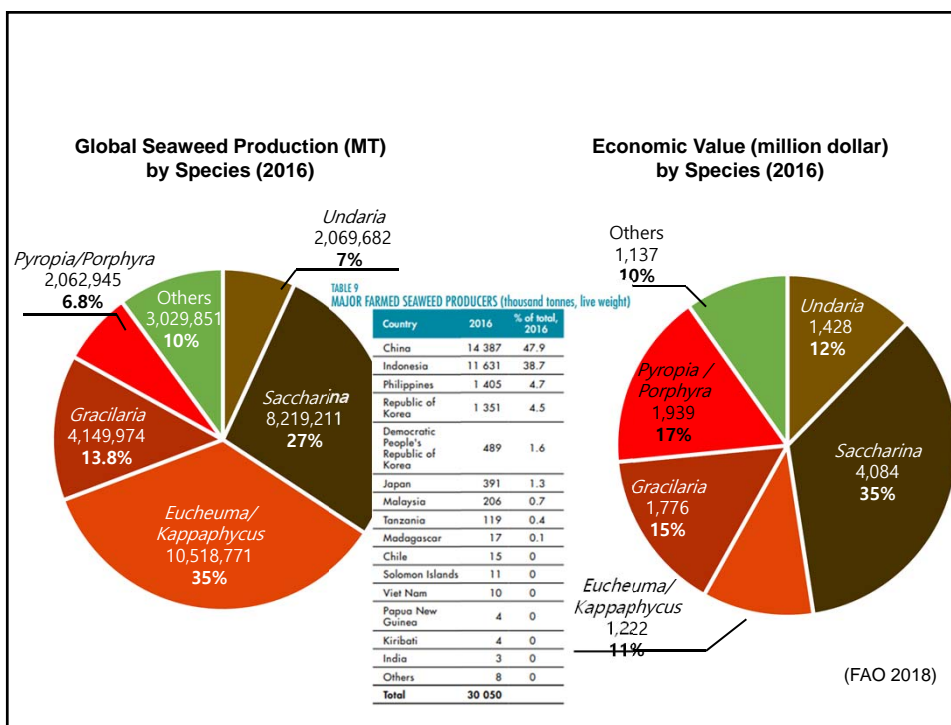


FOOD, FEEDS, FERTILIZERS AND BIOFUELS - OPPORTUNITIES, CHALLENGES AND FUTURE DIRECTIONS OF OPEN WATER SEAWEED AQUACULTURE IN THE USA.

Charles Yarish*¹

S. Lindell, M. Stekoll, J. K. Kim,
J. Zertuche, S. Umanzör, S.
Augyte, J. Kübler, D. Bailey, J-L.
Jannink, M. Huang, B. Smith, K.
Barbery, L. Roberson, C.A.
Goudey,
D. Mangelli, H. Kite-Powell,
E. Ask & B. Perry

¹University of Connecticut
charles.yarish@uconn.edu



Uses of Seaweeds

- Food
- Feed
- Fertilizer
- Medicine
- Cosmetics
- Textile
- Paper
- Leather
- Major sources of phycocolloids
(alginates, carrageenans & agars)
- Biofuels



Alginates are hydrocolloidal products used for thickening, suspending, stabilizing or gel-forming from kelp (*Saccharina* & *Laminaria*) and fucoids (*Ascophyllum* & *Fucus*).

Ice Cream, Salad Dressing, Cosmetics,
Latex Paint, Textiles, Paper, Ceramics,
Dentistry, Regulates water behavior, &
Biodegradable plastics



- **Agar** (hydrocolloid = phycocolloid)
 - Produced by red alga *Gelidium* & *Gracilaria*.
 - Solidifier of nutrient culture media for growth of bacteria; biotechnology; foods.

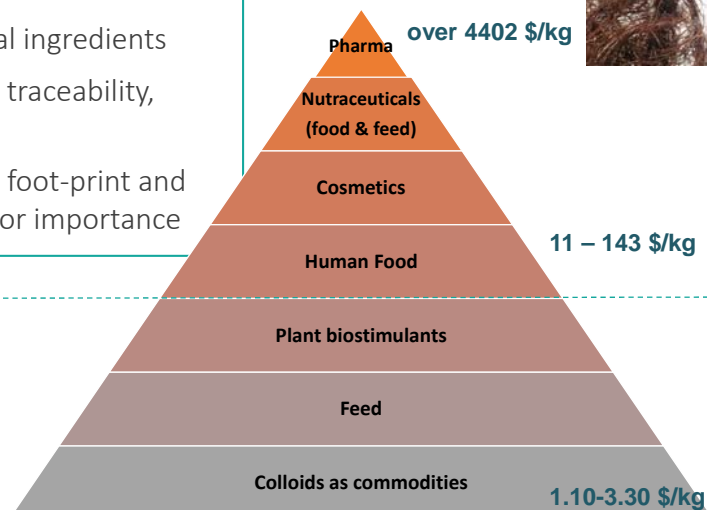


OPPORTUNITY: There is a need for farmed seaweed because

wild harvested can't meet market demand for "high-quality."

WESTERN HIGH VALUE INDUSTRIES

- ✓ Seek for natural ingredients
- ✓ Quality, safety, traceability, standardization
- ✓ Environmental foot-print and origin are of major importance



Courtesy of ALGA+

WHY START WITH FOOD

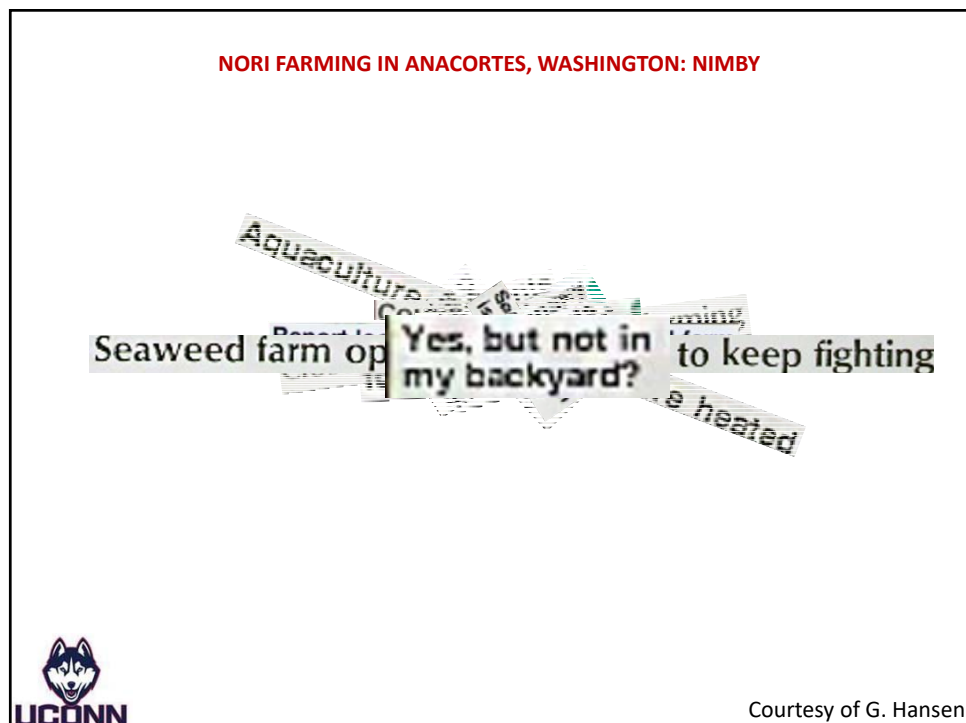
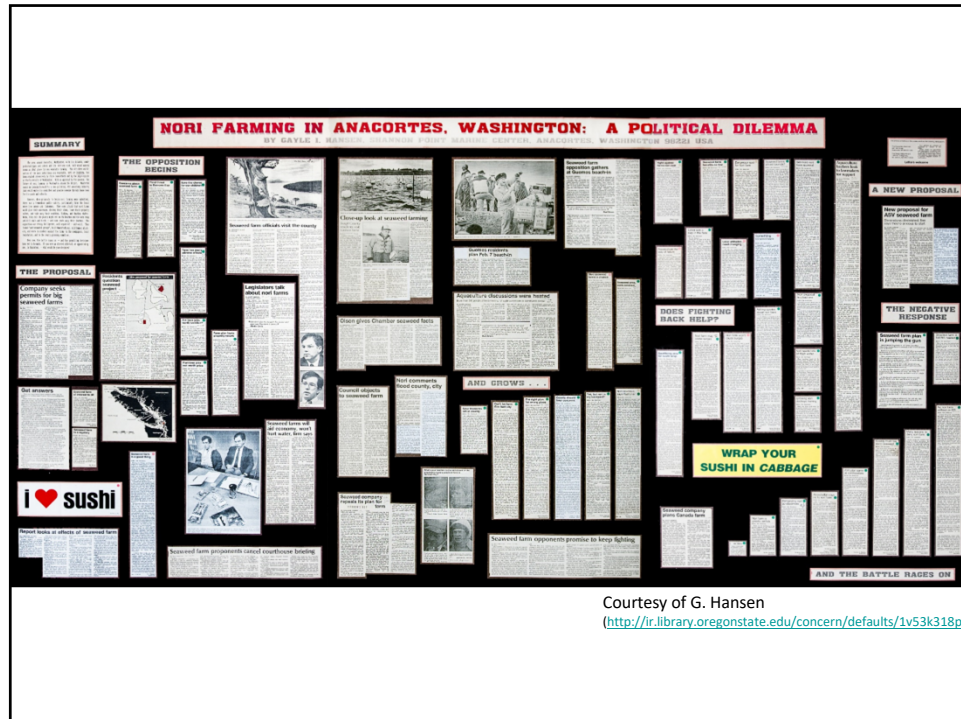
CURRENT FOOD TRENDS

- 1) More and diversified foods produced with high environmental sustainability standards;
- 2) Adoption of healthy food habits:
 - 1) more vegetables
 - 2) reducing animal fat intake
 - 3) reducing salt, sugars
- 3) Food products customised to target consumers needs:
 - 1) nutritional daily routines and convenience
 - 2) organoleptic features in line with the normal diet



Courtesy of Blue Evolution

Courtesy of ALGA+



Obstacles to the Growth of Seaweed Aquaculture in the USA

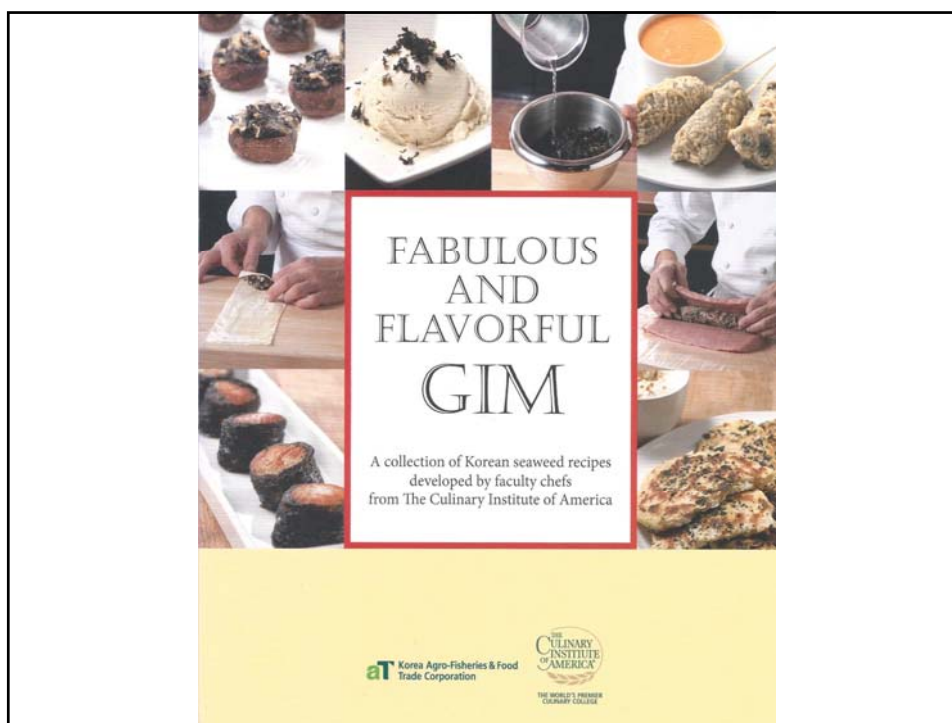
- Coastal zone use conflicts
- ✓ The Social License from the Public to Support Permitting
 - ✓ Nutrient bioextraction, water quality improvement, habitat restoration, new habitat & diversity enhancement
- Permit, licensing, lease application processes
- Compliance with environmental regulations
- ✓ Cost effectiveness of the aquaculture (culture & breeding technologies)
- ✓ Processing
- ✓ Food safety (development of science to inform regulatory agencies)
- ✓ Workforce Development (The working waterfront)

Nutritional Value of *Pyropia*

100 g of this sea vegetable provides:

- 30 – 50 g protein
- Vitamin – A (12,500 I.U)
- Vitamin – B₂ (2.95 mg)
- Vitamin – B₁₂ (0.06 mg)
- Vitamin – C (93 mg)





Sea Vegetable, Gim (Laver)

- Global Sea Food Exported to 109 Countries
- Best Vegetable in Vitamin Contents

※ Comparison of vitamin content in some vegetables

(In 100g dry weight)

Vegetables	Vitamin A (I.U.)	Vitamin B1 (mg)	Vitamin B2 (mg)	Niacin (mg)	Vitamin C (mg)
Undaria	1,850	0.26	1.00	4.5	18
Saccharina	320	0.22	0.45	4.5	18
Pyropia (Gim/laver)	12,500	1.20	2.95	10.4	93
Tomato	200	0.08	0.03	0.3	20
Spinach	2,600	0.12	0.30	1.0	100

Modern *Pyropia* (nori) cultivation



Porphyra/Pyropia species

- Simple, flat sheet gametophyte (high SA/V)
- 1-2 cell layers: all productive
- fast growth (up to 24% d⁻¹)
- high nutrient accumulation (possibility of 6-8% N DW)
- high protein content (up to 50% DW)
- salable harvest (nori, high-value r-phycoerythrin)



Nori

Nursery culture or Ikada System (courtesy of I. Levine)

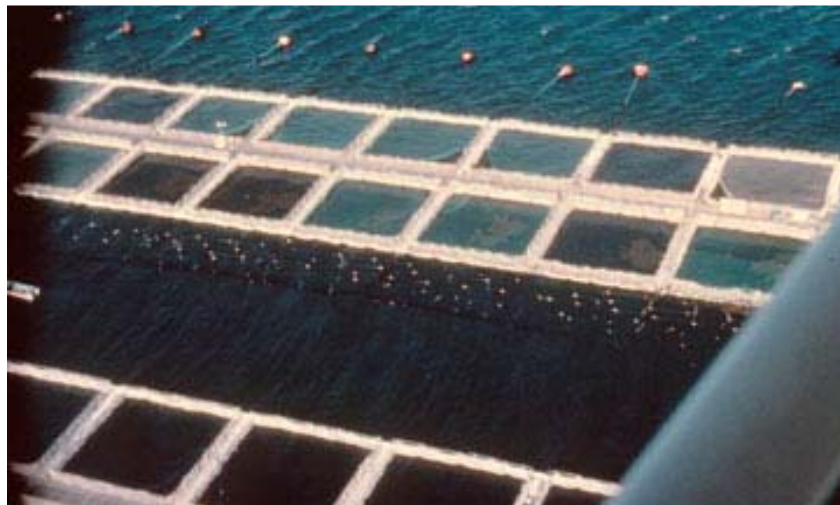


High vs Low Nutrients



If *Porphyra*/*Pyropia* requires all of the nutrients (CO_2 , NH_4 and PO_4) that fish produce as waste products, why not grow them together?

***Porphyra/Pyropia* – Salmon**



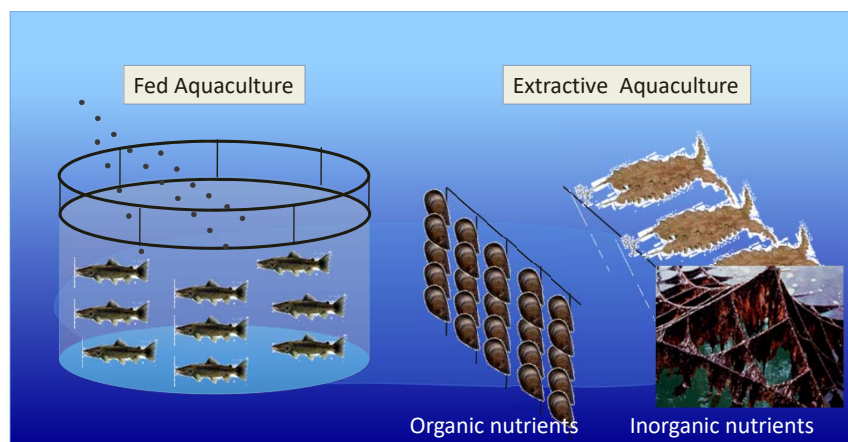
(courtesy I. Levine)

“Balanced” Ecosystem Approach (IMTA)

- Ackefors (1999, pers. comm.)
 - 7.0 kg of P and 49.3 kg of N released into the water column per ton of fish per year
 - How many ***Porphyra/Pyropia*** nets are necessary for the bioremediation of this nutrification of coastal waters?
 - 27 nets for P
 - 22 nets for N

(McVey *et al.* 2002)

Integrated Multi-Trophic Aquaculture (IMTA-1990s)

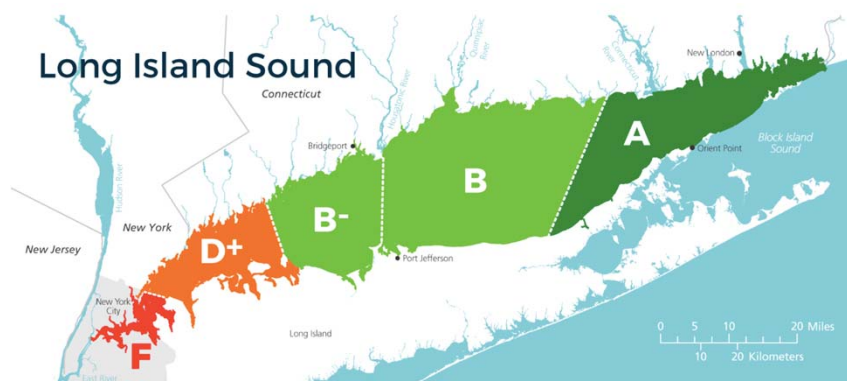


- Mitigates nutrification of marine environment

Courtesy of I. Bricknell

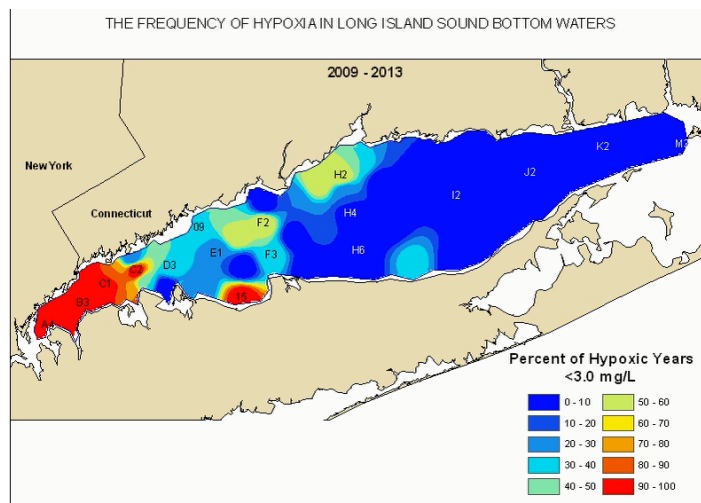
History of Seaweed industry (2010 - present)

- Ecosystem services approach to overcome NIMBY



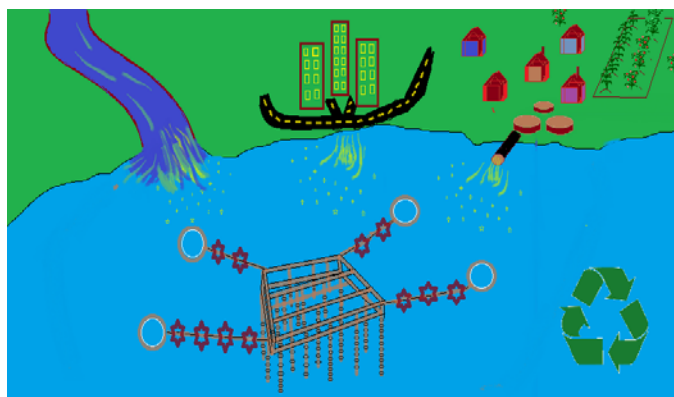
History of Seaweed industry (2010 - present)

- Ecosystem services approach to overcome NIMBY



History of Seaweed industry (2010 - present)

- Ecosystem services approach to overcome NIMBY
- Nutrient Bioextraction

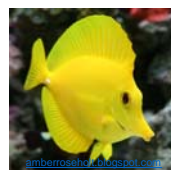
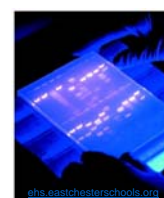
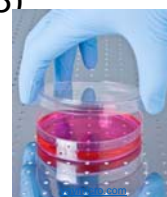




Gracilaria spp.

Uses (~ \$1.78 billion annual value, FAO 2018)

- Agar (multiple grades)
- Fresh Sea Vegetable
- Animal Feeds (fish, shrimp)
- Ornamental Marine Plants
- Fertilizer
- Potential as Antiviral Pharmaceutical
- Biofuels



Gracilaria tikvahiae (red seaweed, a summer crop)*

- Growing season: June – Oct. ($> 15^{\circ}\text{C}$)
- Commercial value of *Gracilaria* ~ \$1.78 billion annual value, FAO 2018



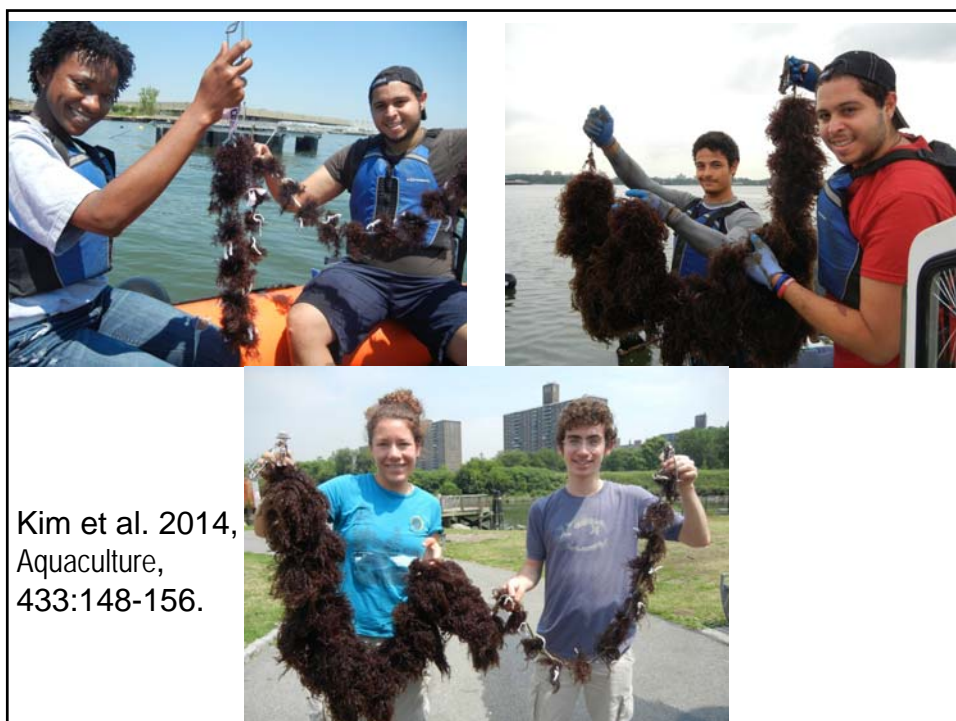
Rocha et al. 2019. Characterization of agar from cultivated *Gracilaria tikvahiae*:... Food Hydrocolloids 89:260-271. <https://doi.org/10.1016/j.foodhyd.2018.10.048>.

Gracilaria nursery systems



Redmond, S., L. Green, C. Yarish, J. Kim, and C. Neefus. 2014. *New England Seaweed Culture Handbook-Nursery Systems*. Connecticut Sea Grant CTSG-14-01; R/A 38. 93 pp. PDF file. URL: <http://digitalcommons.uconn.edu/seagrantweedcult/1/>





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 or < 60 °F)
- Nutrient bioextraction (ecosystem services)
- Biofuels



Productivity

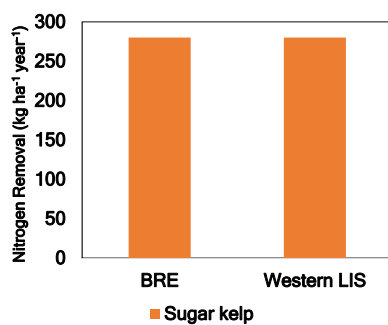
~ 1,752 kg per 100 m longline
(Dec. – May growing season)



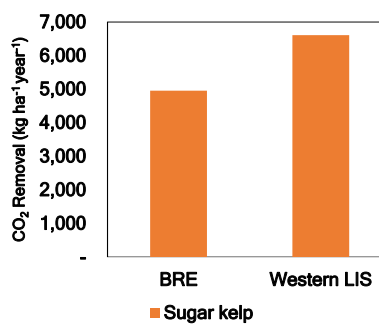
Kim et al.
2015, Marine
Ecol. Prog.
Series

Nutrient Bioextraction by Kelp

Nitrogen Removal



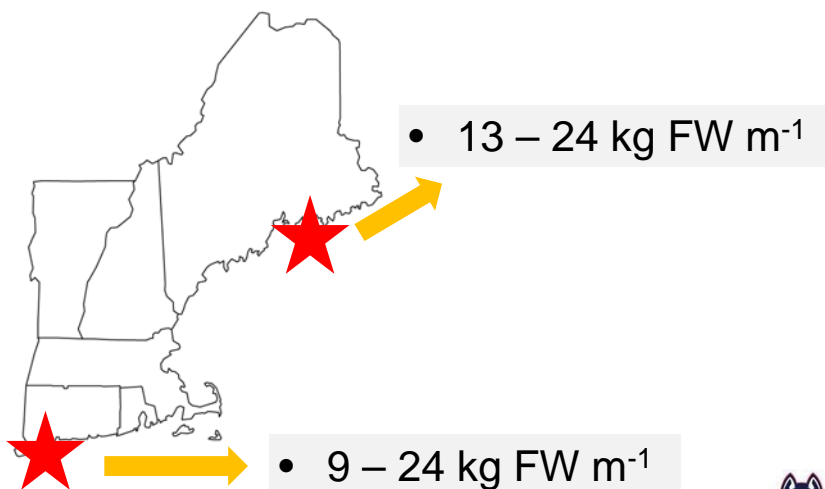
CO₂ Removal



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

Productivity (Southern NE vs. Northern NE)

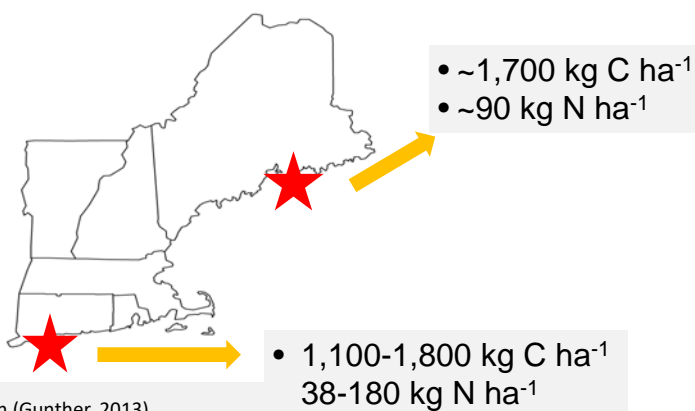
Nov. – May



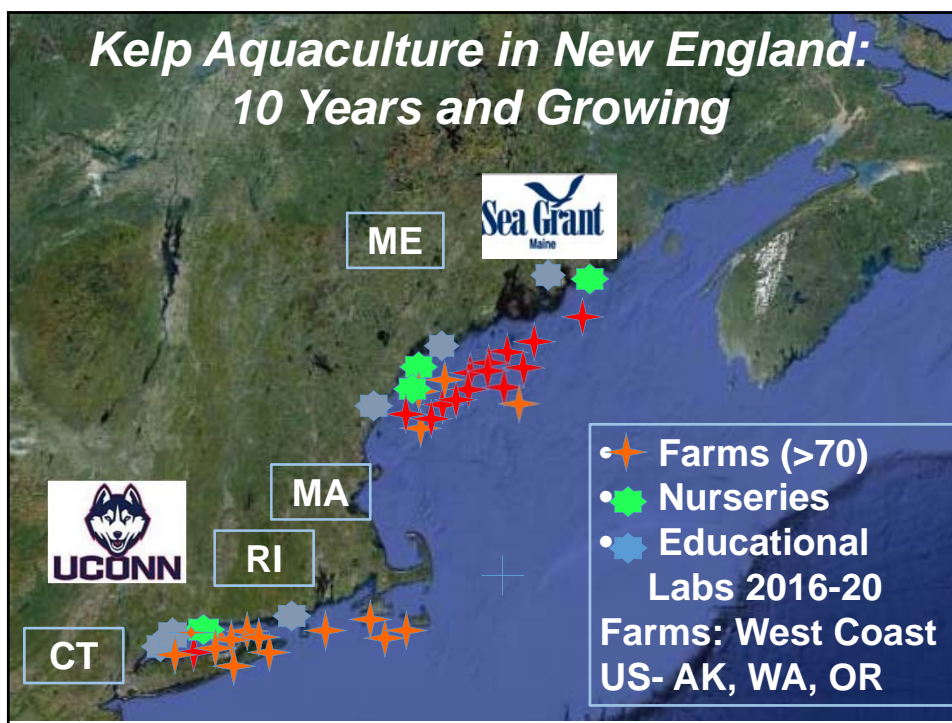
History of Seaweed industry (2010 - present)

– Ecosystem Services evaluation & social acceptance

- Kelp (*Saccharina*) (University of Connecticut; Yarish and Kim)



- CO₂: US\$ 4 – 71 per ton (Gunther, 2013)
CO₂ removal: US\$ 13 million – US\$ 222 million
- Nitrogen: US\$ 13 – 24 per kg (USEPA 2007)
Nitrogen removal: US\$ 845 million – US\$ 1.56 billion



New England Seaweed Culture Handbook

Nursery Systems

Sarah Radmond, Lindsay Green,
Charles Varish, Jang Kim, Christopher Nantais
University of Connecticut & University of New Hampshire

CTSD 13-01
Connecticut Sea Grant 2013

Video Series Shows How to Start Growing Seaweed

Ever wonder what it would be like to grow seaweed? Connecticut Sea Grant has posted a six-part educational video series on YouTube, so when people have to culture and grow four different species of economically important seaweeds. But first, the introduction to the Handbook for Seaweed Culture in New England offers a broad overview of seaweeds and uses in New England. Other chapters describe how to set up a laboratory to culture seaweeds, and several chapters explore the various New England species of Kelp, Chlorella, and Propagules. The videos are also captioned for accessibility.

This project was funded through NOAA's Sea Grant programs in Connecticut and New Hampshire. Research was conducted at the UConn Marine Biotechnology Laboratory in Storrs (Charles Nantais) and at the University of New Hampshire, Durham (Lindsay Green).

Link for the entire Seaweed Handbook playlist: <http://vimeo.com/newenglandseaweed>

Link to individual chapters:

- Part 1 Introduction: <http://vimeo.com/2676212>
- Part 2 Laboratory: <http://vimeo.com/2676212>
- Part 3 Kelp: <http://vimeo.com/2676212>
- Part 4 Chlorella: <http://vimeo.com/2676212>
- Part 5 Chlorella: <http://vimeo.com/2676212>
- Part 6 Chlorella: <http://vimeo.com/2676212>

YouTube

Kelp Farming Manual

A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters

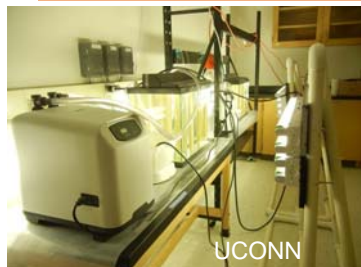
Katie Flavin
Nick Flavin
Bill Flahive, PhD

Ocean APPROVED
FARMING THE NORTH ATLANTIC

Saccharina latissima

Spores Gametophytes Sporophyte

Modular nursery system for the continuous mass production of young *Saccharina* plants

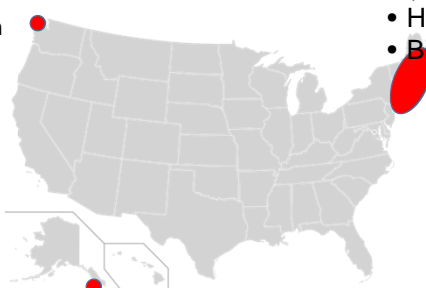


History of Seaweed industry (2010 - present) – Ecosystem Services evaluation

- Connecticut : *Gracilaria* open water & land-based cultivation
- Connecticut + Maine → Washington State → Alaska : Kelp cultivation
(*Saccharina latissima* & other kelps including *Alaria* spp. & *Nereocystis*)


- Ecosystem services (OA reduction)
- Human consumption

- Ecosystem services (CO₂ and N removal)
- Human consumption
- Biodegradable plastics



- Human consumption



THE OPPORTUNITY – SEAWEED AS a SUPER INGREDIENT		
Nutrition	<p><i>J. Phycol.</i> 54, 811–837 (2018) © 2018 Physiological Society of America DOI: 10.1111/jpy.12528</p> <p>REVIEW</p> <p>PROSPECTS AND CHALLENGES FOR INDUSTRIAL PRODUCTION OF SEAWEED BIOACTIVES¹</p> <p><i>Jeff T. Hafting,² James S. Craigie</i> Acadian Seaplans Limited, 30 Brown Avenue, Cornwallis, Nova Scotia, Canada</p> <p><i>Dagmar B. Struel</i> Botany and Plant Science, School of Natural Sciences & Ryan Institute for Environmental, Galway, Ireland</p> <p><i>Rafael R. Loureiro</i> Department of Biology, Ave Maria University, Ave Maria, Florida, USA</p> <p><i>Aljondro H. Buschmann</i> Centroemar & CIBIR, Universidad de Los Lagos, Puerto Montt, Chile</p> <p><i>Charles Varick</i> Department of Ecology & Evolutionary Biology, University of Connecticut, Stamford, Connecticut, USA</p> <p><i>Marce D. Edwards</i> National University of Ireland, Galway, Ireland</p> <p><i>and Alan T. Critchley</i> Acadian Seaplans Limited, 30 Brown Avenue, Cornwallis, Nova Scotia, Canada</p>	
Function	<p>CHAPTER 9</p> <p>Marine Algae and the Global Food Industry</p> <p><i>Maria Helena Abreu,^{1,*} Rui Pereira¹ and Jean-François Sassi^{2,3}</i></p>	
<p>Review</p> <p><i>J. Phycol.</i> 54, 811–837 (2018) © 2018 Physiological Society of America DOI: 10.1111/jpy.12528</p> <p>Antioxidants from macroalgae: potential applications in human health and nutrition</p> <p><i>M. Lynn Cornish¹ and David J. Guiry²</i> ¹James S. Craigie Research Centre, Acadian Seaplans Limited, Cornwallis, NS B0B 1J0, Canada ²Department of Biology, St. Francis Xavier University, Antigonish, NS B0G 1X0, Canada</p>	<p><i>J. Appl. Physiol.</i> (2011) 23, 543–597 DOI: 10.1007/s10931-010-9632-5</p> <p>Bioactive compounds in seaweed: functional food applications and legislation</p> <p><i>Susan Lovstad Holth - Stefan Krause</i></p>	<p>Courtesy of</p> 

History of Seaweed industry (2010 - present)

- Ocean Approved (Atlantic Sea Farms) : Maine
- Thimble Island Oyster Co. (Thimble Island Ocean Farm) : Connecticut





What Do You Do With The Kelp?

UConn and Norwalk Community College

Outreach opportunity in Greenwich, CT



Overview of maximum levels (Europe) for arsenic, cadmium, lead, and mercury

Hazard	Feed ^a	Food ^{b,c}	Food supplements
Arsenic (total)	40 mg/kg	No standard for seaweed	No standard for seaweed
Arsenic (inorganic)	2 mg/kg	No standard for seaweed	No standard for seaweed
Cadmium	1 mg/kg	No standard for seaweed	3.0 mg/kg ww
Lead	10 mg/kg	No standard for seaweed	3.0 mg/kg ww
Mercury	0.1 mg/kg	No standard for seaweed	0.10 mg/kg ww

^a Directive 2002/32/EC specifies undesirable substances in animal feed. The level is relative to a feed with a moisture content of 12%.

^b Regulation (EC) 1881/2006 on setting maximum levels for certain contaminants in foodstuffs. "The maximum level applies to the food supplements as sold."

^c Kim, J.K., G. Kraemer and C. Yarish. 2019 (June). Food safety evaluation of farm grown *Gracilaria tikvahiae* and *Saccharina latissima* in Long Island Sound & New York Estuary. Algal Research 40, June 2019 (<https://doi.org/10.1016/j.algal.2019.101484>).

Future of Seaweed Industry in the US (present -)

ANIMALS

Study: Seaweed in Cow Feed Reduces Methane Emissions Almost Entirely



Seaweeds have a wide range of potential uses:

antibiotic, anti-oxidant, anti-inflammatory, immunostimulants, prebiotics, etc. Different species of macroalgae differ in their anti-methanogenic efficiency

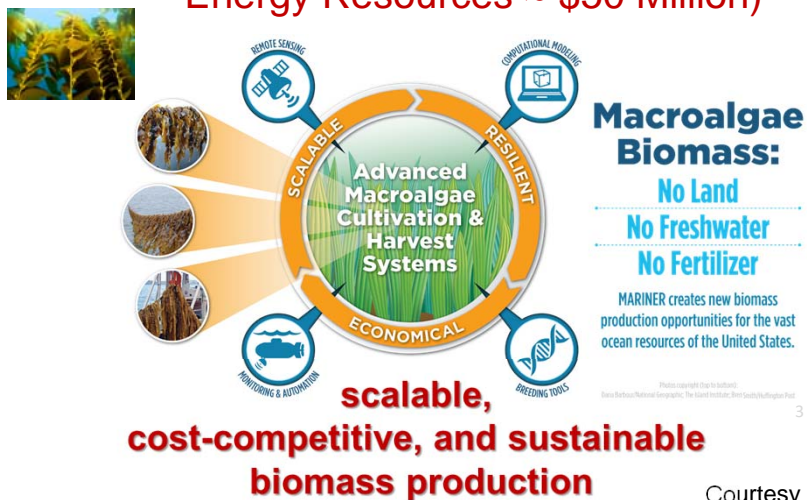
An Australian study found 99% methane reduction with 2% (feed DM)

Asparagopsis taxiformis in vitro



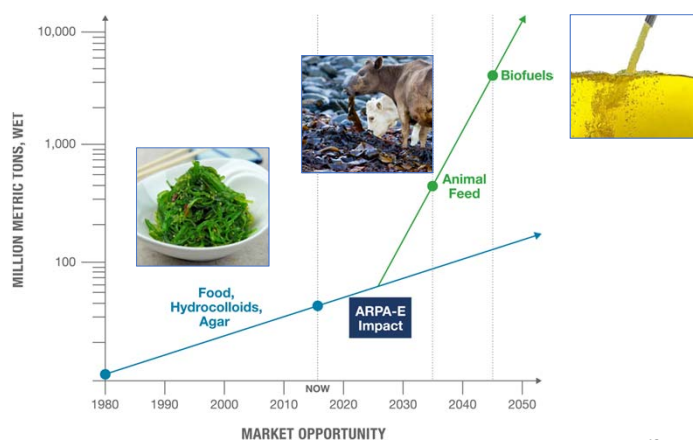
Courtesy of A. Hristov

The ARPA-E MARINER Program (MacroAlgae Research Inspiring Novel Energy Resources ~ \$50 Million)



Courtesy of ARPA-E

Earn to Learn: Pathways to fuels scale



Courtesy of ARPA-E



UNIVERSITY OF ALASKA
FAIRBANKS



WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930



arpa-e
Advanced Research Projects Agency • ENERGY

Development of Scalable Coastal and Offshore Macroalgal Farming (PI M. Stekoll, UAF)

Project Vision

Develop replicable model farms on the East Coast and Alaska that meet the cost criteria of less than \$80 per dry metric tonne of macroalgal production of sugar kelp, *Saccharina latissima*.

Project Impact

Transformative development of efficient, integrated seaweed farm design and operations (low CapEx & OpEx) that can be automated from direct seeding onto ropes through harvest and re-seeding.



Kodiak, AK harvest

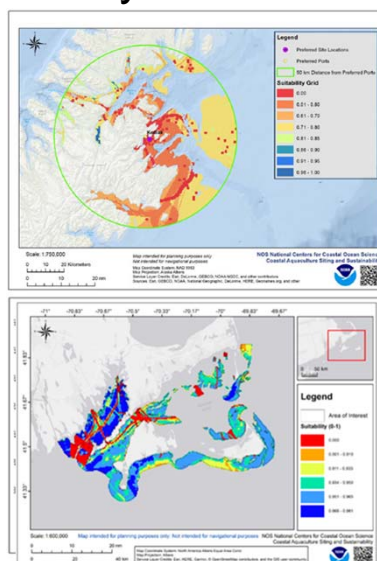







Technical Details: Scalability Assessment

- **Scalability for Alaska**
 - Depth 10-100 m
 - Farm size 10-1,000 ha
 - Total possible Alaska farm area = ~16.5 million ha
 - Within 50 Km of ports: >3.5 million ha
- **Scalability for NE**
 - Depth 10-100 m
 - Within 50 nm of a port
 - Farm size 20+ ha.
 - Total possible NE farm area = ~7.5 million ha
 - > 1 million ha may fit suitability criteria



Thanks to Coastal Aquaculture Siting and Sustainability NOAA / NOS / NCCOS
 Virginia C. Crothers, M.S.¹, Seth J. Theuerkauf, Ph.D.¹, Lisa C. Wickliffe, Ph.D.¹, Kenneth L. Riley, Ph.D.², James A. Morris, Jr., Ph.D.², Jon Jossart, M.S.¹
¹CSS, Inc. for NOAA NOS/NCCOS, Beaufort, NC. ²NOAA NCCOS, Beaufort, NC



1930

Selective Breeding Technologies for Scalable Offshore Seaweed Farming



Advanced Research Projects Agency • ENERGY

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



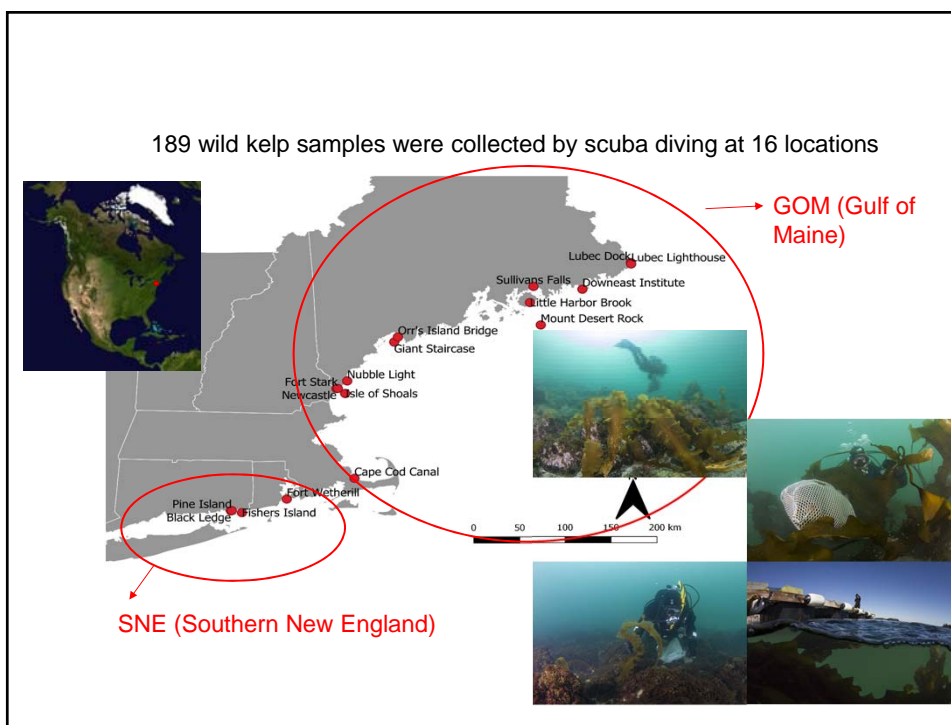
UCONN

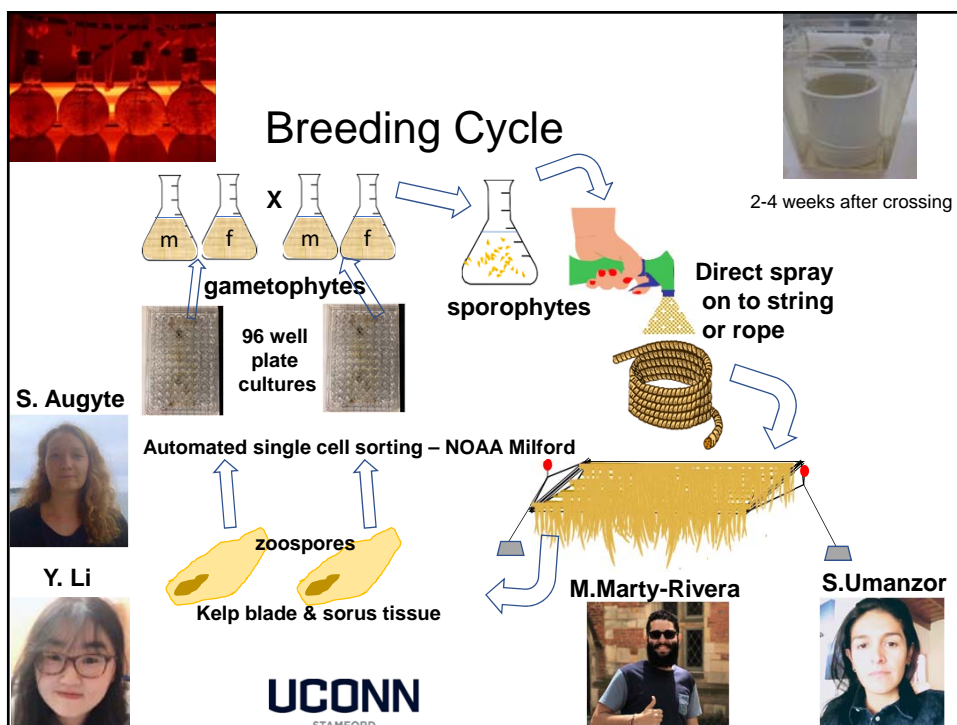
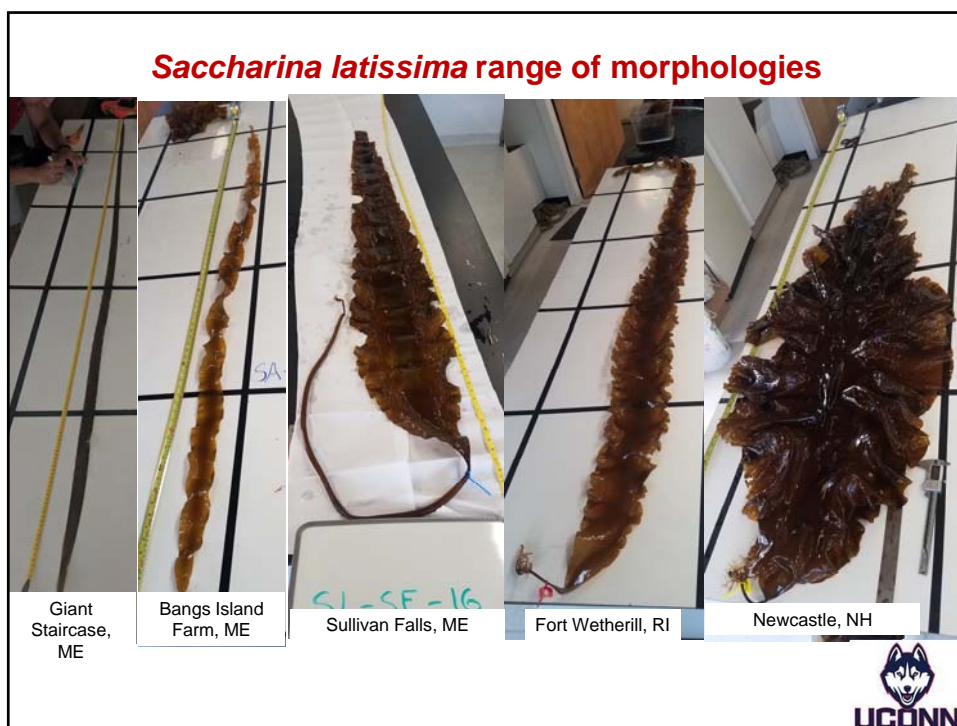


GreenWave



Augyte et al 2018





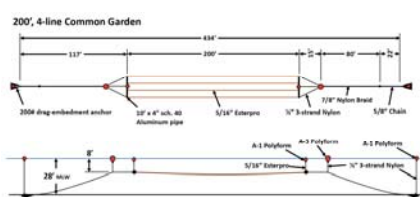
Domestication Program

“Common Garden” Comparisons

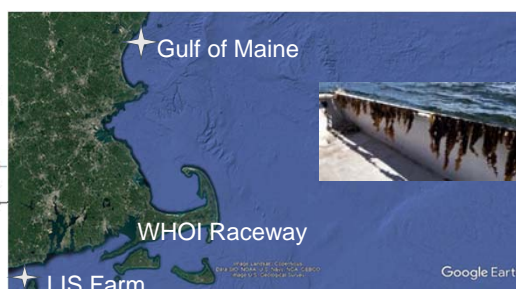
- Created and planted 326 (Yr.1) & 380 (yr.2) unique families plus reference crosses in The Gulf of Maine (UNH-2019&2020) & Southern New England (GW-2020)
- Demonstrated ability to generate single gametophytes males and females in sufficient quantity in less than 6 months thus conceivably producing selective improvements annually.



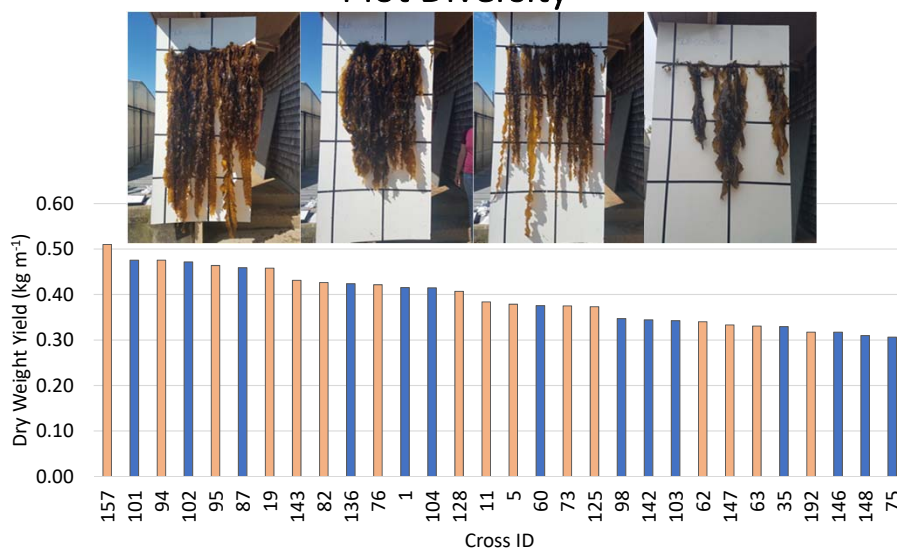
Phenotyping & genotyping still underway; Fresh Wt, Dry Wt, Composition of sugars & ions, growth rate, maturity, morphological traits & microbiome



C.A. Goudey & Assoc. Engineering



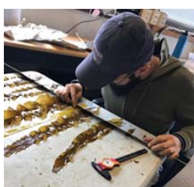
Plot Diversity



Top 30 Plots Dry Weight Yield (kg m⁻¹)

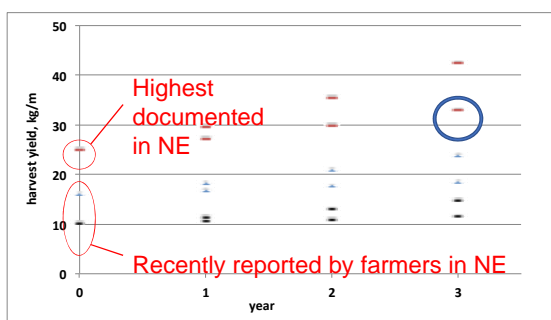
2019 Phenotyping for GMO

- 8 personnel from WHOI/CA Goudey/UNH/GreenWave harvested farm in 1 day
- 14 WHOI/UConn/GreenWave personnel phenotyped over 3 days (+1 MBL)
- Measurements for each family:
 - Plot (1m) photo documented
 - Total Wet Weight, 5 random sample wet weights, sample dry weight
 - 15 individual blades randomly selected from sample weights for 9 traits
 - blade length, blade width (2), thickness of blade
 - stipe length & width, reproductive status (**sorus** formation)
 - fouling &/or evidence of pathogen damage



From L to R (top row) M. Stephens (GW), C. Yarish (UConn), J. Pegnataro (GW), S. Lindell (WHOI), M. Marty-Rivera (UConn) (bottom row), M. Aydtlett (WHOI), S. Augyte (UConn), D. Bailey (WHOI), M. Currie (WHOI), S. Umanzör (UConn)

Potential Improvements in Yield with 10% and 20% improvement/year



Development of the Bioeconomy Workforce

GreenWave

Organizational Impact



Trained and supported over 100 current and emerging farmers in 7 states



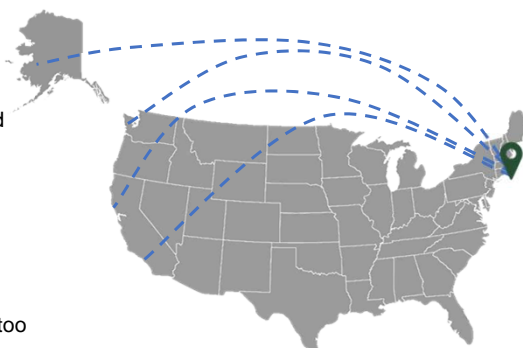
Developed ocean farming toolkit and supported national network of seaweed hatcheries (www.greenwave.org/toolkit)



Incubating kelp carbon, sensor, fertilizer and bioplastics projects



Developing national Buyer Network to scale markets and infrastructure



Train 500 farmers in 10 regions by 2023



Algal-based STEM Educational Initiatives for a Sustainable Future and the Development of the Bioeconomy Workforce



Algaefoundationatec.org
Thealgaefoundation.org



Algae Cultivation Extension Short-courses (ACES) Part-1 Seaweeds

http://www.algaefoundationatec.org/aces_intro.html

Aquaculture Introduction

- Overview: What is aquaculture, why is it important
- Dana Morse "What is Aquaculture?"
- International Mariculture of Seaweeds; An introduction to Seaweed Aquaculture. Dr. Charles Yarish
- From Sea to Table, University of Connecticut Research Benefits
- Seaweed Culture in New England: Overview of Seaweeds and Their Uses
- Seaweed in New England: A Seaweed Visionary. Interview with Shep Erhart, Maine Coast Sea Vegetables

Economically important species

- Seaweed culture in New England: Kelp, *Gracilaria*, *Chondrus*, *Porphyra*, *Palmaria* (Dulse), *Kappaphycus* and *Euclima*

Seaweed Aquaculture: Nursery

- Elements of a Seaweed Lab
- Introduction to Sugar Kelp Nursery Methods. University of New England

Seaweed Aquaculture: Leasing

- Permits/Leases/Regulations. Jon Lewis, Maine Dept. of Marine Resources

Seaweed Farm design and gear

- A Simple Method of Setting Seaweed Long Lines, Tollef Olson, President, Ocean's Balance

Outplanting seaweed seed :

- Field clips of outplanting seaweed lines with Maine Sea Farms

Seaweed Husbandry:

- Winter on a Kelp Farm, Ocean Approved

Seaweed Aquaculture: Farming

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Harvesting :

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Seaweed Processing/marketing:

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