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

Global Seaweed Production (MT) by Species (2016)

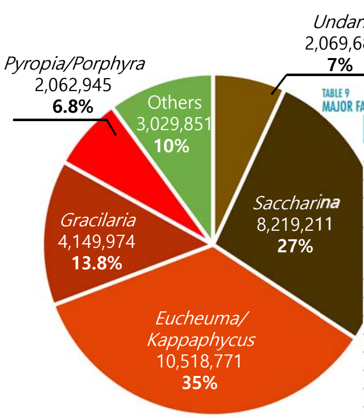
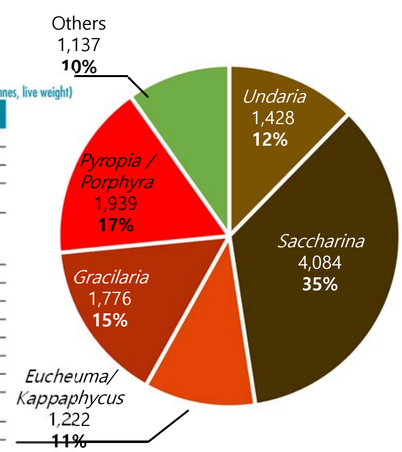


TABLE 9
MAJOR FARMED SEAWEED PRODUCERS (thousand tonnes, live weight)

Country	2016	% of total, 2016
China	14 387	47.9
Indonesia	11 631	38.7
Philippines	1 405	4.7
Republic of Korea	1 351	4.5
Democratic People's Republic of Korea	489	1.6
Japan	391	1.3
Malaysia	206	0.7
Tanzania	119	0.4
Madagascar	17	0.1
Chile	15	0
Solomon Islands	11	0
Viet Nam	10	0
Papua New Guinea	4	0
Kiribati	4	0
India	3	0
Others	8	0
Total	**30 050**	

Economic Value (million dollar) by Species (2016)



(FAO 2018)

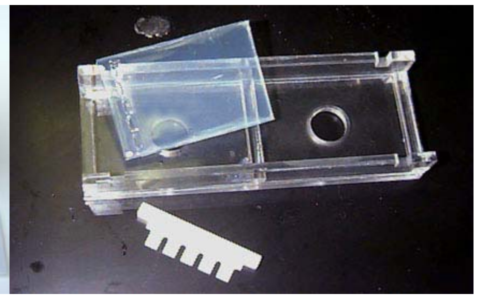
Uses of Seaweeds

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

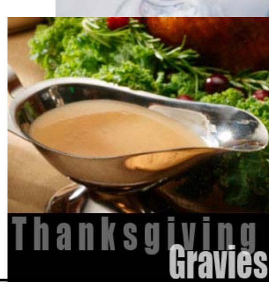
Alginates are hydrocolloidal products used for thickening, suspending, stabilizing or gel-forming from kelp (*Saccharina* & *Laminaria*) and fucoids (*Ascophyllum* & *Fucus*).

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.



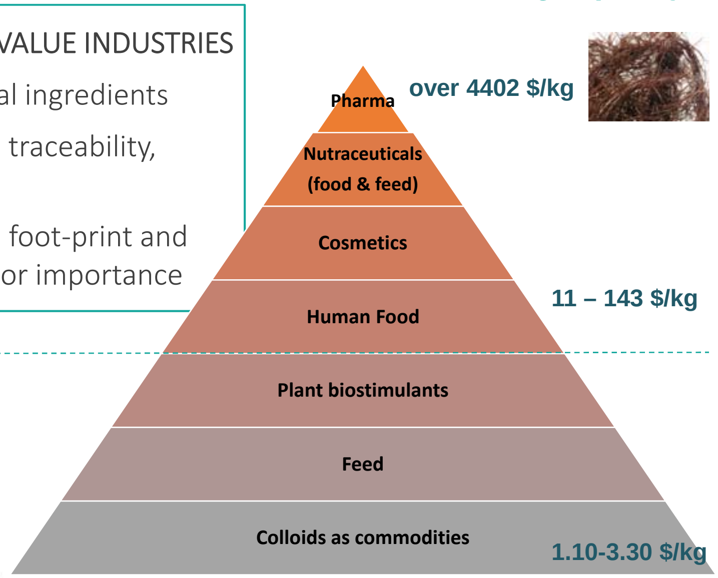
Carrageenans



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

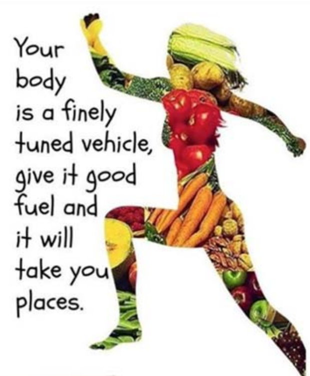


Courtesy of ALGA+

WHY START WITH FOOD

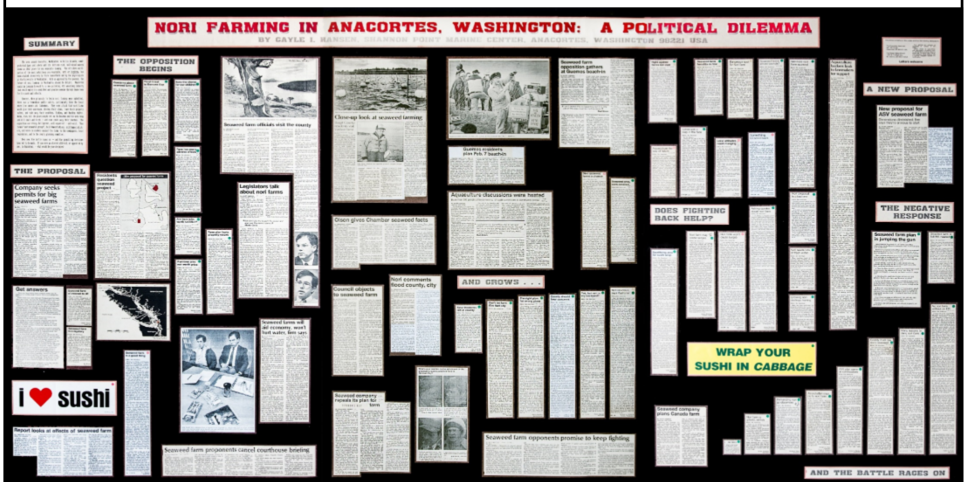
CURRENT FOOD TRENDS

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



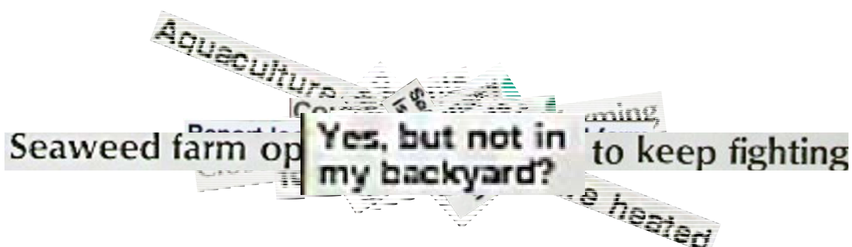
Courtesy of Blue Evolution

Courtesy of ALGA+



Courtesy of G. Hansen
(http://ir.library.oregonstate.edu/concern/defaults/1v53k318p)

NORI FARMING IN ANACORTES, WASHINGTON: NIMBY



Courtesy of G. Hansen

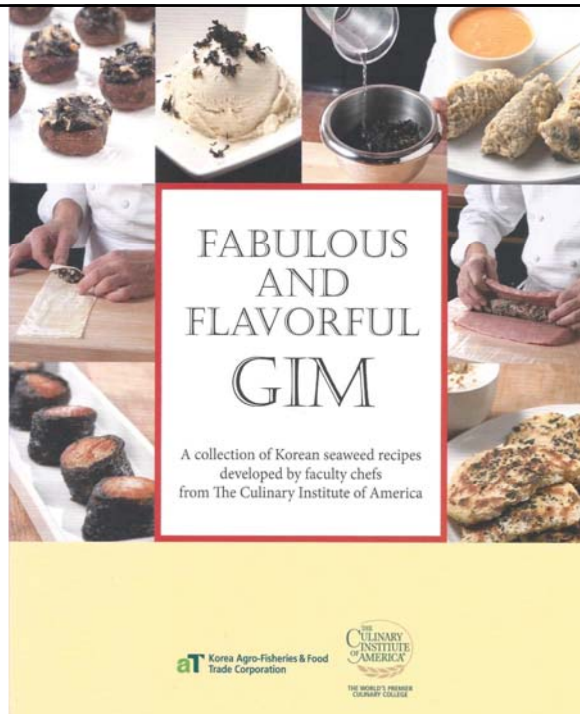
Obstacles to the Growth of Seaweed Aquaculture in the USA

- 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 – B_2 (2.95 mg)**
- **Vitamin – B_{12} (0.06 mg)**
- **Vitamin – C (93 mg)**



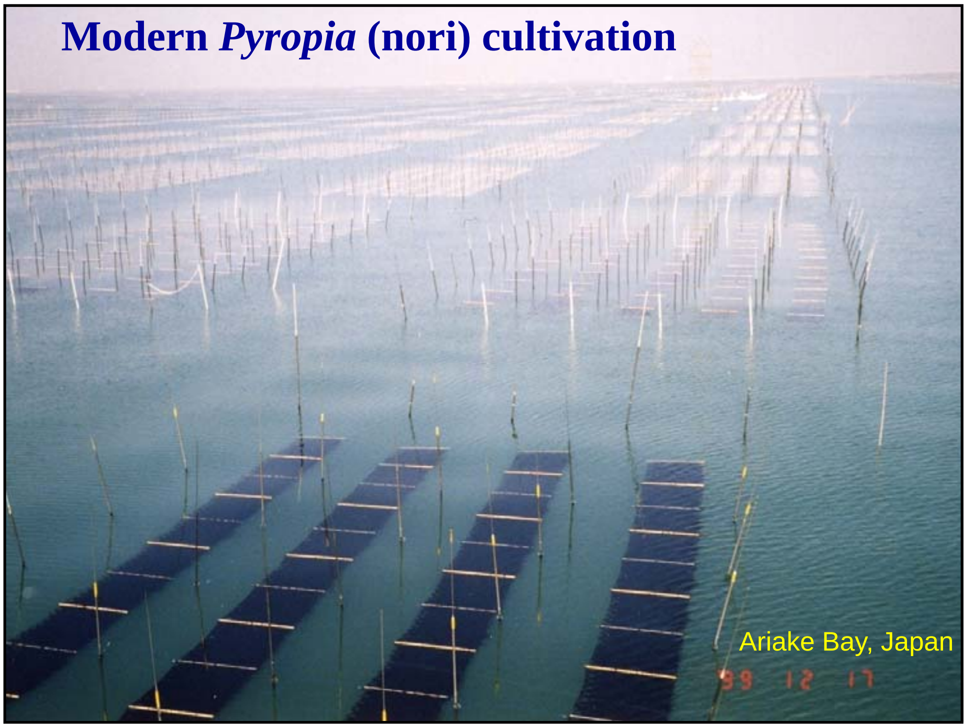
Sea Vegetable, Gim (Laver)

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

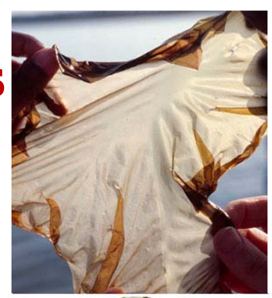
※ Comparison of vitamin content in some vegetables (In 100g dry weight)

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



Nori

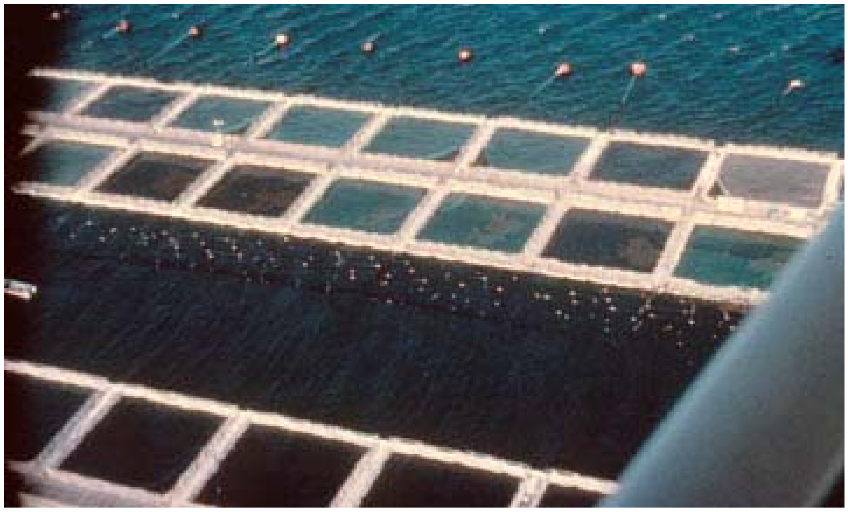
- Simple, flat sheet gametophyte (high SA/V)
- 1-2 cell layers: all productive
- fast growth (up to 24% d^{-1})
- high nutrient accumulation (possibility of 6-8% N DW)
- high protein content (up to 50% DW)
- salable harvest (nori, high-value r-phycoerythrin)

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

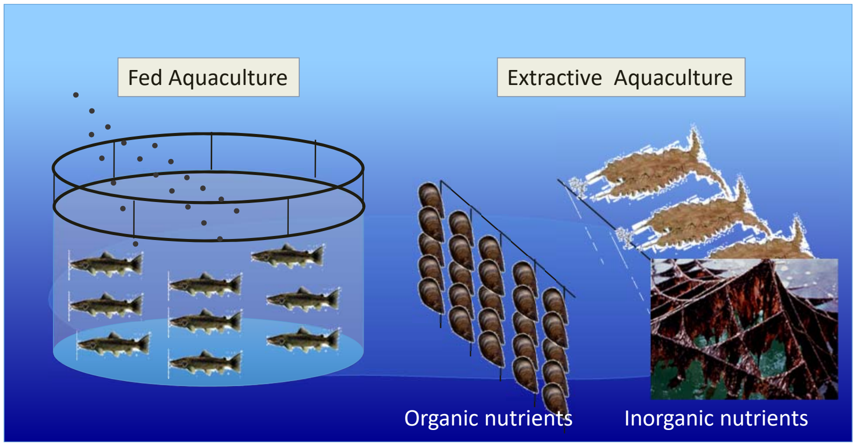


(courtesy I. Levine)

"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)

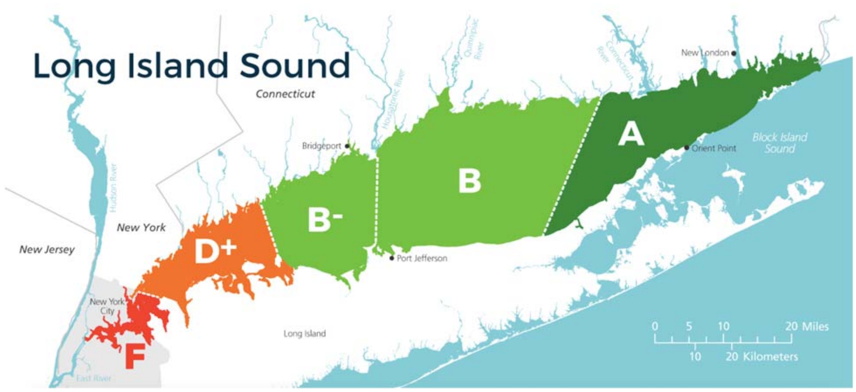


- Mitigates nutrification of marine environment

Courtesy of I. Bricknell

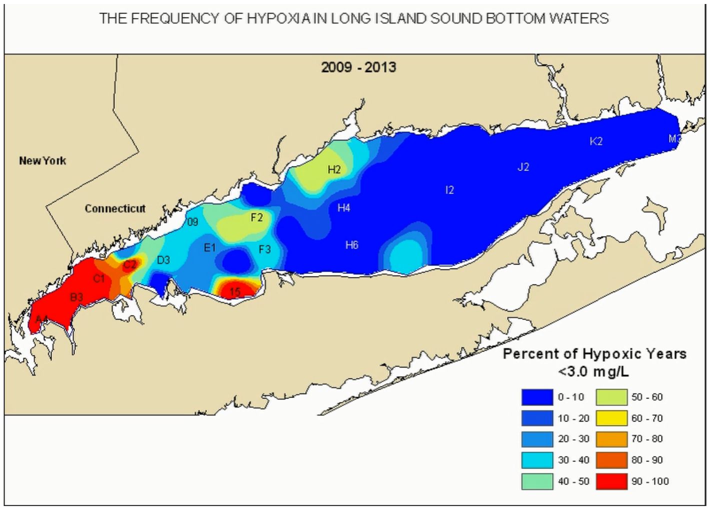
History of Seaweed industry (2010 - present)

- **Ecosystem services approach to overcome NIMBY**



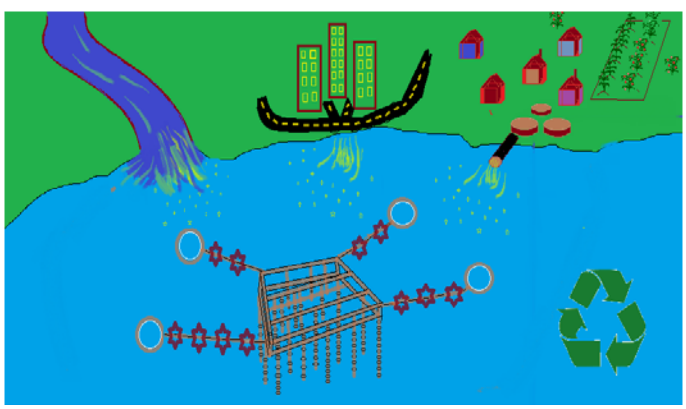
History of Seaweed industry (2010 - present)

- **Ecosystem services approach to overcome NIMBY**



History of Seaweed industry (2010 - present)

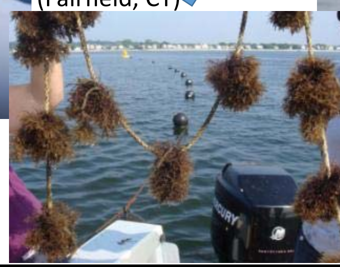
- **Ecosystem services approach to overcome NIMBY**
- **Nutrient Bioextraction**



Nearshore seaweed farms

Bronx, NY (BRE)

Western LIS
(Fairfield, CT)

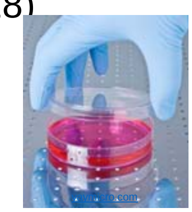


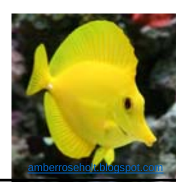
Central LIS
Branford, CT

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 °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/seagrant_weedcult/1/

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

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

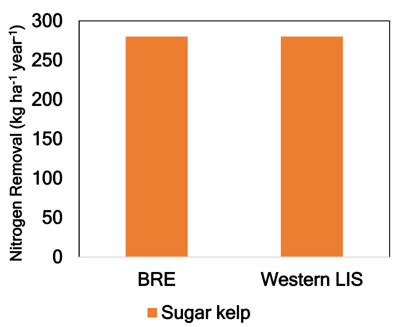
Productivity

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

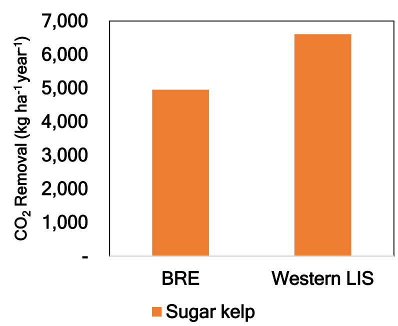
Kim et al. 2015, Marine Ecol. Prog. Series

Nutrient Bioextraction by Kelp

Nitrogen Removal



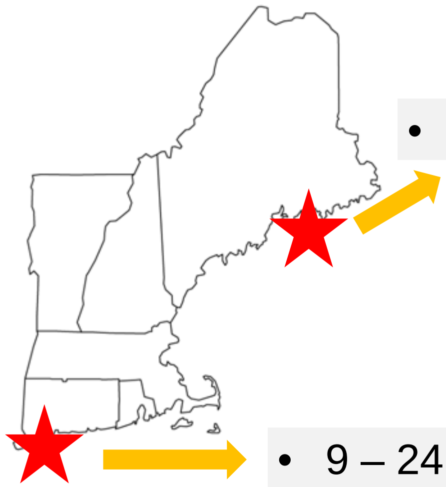
CO_2 Removal



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

Productivity (Southern NE vs. Northern NE)

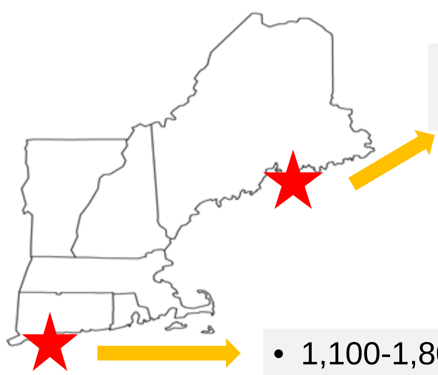
Nov. – May



- 13 – 24 kg FW m^{-1}
- 9 – 24 kg FW m^{-1}

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

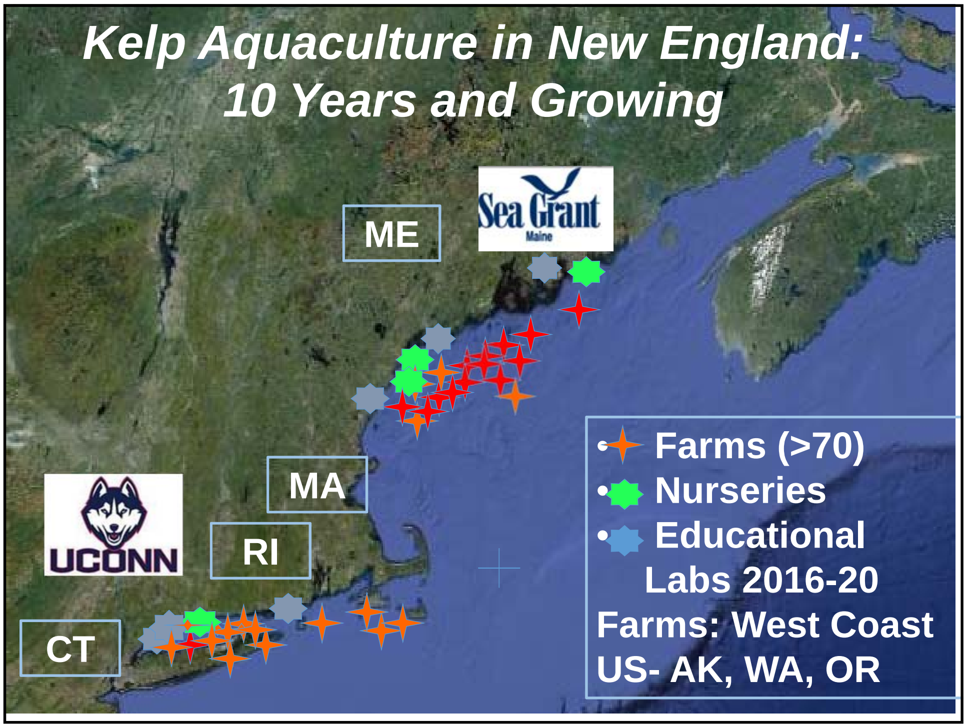
- **Kelp (*Saccharina*) (University of Connecticut; Yarish and Kim)**



- ~1,700 kg C ha^{-1}
- ~90 kg N ha^{-1}

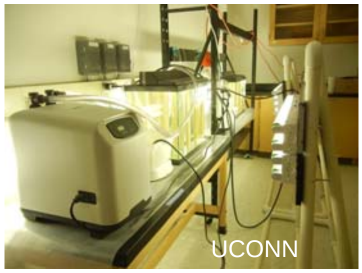
- 1,100-1,800 kg C ha^{-1}
  38-180 kg N ha^{-1}

- CO_2: US$ 4 – 71 per ton (Gunther, 2013)
  CO_2 removal: US$ 13 million – US$ 222 million
- Nitrogen: US$ 13 – 24 per kg (USEPA 2007)
  Nitrogen removal: US$ 845 million – US$ 1.56 billion


Kelp Aquaculture in New England:
10 Years and Growing
ME
Sea Grant
Maine
MA
RI
CT
UCONN
Farms (>70)
Nurseries
Educational
Labs 2016-20
Farms: West Coast
US- AK, WA, OR


New England
Seaweed Culture Handbook
Nursery Systems
Video Series Shows
How to Start Growing Seaweed
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
Saccharina latissima
5 µm
250 µm
Spores
Gametophytes
Sporophyte
UCONN

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

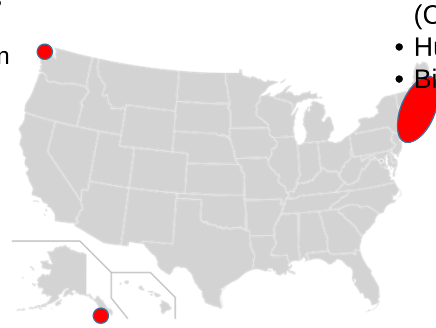


History of Seaweed industry (2010 - present) – Ecosystem Services evaluation

- **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 (CO_2 and N removal)
- Human consumption
- Biodegradable plastics



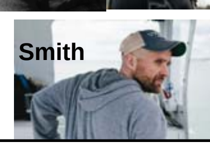
Dobbins

Olson

Perry

- Human consumption

Smith



THE OPPORTUNITY – SEAWEED AS a SUPER INGREDIENT

Nutrition

- *Protein* (3% - 47%)
- Fiber (up to 63%)
- Lipids: (up to 8%; mainly PUFAS)
- Minerals: Ca, Fe, I, *K/Na*, Mg
- Vitamins: A, B, C, E

Function

- Texturizing, Thickener, Emulsifier
- Antioxidant, Anti-inflammatory, Anti-bacterial, Anti-viral, Anti-fungal....

J. Phycol. 51, 821–837 (2015)
© 2015 Phycological Society of America
DOI: 10.1111/jpy.12326

REVIEW

PROSPECTS AND CHALLENGES FOR INDUSTRIAL PRODUCTION OF SEAWEED BIOACTIVES[1]

Jeff T. Hafting,[2] James S. Craigie
Acadian Seaplants Limited, 30 Brown Avenue, Cornwallis, Nova Scotia, Canada
Dagmar B. Stengel
Botany and Plant Science, School of Natural Sciences & Ryan Institute for Environmental, Galway, Ireland
Rafael R. Loureiro
Department of Biology, Ave Maria University, Ave Maria, Florida, USA
Alejandro H. Buschmann
Centro i-mar & CeBiB, Universidad de Los Lagos, Puerto Montt, Chile
Charles Yarish
Department of Ecology & Evolutionary Biology, University of Connecticut, Stamford, Connecticut, USA
Maeve D. Edwards
National University of Ireland, Galway, Ireland
and Alan T. Critchley
Acadian Seaplants Limited, 30 Brown Avenue, Cornwallis, Nova Scotia, Canada

CHAPTER 9

Marine Algae and the Global Food Industry

Maria Helena Abreu,[1,*] Rui Pereira[1] and Jean-François Sassi[2,3]

Review

Antioxidants from macroalgae: potential applications in human health and nutrition

M. Lynn Cornish and David J. Garbary

J Appl Phycol (2011) 23:543–597
DOI 10.1007/s10811-010-9632-5

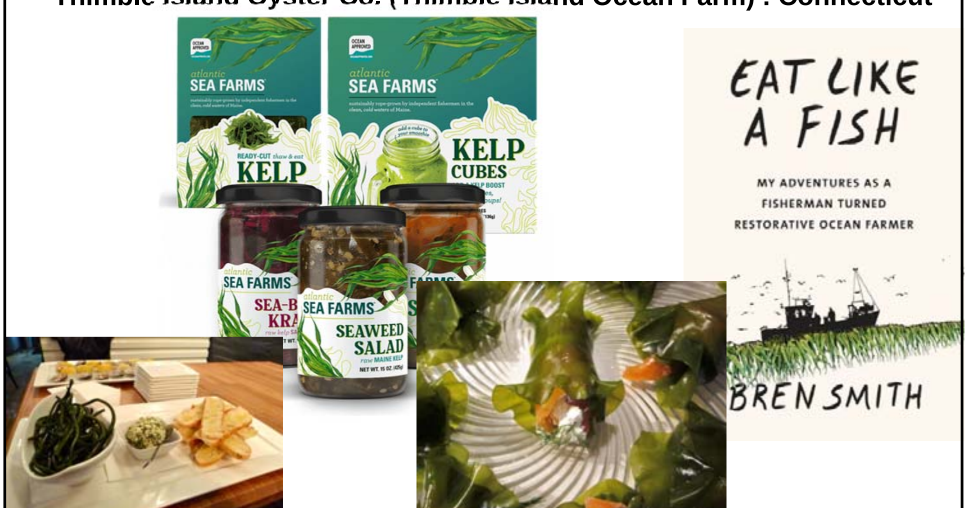
Bioactive compounds in seaweed: functional food applications and legislation

Susan Løvstad Holdt · Stefan Kraan

Courtesy of ALGA+

History of Seaweed industry (2010 - present)

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



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What Do You Do With The Kelp?

UCONN and Norwalk Community College

UCONN

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

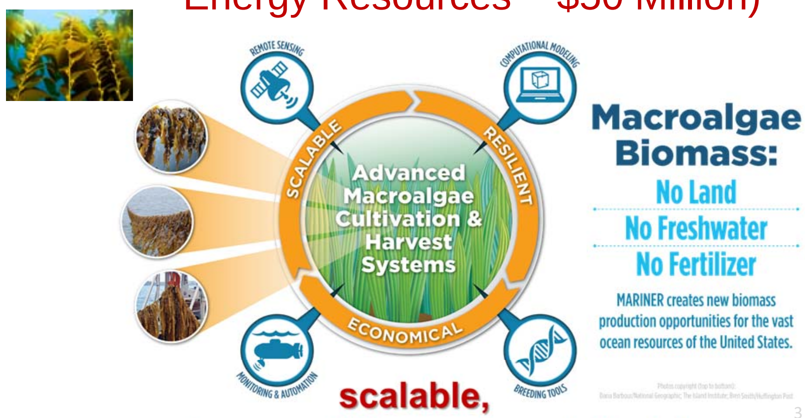
Study: Seaweed in Cow Feed Reduces Methane Emissions Almost Entirely

An Australian study found 99% methane reduction with 2% (feed DM) *Asparagopsis taxiformis in vitro*

Courtesy of A. Hristov

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

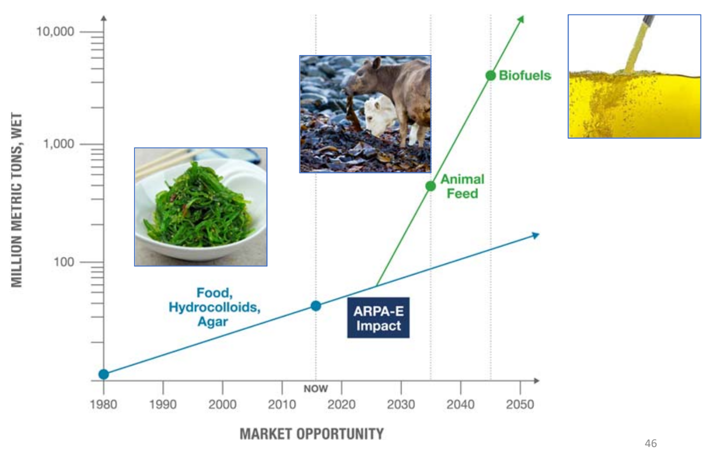
The ARPA-E MARINER Program
(MacroAlgae Research Inspiring Novel Energy Resources ~ $50 Million)



scalable, cost-competitive, and sustainable biomass production

Courtesy of ARPA-E

Earn to Learn: Pathways to fuels scale



Courtesy of ARPA-E

UNIVERSITY OF ALASKA FAIRBANKS

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*.

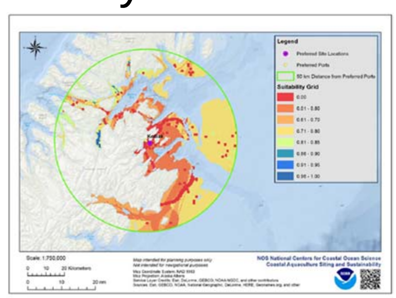
Project Impact

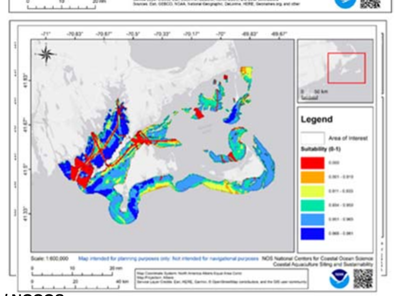
Transformative development of efficient, integrated seaweed farm design and operations (low CapEx & OpEx) that can be automated from direct seeding onto ropes though harvest and re-seeding.

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]
[1]CSS, Inc. for NOAA NOS/NCCOS, Beaufort, NC. [2]NOAA NCCOS, Beaufort, NC

Selective Breeding Technologies for Scalable Offshore Seaweed Farming

Advanced Research Projects Agency • ENERGY

Project Vision

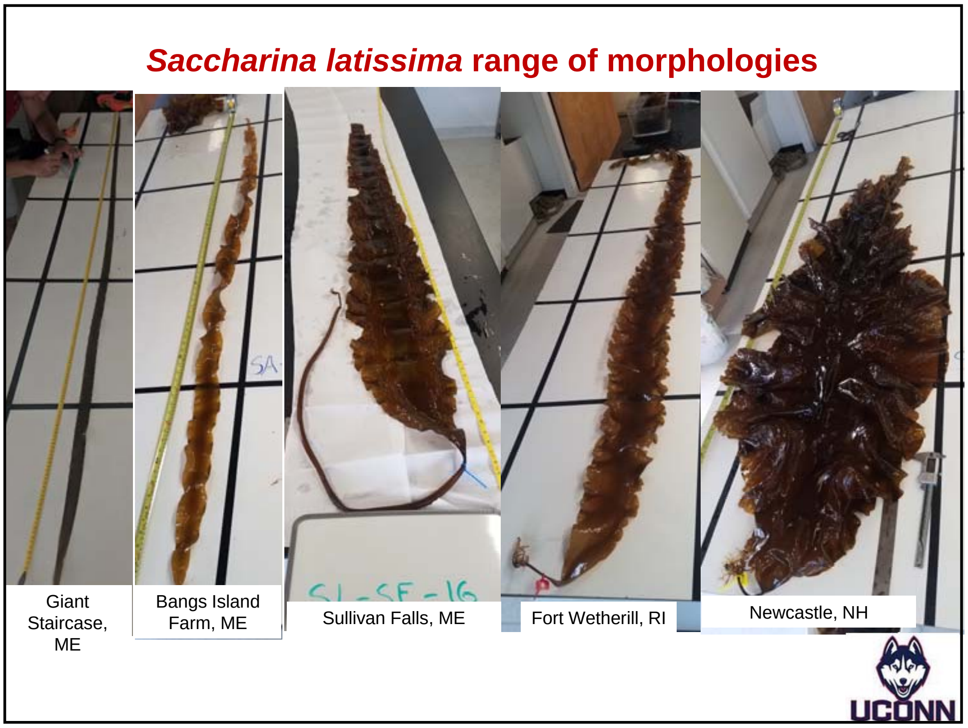
Develop tools to identify and breed superior sugar kelp cultivars, improving productivity 10 to 20% per generation.

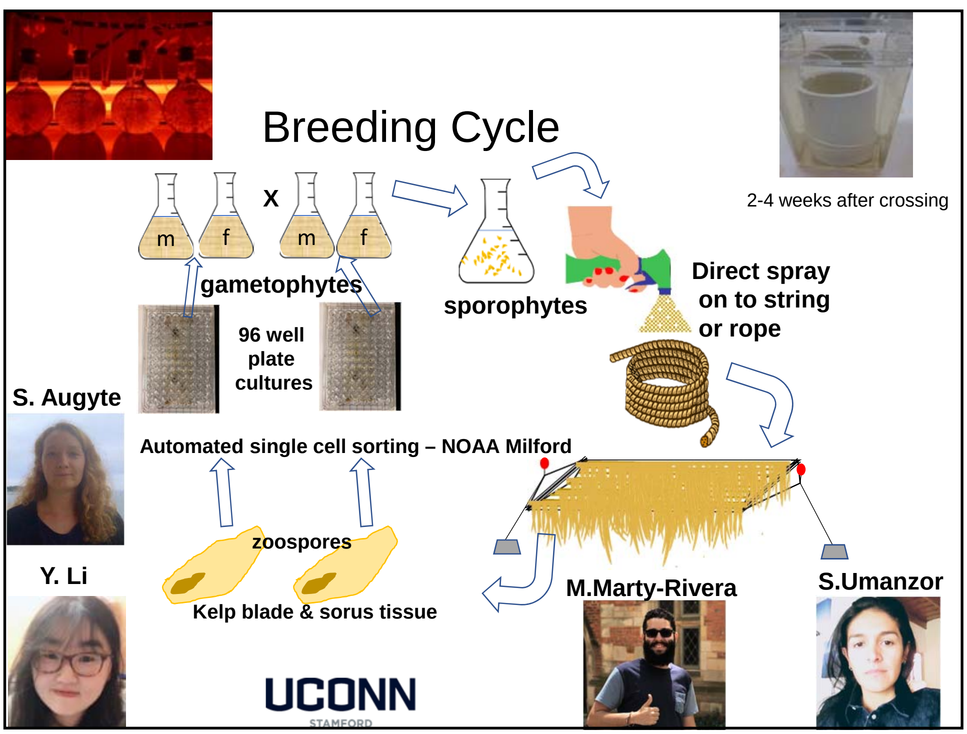
Project Impact

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

189 wild kelp samples were collected by scuba diving at 16 locations


Saccharina latissima range of morphologies
Giant Staircase, ME
Bangs Island Farm, ME
Sullivan Falls, ME
Fort Wetherill, RI
Newcastle, NH
UCONN

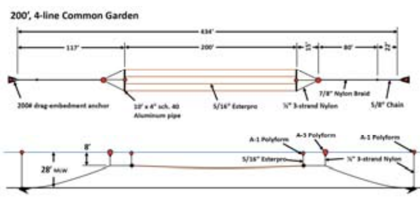

Breeding Cycle
2-4 weeks after crossing
m
f
x
m
f
gametophytes
sporophytes
Direct spray on to string or rope
96 well plate cultures
S. Augyte
Automated single cell sorting – NOAA Milford
zoospores
Y. Li
Kelp blade & sorus tissue
M.Marty-Rivera
S.Umanzor
UCONN

Domestication Program

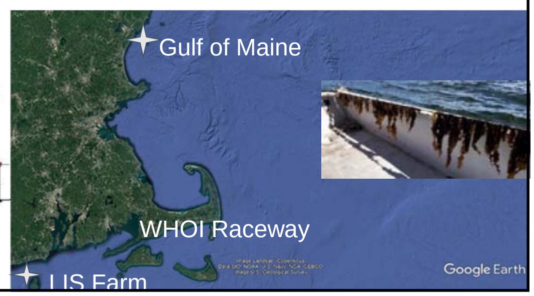
"Common Garden" Comparisons

- 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 that 6 months thus conceivably producing selective improvements <u>annually.</u>

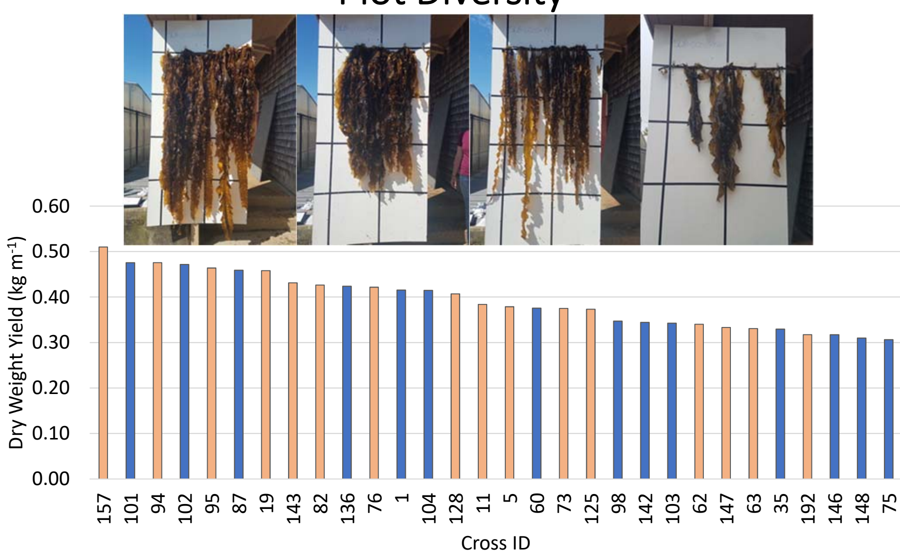
Phenotypying & genotyping still underway; Fresh Wt, Dry Wt, Composition of sugars & ions, growth rate, maturity, morphological traits & microbiome



C.A. Goudey & Assoc. Engineering



Plot Diversity



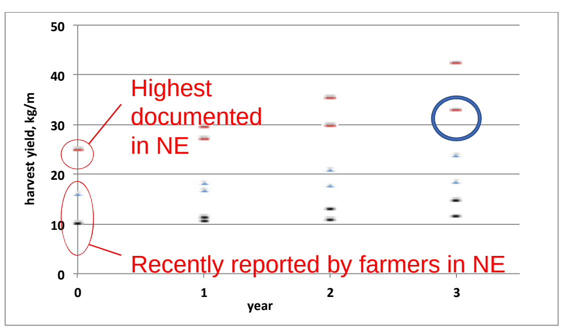
Top 30 Plots Dry Weight Yield (kg m^{-1})

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. Aydlett (WHOI), S. Augyte (UCONN), D. Bailey (WHOI), M. Currie (WHOI), S. Umanzőr (UCONN)

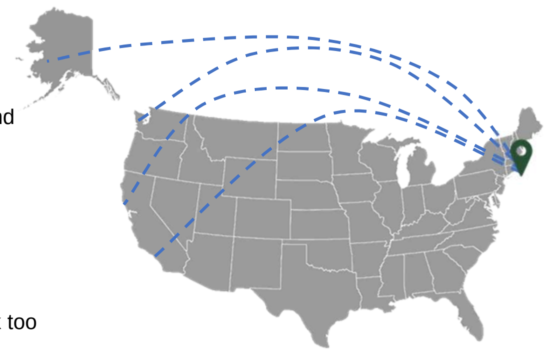
Potential Improvements in Yield
with 10% and 20% improvement/year



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 too scale markets and infrastructure



Train 500 farmers in 10 regions by 2023

GreenWave

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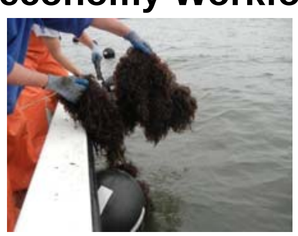
thealgaefoundation

ATEC ALGAE TECHNOLOGY EDUCATIONAL CONSORTIUM

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 *Eucheuma*

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

- Seaweed Farms of Maine
- Maine Sea Farms Explains Kelp Farming
- Seaweed Farming, Tollef Olson, Oceans Balance Inc.

Harvesting :

- Pulling Seaweed Lines (Ocean Approved)
- Harvesting Kelp with Maine Sea Farms, spring 2018

Seaweed Processing/marketing:

- Greenhouse drying of seaweed with Maine Sea Farms
- Seaweed Product Forms, Lisa Scali, Ocean Approved Inc.

Acknowledgements

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Advanced Research Projects Agency • ENERGY

Acknowledgements

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- 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)