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

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Global Seaweed Production (MT) by Species (2016)

- Eucheuma/Kappaphycus: 10,518,771 MT, 35%
- Saccharina: 8,219,211 MT, 27%
- Gracilaria: 4,149,974 MT, 13.8%
- Pyropia/Porphyra: 2,062,945 MT, 6.8%
- Undaria: 2,069,682 MT, 7%
- Others: 3,029,851 MT, 10%

Economic Value (million dollar) by Species (2016)

- Eucheuma/Kappaphycus: 1,222 million dollars, 11%
- Saccharina: 4,094 million dollars, 35%
- Pyropia/Porphyra: 1,939 million dollars, 17%
- Undaria: 1,428 million dollars, 12%
- Gracilaria: 1,776 million dollars, 15%
- Others: 1,137 million dollars, 10%

(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.

![Agar images](image1.png)
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 footprint and origin are of major importance

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

WHY START WITH FOOD

Your body is a finely tuned vehicle, give it good fuel and it will take you places.

Courtesy of Blue Evolution

Courtesy of ALGA®
NORI FARMING IN ANACORTES, WASHINGTON: A POLITICAL DILEMMA

NORI FARMING IN ANACORTES, WASHINGTON: NIMBY

Courtesy of G. Hansen

http://ir.library.oregonstate.edu/concern/defaults/v69k3187w

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 – 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 Content

<table>
<thead>
<tr>
<th>Vegetables</th>
<th>Vitamin A (I.U.)</th>
<th>Vitamin B1 (mg)</th>
<th>Vitamin B2 (mg)</th>
<th>Niacin (mg)</th>
<th>Vitamin C (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Udaria</td>
<td>1,850</td>
<td>0.26</td>
<td>1.00</td>
<td>4.5</td>
<td>18</td>
</tr>
<tr>
<td>Saccharina</td>
<td>320</td>
<td>0.22</td>
<td>0.45</td>
<td>4.5</td>
<td>18</td>
</tr>
<tr>
<td>Pyropia (Gim/lever)</td>
<td>12,500</td>
<td>1.20</td>
<td>2.95</td>
<td>10.4</td>
<td>93</td>
</tr>
<tr>
<td>Tomato</td>
<td>200</td>
<td>0.08</td>
<td>0.03</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>Spinach</td>
<td>2,600</td>
<td>0.12</td>
<td>0.30</td>
<td>1.0</td>
<td>100</td>
</tr>
</tbody>
</table>
Modern *Pyropia* (nori) cultivation

- Simple, flat sheet gametophyte (high SA/V)
- 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)

*Porphyra/Pyropia* species

- 1-2 cell layers: all productive

Ariake Bay, Japan
Nursery culture or Ikada System (courtesy of I. Levine)

High vs Low Nutrients

If *Porphyra/Pyropia* requires all of the nutrients (CO₂, NH₄, and PO₄) 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

History of Seaweed industry (2010 - present)

- Ecosystem services approach to overcome NIMBY
History of Seaweed industry (2010 - present)

- Ecosystem services approach to overcome NIMBY

The Frequency of Hypoxia in Long Island Sound Bottom Waters

**Percent of Hypoxic Years**
- <3.0 mg/L
- 3.0 - 5.0
- 5.0 - 10
- 10 - 20
- 20 - 30
- 30 - 50
- 50 - 70
- 70 - 90
- 90 - 100

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)

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**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


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**Gracilaria nursery systems**

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 alginites (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

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
- 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
- 1,100-1,800 kg C ha⁻¹
- 38-180 kg N ha⁻¹
Kelp Aquaculture in New England: 10 Years and Growing

- Farms (>70)
- Nurseries
- Educational Labs 2016-20

Farms: West Coast US- AK, WA, OR

Kelp Aquaculture in New England:
10 Years and Growing

New England Seaweed Culture Handbook


Saccharina latissima

Sporophyte


Katie Flavin
Nick Flavin
Bill Habiva, PhD

Saccharina latissima

Sporophyte

Video Series Shows How to Start Growing Seaweed
Modular nursery system for the continuous mass production of young *Saccharina* plants

- 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

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

- Connecticut: *Gracilaria* open water & land-based cultivation
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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....

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

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Feed(^a)</th>
<th>Food(^b,c)</th>
<th>Food supplements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic (total)</td>
<td>40 mg/kg</td>
<td>No standard for seaweed</td>
<td>No standard for seaweed</td>
</tr>
<tr>
<td>Arsenic (inorganic)</td>
<td>2 mg/kg</td>
<td>No standard for seaweed</td>
<td>No standard for seaweed</td>
</tr>
<tr>
<td>Cadmium</td>
<td>1 mg/kg</td>
<td>No standard for seaweed</td>
<td>3.0 mg/kg ww</td>
</tr>
<tr>
<td>Lead</td>
<td>10 mg/kg</td>
<td>No standard for seaweed</td>
<td>3.0 mg/kg ww</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.1 mg/kg</td>
<td>No standard for seaweed</td>
<td>0.10 mg/kg ww</td>
</tr>
</tbody>
</table>

\(^a\) 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.”


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

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

Courtesy of A. Hristov
The ARPA-E MARINER Program
(MacroAlgae Research Inspiring Novel Energy Resources ~ $50 Million)

Earn to Learn: Pathways to fuels scale
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

¹CSS, Inc. for NOAA NOS/NCCOS, Beaufort, NC. ²NOAA NCCOS, Beaufort, NC
Selective Breeding Technologies for Scalable Offshore Seaweed Farming

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.

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

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

GOM (Gulf of Maine)
SNE (Southern New England)
**Saccharina latissima** range of morphologies

Breeding Cycle

- **Gametophytes**
  - m
  - f

- **Sporophytes**

- **Direct spray on to string or rope**

- **Automated single cell sorting – NOAA Milford**

- **Kelp blade & sorus tissue**

- **M. Marty-Rivera**

- **S. Umanzor**

- 2-4 weeks after crossing

- S. Augyte

- Y. Li
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 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. Aydlett (WHOI), S. Augyte (UCONN), D. Bailey (WHOI), M. Currie (WHOI), S. Umanzör (UCONN)

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

![Graph showing potential improvements in yield with 10% and 20% improvement/year.]

- Highest documented in NE
- Recently reported by farmers in NE
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](http://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

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

[Algaefoundationatec.org](http://Algaefoundationatec.org)  
[Thealgaefoundation.org](http://Thealgaefoundation.org)
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, Porphyras, 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.

Algae Cultivation Extension Short-courses (ACES) Part-1 Seaweeds
http://www.algaefoundationatec.org/aces_intro.html

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• 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)