Alternative Development Pathways for Seaweed Aquaculture

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Seaweeds as Great Opportunities in Aquaculture's "New Geographies"

Some Seaweed Facts and Fantasies

Seaweed Aquaculture and Rural Fishing Livelihoods

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EDITORIAL

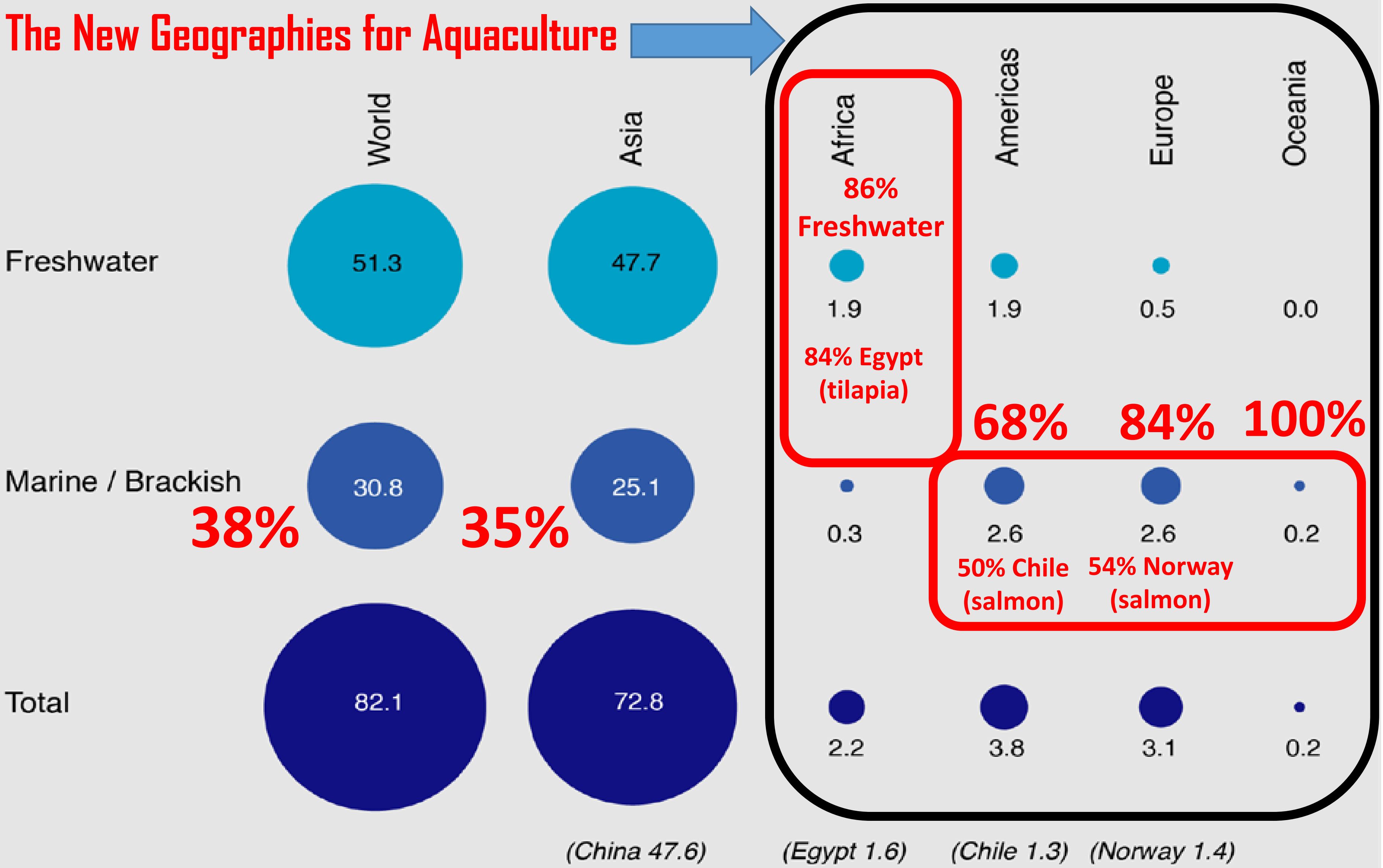
A decadal outlook for global aquaculture

Mair, G.C., Halwart, M., Derun, Y., and B.A. Costa-Pierce (2023). A decadal outlook for global aquaculture. *Journal of the World Aquaculture Society* 54(2): 196-205. https://doi.org/10.1111/jwas.12977

Costa-Pierce, B.A. and T. Chopin (2021). The hype, fantasies and realities of aquaculture development globally and in its new geographies. *World Aquaculture* 52 (2): 23-35.

Aquaculture Production by Regions and the Leading Producers

Numbers in million metric tons (MMT)



Data: FAO 2020

Inconvenient blue foods facts

I. Asia dominates in every way...**STILL** 89%
II. China is the world's leader..... **STILL** 58%
III. Most is freshwater.................. **STILL** 62%

“OLD Geographies”

China	18.5 (57.1)
Indonesia	9.3 (28.8)
Republic of Korea	1.7 (5.3)
Philippines	1.5 (4.6)
Democratic People’s Republic of Korea	0.5 (1.7)
Japan	0.4 (1.2)
Malaysia	0.2 (0.5)
China - Taiwan	0.1 (0.2)
Vietnam	0.0 (0.1)
Total Asian seaweed production	32.2 (99.5)
Zanzibar, United Republic of Tanzania	0.1 (0.3)
Chile	0.0 (0.1)
Other producers in the world	0.1 (0.1)
Total world seaweed production	32.4 (100)

Saccharina japonica (kombu)	11.4
Eucheuma spp.	9.4
Oysters	5.8
Penaeus vannamei (whiteleg shrimp)	5.0
Ruditapes philippinarum (Manila clam)	4.1
Gracilaria spp.	3.4
Porphyra/Pyropia spp. (nori)	2.9
Salmo salar (Atlantic salmon)	2.4
Undaria pinnatifida (wakame)	2.3
Scallops	1.9
Kappaphycus spp.	1.6
Mussels	1.6
Sinovovacula constricta (Chinese razor clam)	0.9
Penaeus monodon (giant tiger prawn)	0.8
Anadara granosa (blood cockle)	0.4
Sargassum spp.	0.3
Apostichopus japonicus (Japanese sea cucumber)	0.2

Numbers are in million metric tons live weight (FAO 2020); brown seaweeds in brown font, red seaweeds in red font.

New Geographies – North America and Europe

>90% of the seaweeds harvested annually from
North America and Europe
are from

SEAWEED FISHERIES, not aquaculture

"New Geographies"

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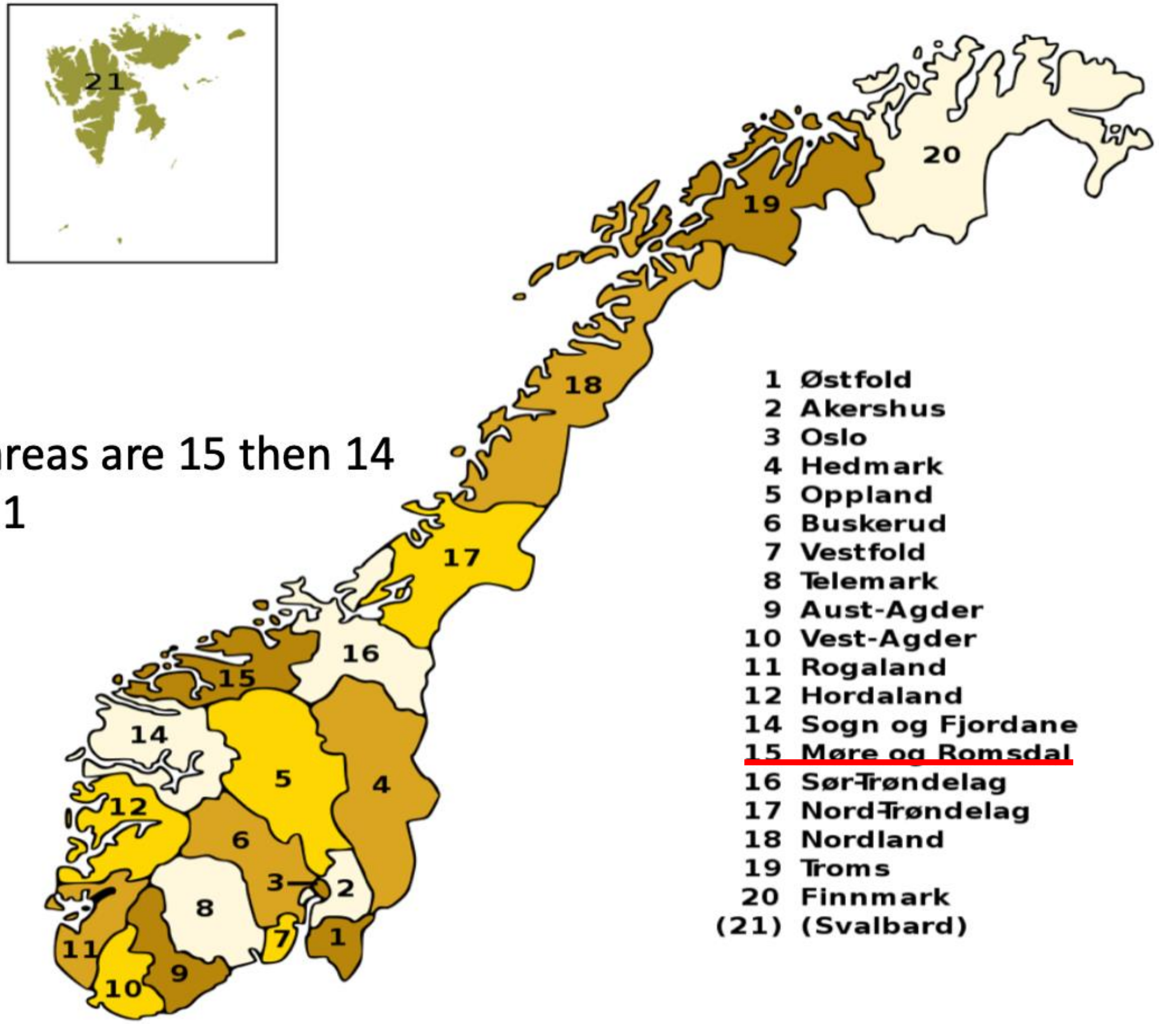
LH Harvesting areas in Norway



Main harvest areas are 15 then 14 then 16 then 11

from Marine Biopolymers proposal to Iceland (2020)

Total laminaria hyperborea harvesting Norway

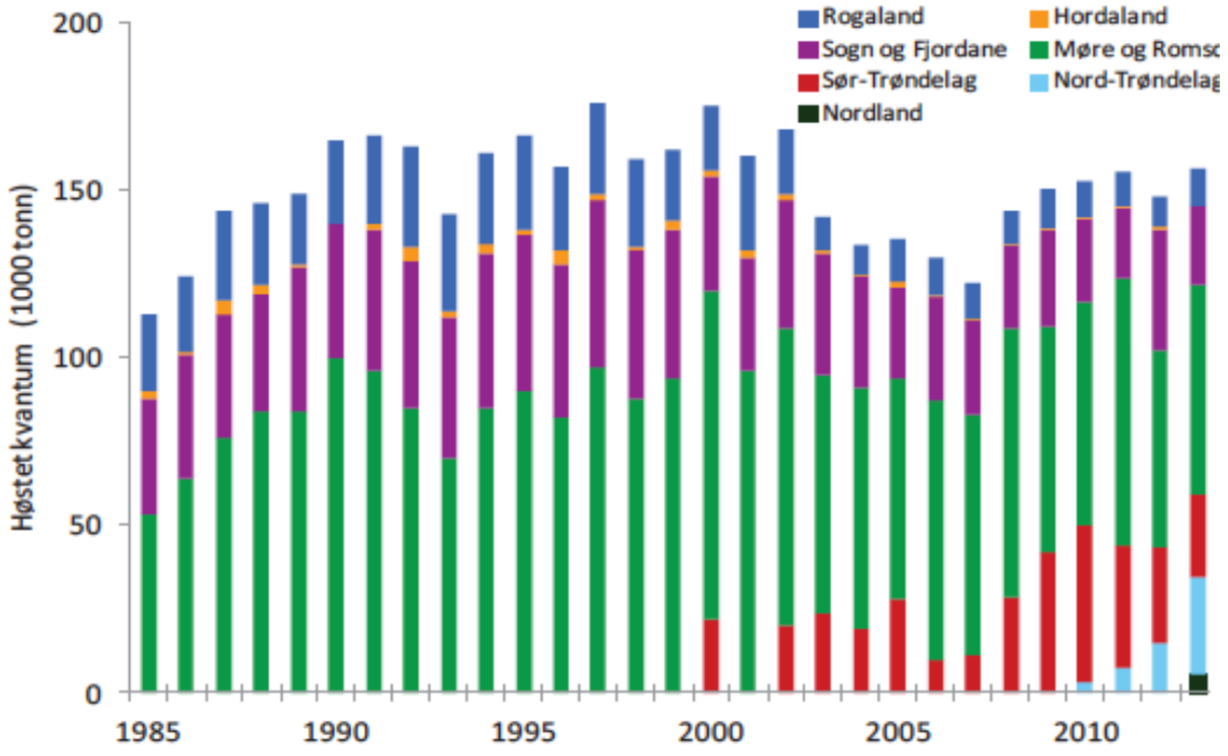


Figure 1. County quantity harvested (in thousand tonnes) of kelp (Laminaria hyperborea) in the period 1985-2013.

From Marine Biopolymers proposal to Iceland (2020)

MARINE BIOPOLYMERS


Raudeberg
95D
94A
Måløy
93B
92C
Bryggja
Eldevika
91D
Bremangerlandet
90E
Oldeide
89D
Rugsund
88B
Bremanger
Leirgulen
86E
Frøya
85D
Bortnen
84B
Kalvåg
Vingelva
83A
Frøysjøen
82C
Smørhamn
Nordfjo
Svelgen
80E
Midtgulen
Kvanhovden
79D
78A
Hovden
77C
76D
75B
Grytadalsbu
74A
Skorpa
73C
Flora
Brandsøy
Ytterøyane
72B
Stabben
71A
Rognalds-
våg
Kinn
70D
Høydals-
fjorden
Eikefjord
Stavøya
69E
68C
Askrova
Bru
Ryggsteinhav
63E
67C
66B
Svanøya
65A
62B

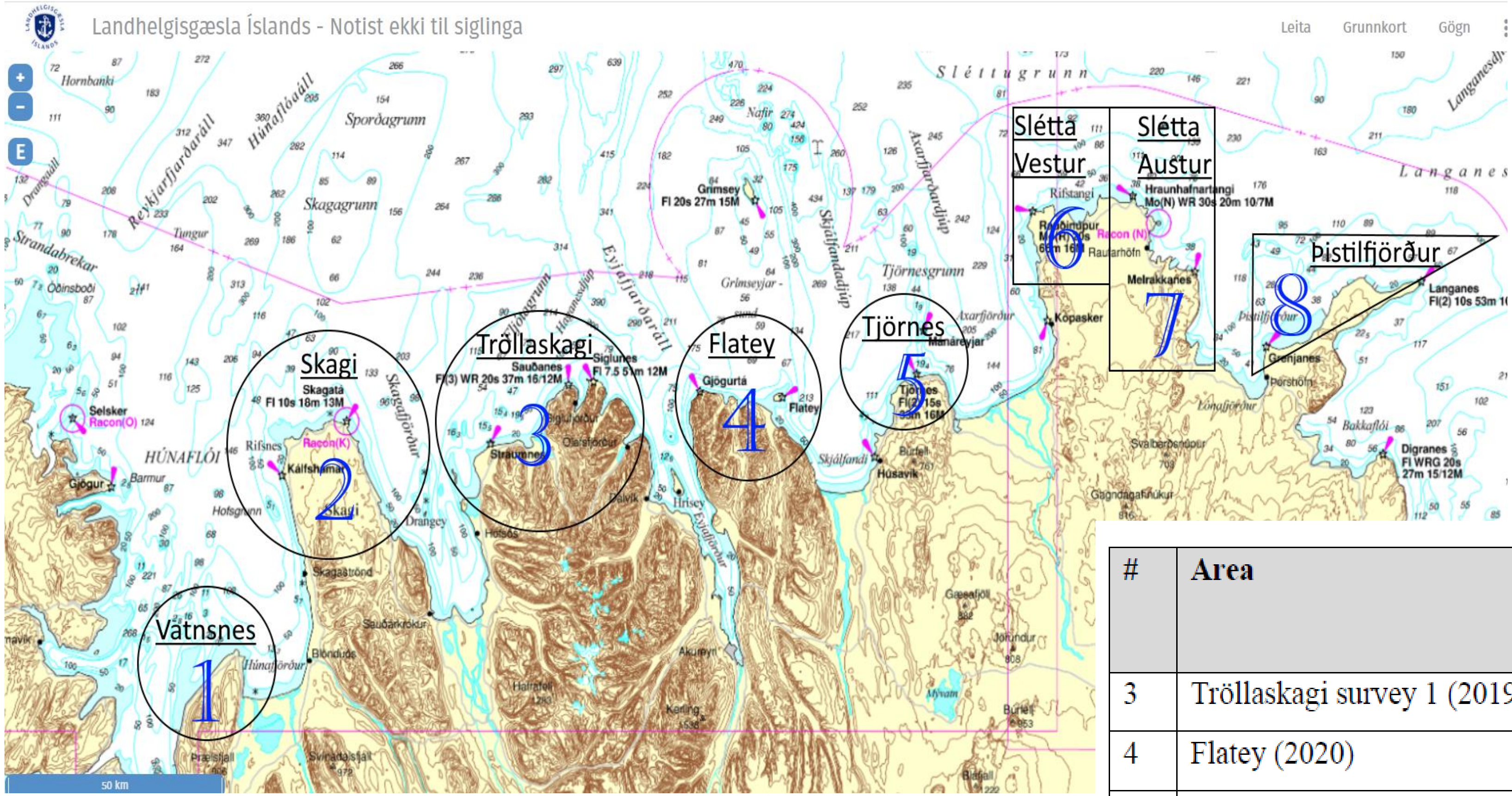

Thorverk Ltd. Reykhólar, Iceland

Breidafjördur fjord - harvest wild *Ascophyllum nodosum* (rockweed) and *Laminaria digitata* (oar kelp).

95% of Thorverk's products are exported (dried seaweed meal)

Most of Reykhólar's ~120 people are employed by the seaweed factory

Institute Marine Research



#	Area	Estimated Biomass (MT)	Surveyed Biomass to Date (MT)
3	Tröllaskagi survey 1 (2019)	125,000	125,000
4	Flatey (2020)	287,000*	191,800
5	Tjornes (2020)	111,000	109,500
6/7	Sletta Vest/Astur (2021)	550,000	**
8	Pistilfjordour/Langanes West (2021)	389,000	**
3	Tröllaskagi survey 2 (2021)	165,000	**
2	Skagi (2021)	173,000	**
1	Vatnsnes (2021)	400,000	**
	TOTAL	**2,200,000**	

CANADA
QUÉBEC
Q U É B E C
Montmagny
St-Laurent
Saint-Laurent
St-Georges
Trois-Rivières
Lac St-Pierre
Victoriaville
Drummondville
St-Hyacinthe
Montréal
Lac Memphrémagog
Edmundston
Grand Falls (Grand Sault)
Perth-Andover
CANADA
Moncton
Grand Lake
FREDERICTON
Sussex
Woodstock
St John
Oromocto
Houlton
NEW BRUNSWICK
Oromocto Lake
Grand L.
Spednic L.
Bay of Fundy
Saint Stephen
Big L.
NOVA SCOTIA
St John
Grand Lake Seboeis
W. Br. Penobscot
Chesuncook L.
Pemadumcook L.
Penobscot
Moosehead Lake
MAINE
Flagstaf L.
Bangor
Mt Desert I.
Yarmouth
AUGUSTA
Gulf of Maine
Lewiston
ATLANTIC OCEAN
Sebago Lake
Portland
NEW HAMPSHIRE
Connecticut
Lake Champain
Burlington
MONTPELIER
NEW YORK
VERMONT
Lake Winnipesaukee
Rutland
CONCORD
0 km 30 60 90 km
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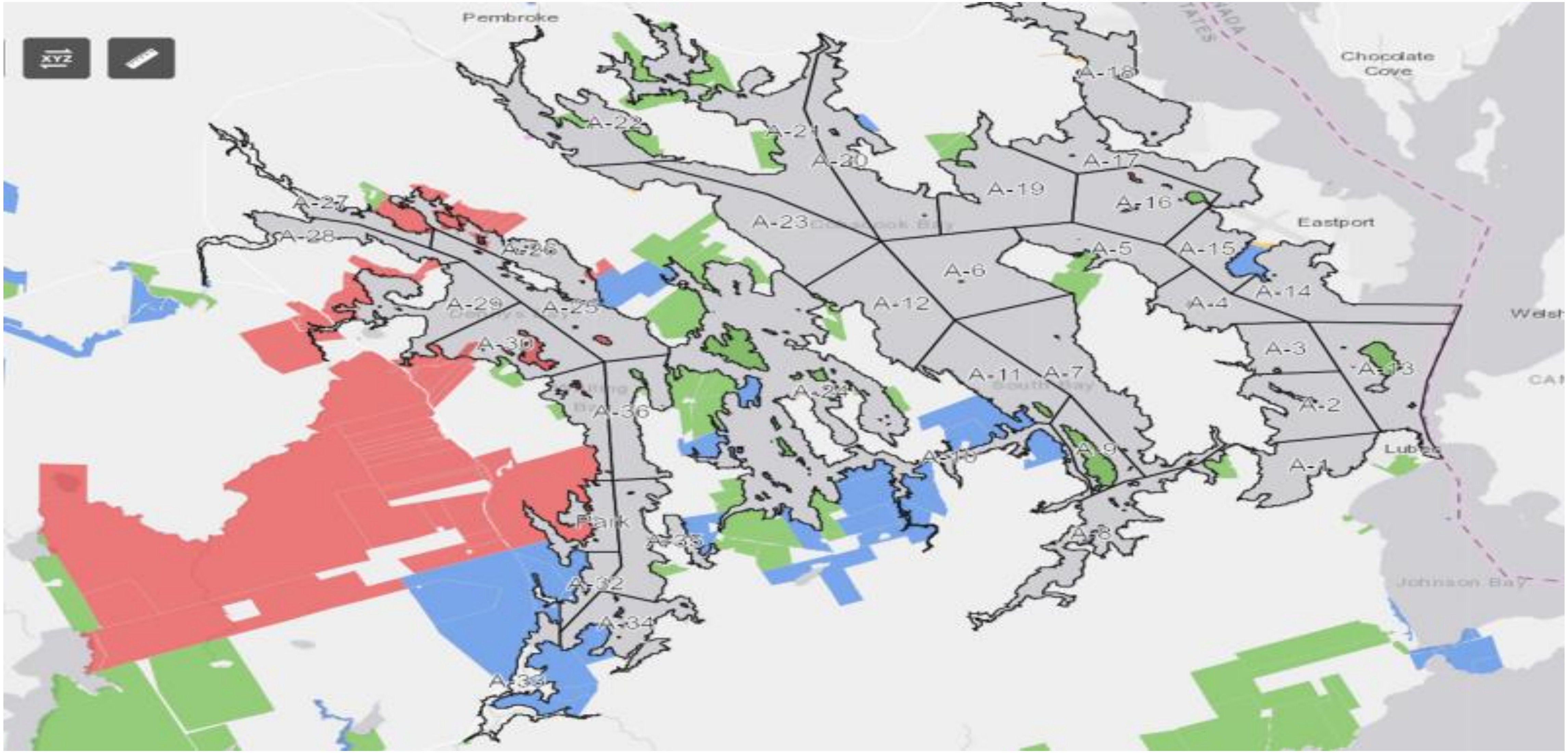
Seaweed Fisheries in North America…



Seaweed Fisheries in North America…

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Some Seaweed Facts and Fantasies

Seaweed Aquaculture and Rural Fishing Livelihoods

Fantasy – **Quick Fix for Climate?**

Carbon - "Sequestration"

Methane - Cattle Burbs and Farts

BLUE WASHING?

Krause-Jensen, D. & Duarte, C. (2016) Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* 9

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Gallagher, J.B. et al. (2021). Missing the forest for the trees: Do seaweed ecosystems mitigate atmospheric CO_2 emissions? bioRxiv doi: 10.1101/2021.09.05.459038

Troell et al. (2022). Farming the Ocean – Seaweeds as a Quick Fix for the Climate? *Reviews in Fisheries Science & Aquaculture* doi: 10.1080/23308249.2022.2048792

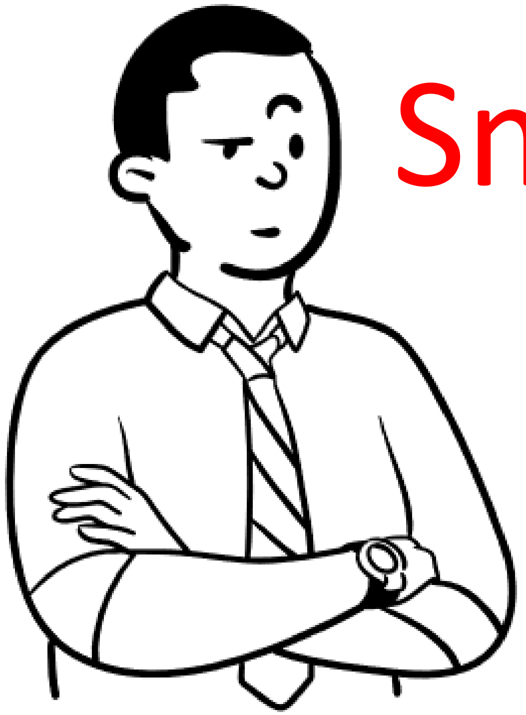
Chopin et al. (2024). Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass. *One Earth* (2024), https://doi.org/10.1016/j.oneear.2024.01.013


AL
INCONVENIENT
TRUTH

TABLE 1. Extrapolated ecosystem services from 500 million tons (dry weight) of seaweeds.

Ocean area required	500,000 km^2	Based on average annual yield of 1,000 dry tons/km^2 undert current best practice. Equals 0.03% of the ocean surface area.
Protein for people and animals	50,000,000 tons	Assumes average protein content of 10% dry weight. Estimated value $28 billion. Could completely replace fishmeal in animal feeds.
Algal oil for people and animals	15,000,000 tons	Assumes average lipid content of 3% dry weight. Estimated value $23 billion. Could completely replace fish oil in animal feeds.
Nitrogen removal	10,000,000 tons	Assumes nitrogen content 2% of dry weight. Equals 18% of the nitrogen added to oceans through fertilizer.
Phosphorous removal	1,000,000 tons	Assumes phosphorous content 0.2% of dry weight. Represents 61% of the phosphorous input as fertilizer.
Carbon assimilation	135,000,000 tons	Assumes carbon content 27% of dry weight. Equals 6% of the carbon added annually to oceans from greenhouse gas emissions.
Bioenergy potential	1,250,000,000 MWH	Assumes 50% carbohydrate content, converted to energy. Equals 1% of annual global energy use.
Land sparing	1,000,000 km^2	Assumes 5 tons/ha average farm yield. Equals 6% of global cropland.
Freshwater sparing	500 km^3	Assumes agricultural use averages 1 m^3 water/kg biomass. Equals 14% of annual global freshwater withdrawals.

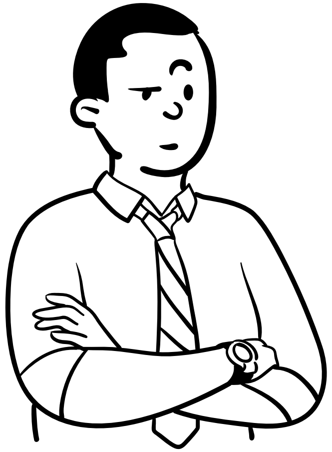
“Only” 0.03% of ocean space



Small?

18% of N as fertilizers
61% of P as fertilizers
6% of C added to oceans
1% of global energy use
Spares 6% global cropland
Spares 14% of global water withdrawls

"Only" 0.03% of Ocean Space SMALL?



Big! 500,000 km² Dry to WW 5-10X

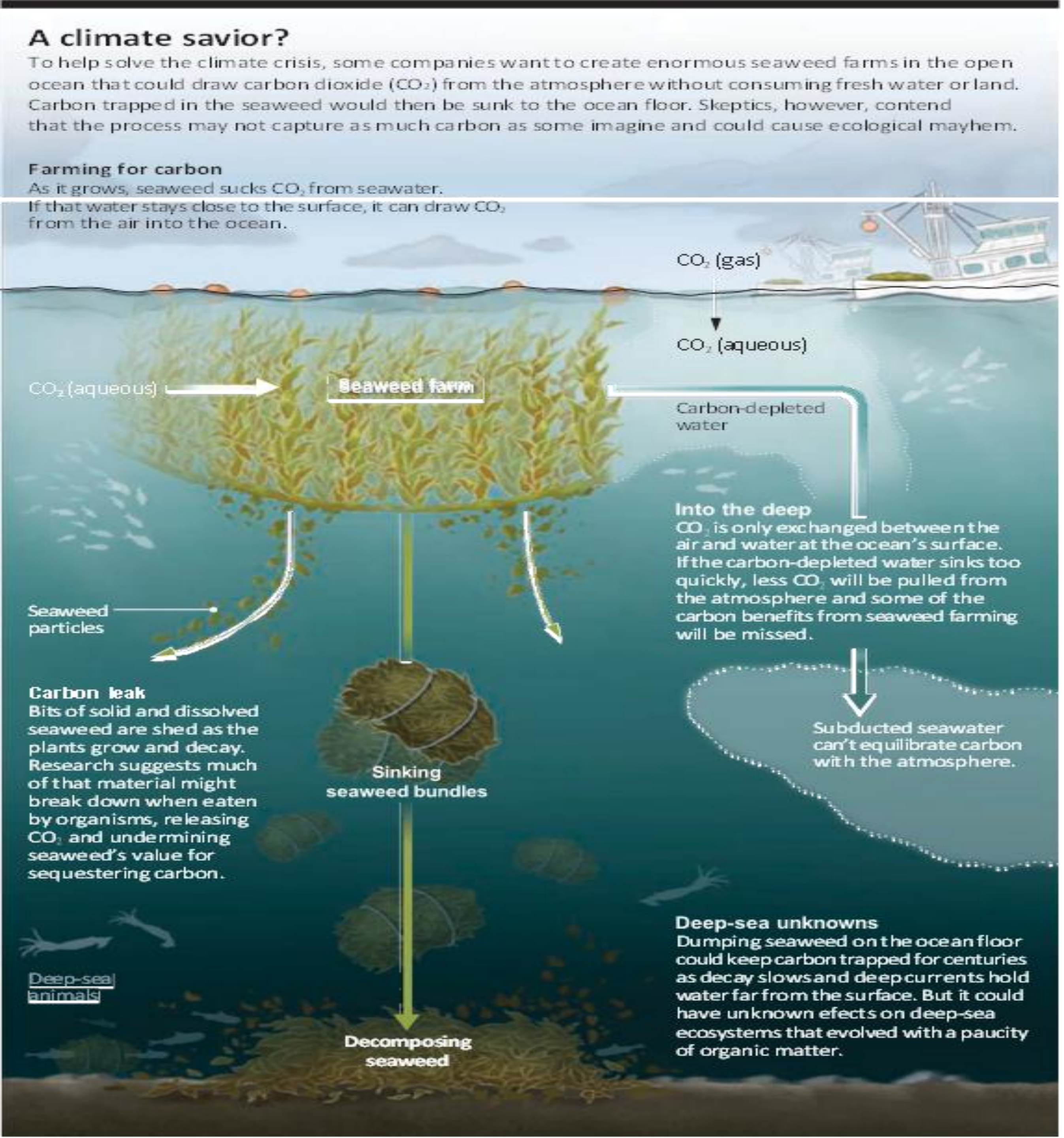
2.5 to 5 million km²

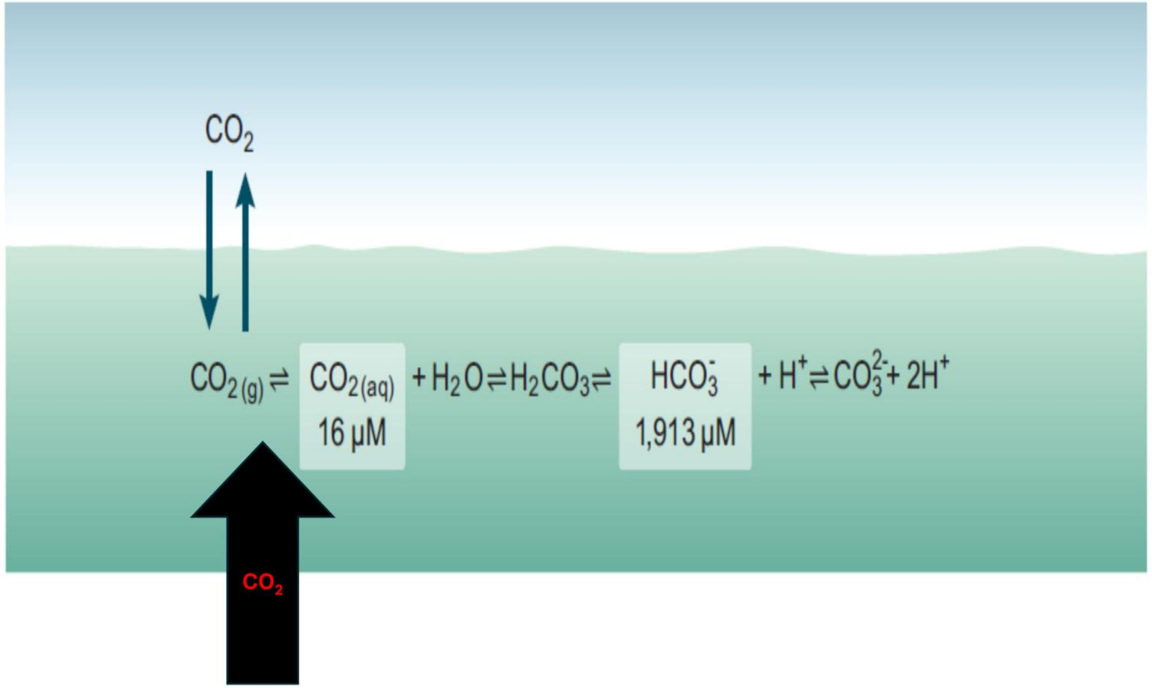
ONLY
6% of C?

Dry ~Size of Spain or France

~Size of All Canada's Agricultural Lands

Wet ~Size of Australia





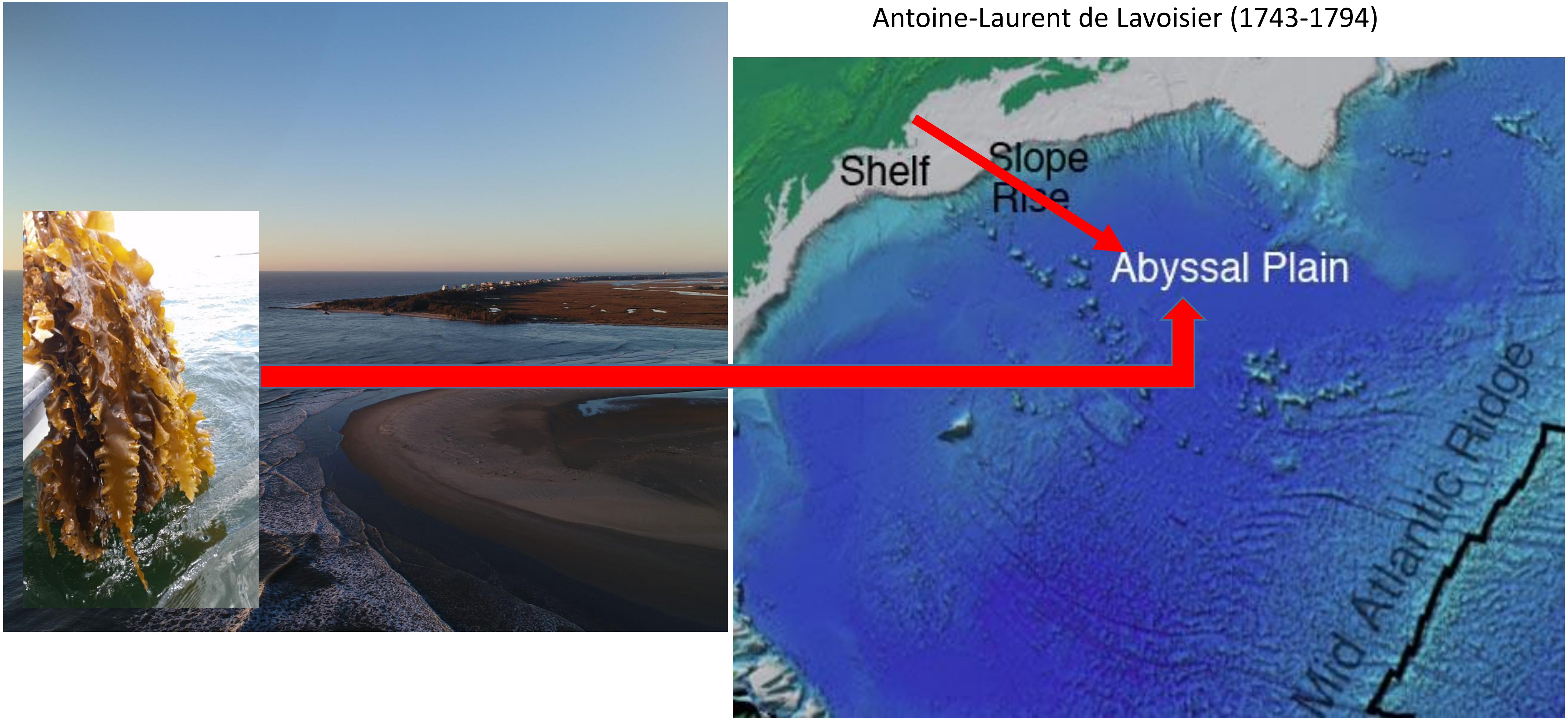
Hurd et al. (2023). Air-sea carbon dioxide equilibrium: Will it be possible to use seaweeds for carbon removal offsets? *J. Phycology*. 2023;00:1–11.

Cornwall, W. (2024) *Science* 385(6712):924-927.

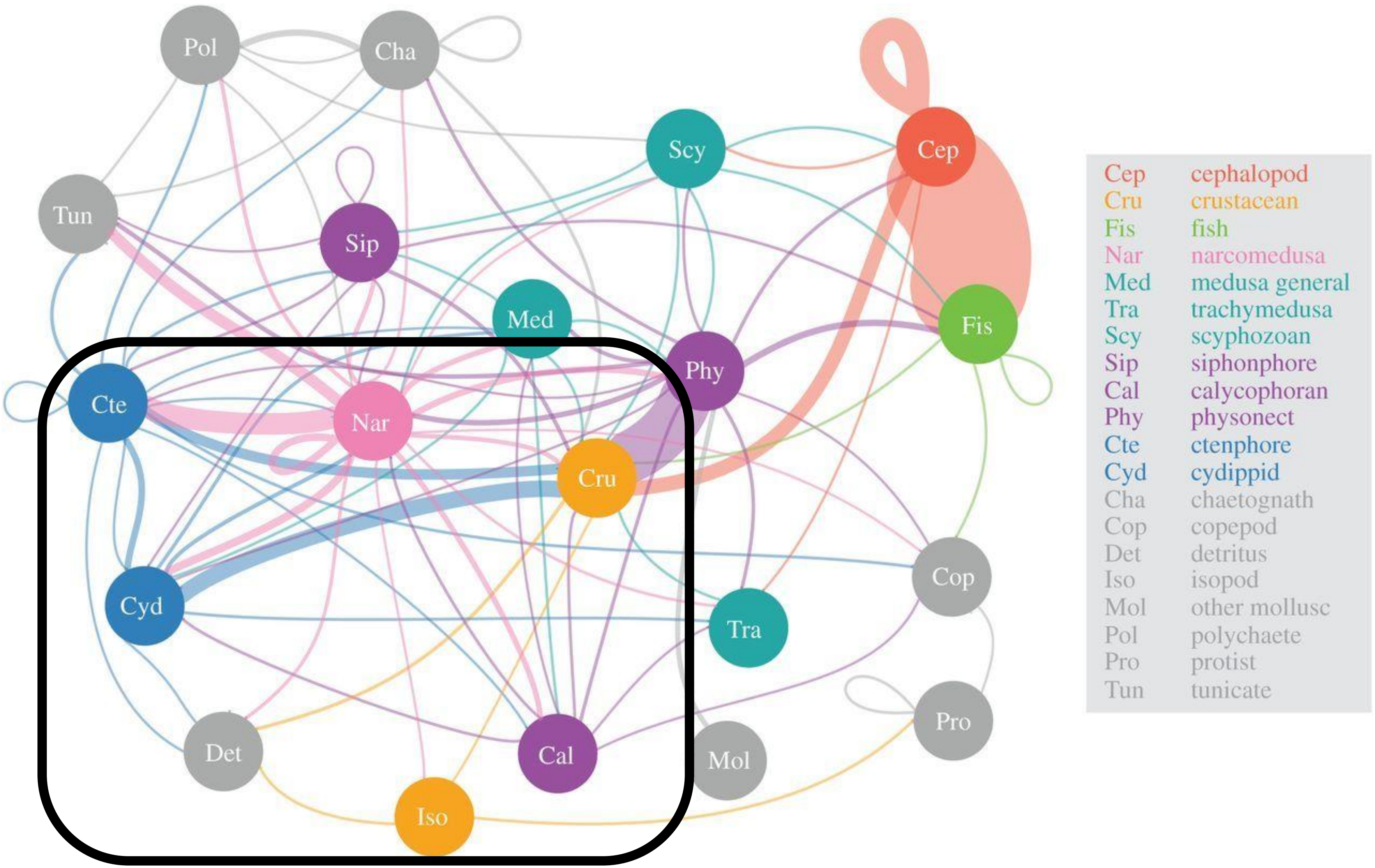
Law of Conservation of Mass

"Nothing is lost, nothing is created, everything is transformed."

Antoine-Laurent de Lavoisier (1743-1794)



Choy, C.A. et al. (2017). Deep pelagic food web structure as revealed by in situ feeding observations. *Proceedings of the Royal Society B*. 284: 20172116, doi: 10.1098/rspb.2017.2116

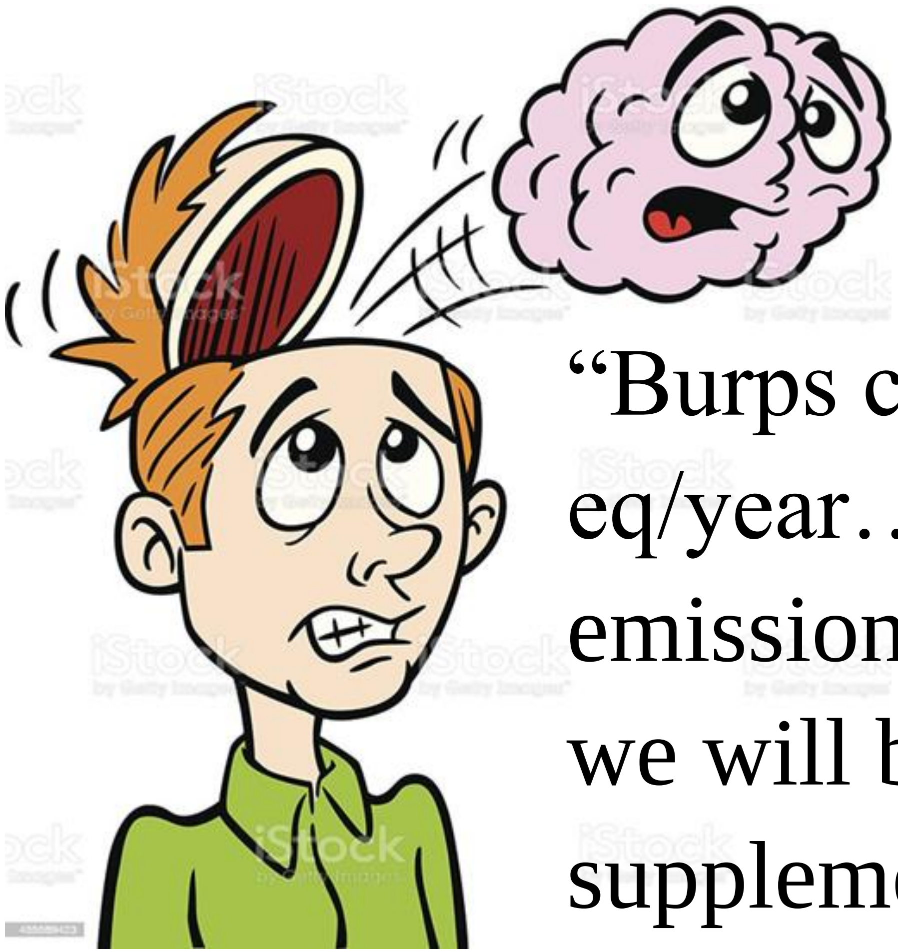


For Nearshore Oceans

It's NITROGEN

"The forgotten element of CLIMATE CHANGE"

Asparagopsis taxiformis



"Burps contribute ~2 billion tonnes of CO_2 eq/year…more than 4% of all greenhouse emissions globally. By the end of this decade, we will be growing enough of our seaweed to supplement **all 100 million cattle in the US, all on a plot of land that is smaller than Chicago's O'Hare airport (7200 acres)**"

Kinley et al. (2016) Experiments done *in vitro* (in artificial rumens) not *in vivo*. **There was no real cow rumen** absorbing one gram of the red seaweed *Asparagopsis taxiformis*

Bromoform is the halogenated compound that reduces enteric methane emissions in cows.

In experiments with real cows -

*Animals regularly refused the feed or selected against *Asparagopsis*

*Cows rumen walls showed inflammation

Bromoform residues have been found in cow urine & milk

Muizelaar et al. (2021). Safety and transfer study: Transfer of bromoform present in *Asparagopsis taxiformis* to milk and urine of lactating dairy cows. *Foods 10*(3),584 https://doi.org/10.3390/foods10030584

Algal Research 64 (2022) 102673

Contents lists available at ScienceDirect

Algal Research

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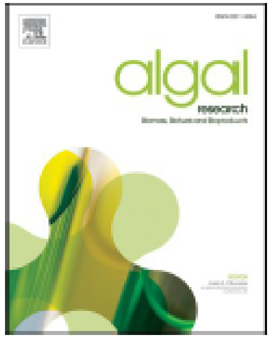


Review article

Benefits and risks of including the bromoform containing seaweed *Asparagopsis* in feed for the reduction of methane production from ruminants

Christopher R.K. Glasson [a], Robert D. Kinley [b], Rocky de Nys [c], Nick King [d], Serean L. Adams [d], Michael A. Packer [d], Johan Svenson [d], Charles T. Eason [d,1,2], Marie Magnusson [a,*]

[a] *University of Waikato, Te Aka Mātuatua - School of Science, Environmental Research Institute, Tauranga 3110, New Zealand*
[b] *Commonwealth Scientific and Industrial Research Organisation (CSIRO), Agriculture and Food, Townsville, QLD 4811, Australia*
[c] *James Cook University, Centre for Macroalgal Resources and Biotechnology, and College of Science and Engineering, Townsville, QLD 4811, Australia*
[d] *Cawthron Institute, Nelson 7010, New Zealand*

A. taxiformis (and *A. armata*) are small red seaweeds, not ubiquitous, and have complex life histories. They can be produced with great care in academic settings…but not be easy to produce at the large biomass levels necessary to feed a **global cattle population ~1 billion head (2020)**

~ 60% of the world's cattle are not in feedlots but ranched in free-range pastures *where they are encountered infrequently*, mainly when counted or branded.

Even in countries where feedlots are common, cattle normally remain in a feedlot for **only 3-5 months of their 36-month average production cycle.**

Costa-Pierce, B.A. and T. Chopin. 2021. The hype, fantasies and realities of aquaculture development globally and in its new geographies. *World Aquaculture* 52 (2): 23-35.

Can we now all eat guilt-free burgers" ??

Seaweeds as Great Opportunities in Aquaculture's "Geographies"

Some Seaweed Facts and Fantasies

Seaweed Aquaculture and Rural Fishing Livelihoods

Scale is one of the most controversial aspects of aquaculture today

Scaling issues play a central role in the political and regulatory obstacles to advancing aquaculture

Most aquaculture development occurs in rural areas

SCALING OUT, NOT ONLY UP

Frontiers Research Topic (frontiersin.org) 82 authors in 10 articles

Barry Antonio Costa-Pierce, USA & PORTUGAL
Helgi Thor Thorarensen, NORWAY
Åsa Strand, SWEDEN

"Ocean/Aquatic Food Systems: Interactions with Ecosystems, Fisheries, Aquaculture, and People"

FOUR RECURRING THEMES

“Promotion of **diverse aquaculture scales** may allow development of new ecological and social synergies for **smaller farms to achieve economic viability at regional scales**”

#1 IMPORT SUBSTITUTION

U.S. farm harvests only
~454,000 kg (2019)

Imports **8.6 million kg**
edible seaweeds from Asia
>50% from China, South Korea

New Technology → New Markets

Market-Driven Technology Development

Existing Markets → Appropriate Technology Development

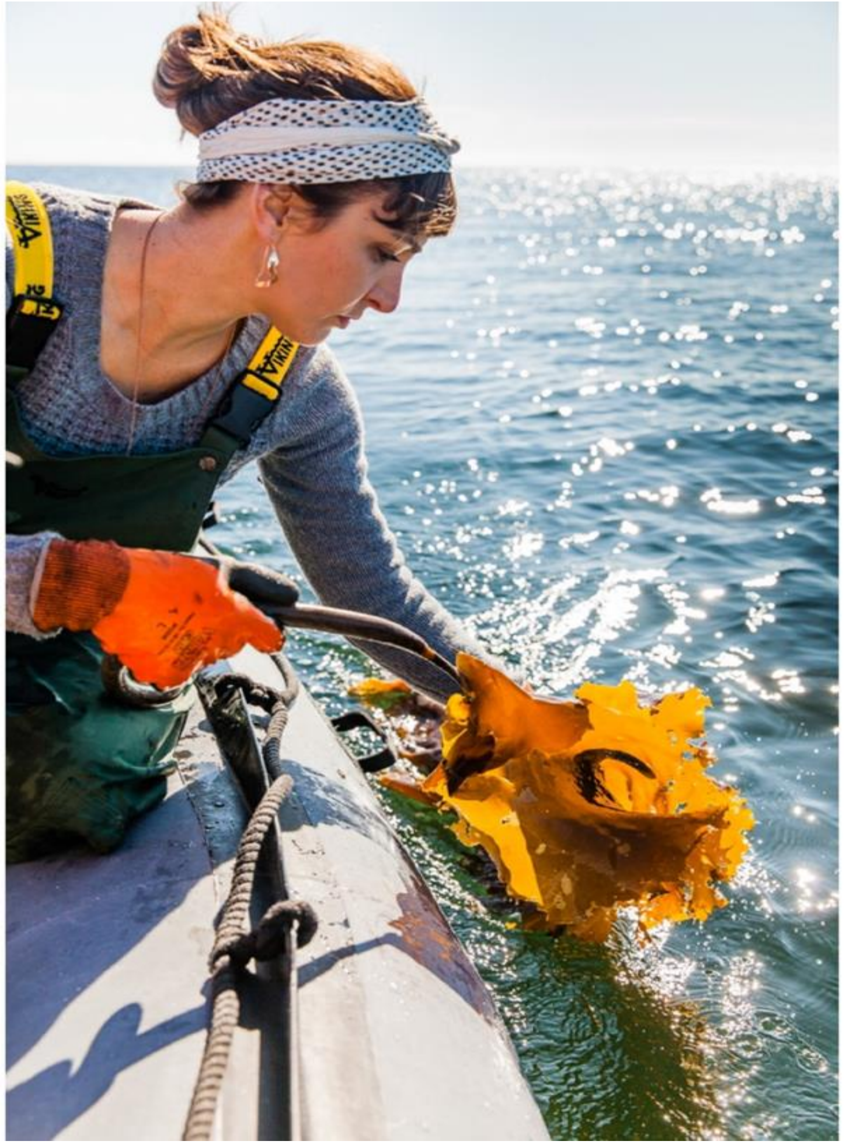
Edible Seaweed Market Analysis

ISLAND INSTITUTE

Growing and harvesting the primary farmed edible seaweed species (sugar/skinny kelp and alaria) is a relatively low cost, easily implementable process that can deliver supplemental revenue and asset utilization. For most harvesters that lack processing capabilities, edible seaweed provides supplemental revenue rather than their primary source of revenue.

The annual revenue potential for harvesters varies significantly depending on lease acreage and processing practices. Harvesters without processing capabilities can expect to realize approximately $0.40 – $0.70 per wet pound for bulk unprocessed seaweed. For these harvesters, securing access to processing capabilities prior to initiating the growing process, either via established contracts with processors or investing in first stage processing (typically drying) capabilities, is critical to success. Maine infrastructure requirements to support continued growth include:

- Expanded processing capacity
- Value-added product development
- Distribution network expansion
- Brand building/consumer awareness



Atlantic Sea Farms

Successful "Scaling Out" Model of Seaweed Farming – most ~2 ha

*27 independent ASF partner farmers, primarily fishing families who already have boats/gear

*Trains/Provides free seed/Contracts to buy harvests

Make US$ 40,000 to $110,000/season as supplemental income

#2 Community Scale

"Grant cycles live and die. Business doesn't. The world is ready for seaweed. It doesn't need to be subsidized."

Brianna Warner
CEO
Atlantic Sea Farms

#3 PARTNERSHIPS WITH APPLIED ACADEMIA

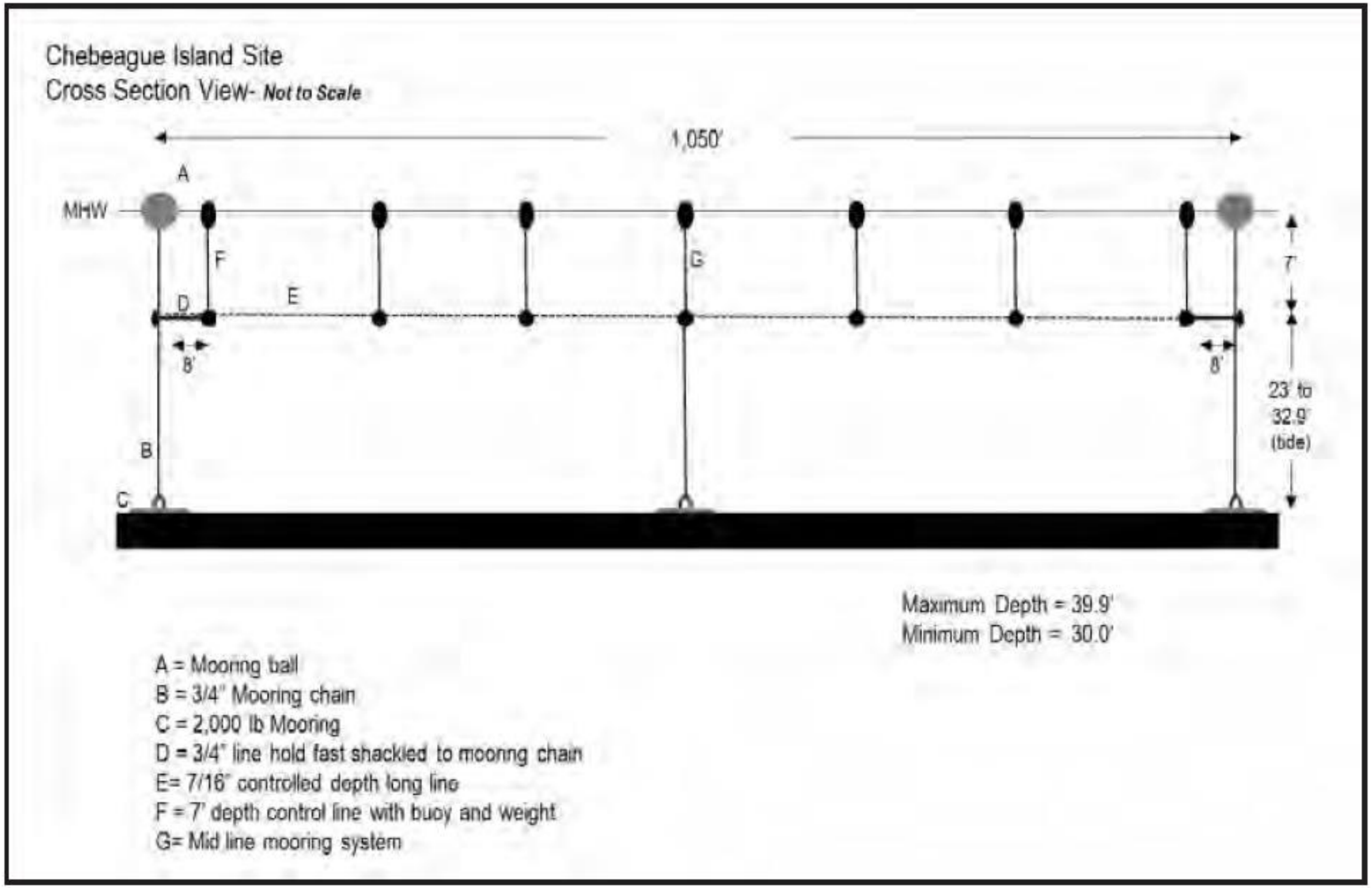
Science Based DESIGN CRITERIA…SURVIVABLE, SOPHISTICATED ENGINEERING BUT VERY LOW COST

- Minimalist approach to gear
  - low capital…use existing fishing assets
  - highly mobile
  - easily deployed
  - easily permitted
- Submerged technology
- No conflicts with the "fishing/tourism summers"
- Cash on harvests
- High education value = easy tech transfer

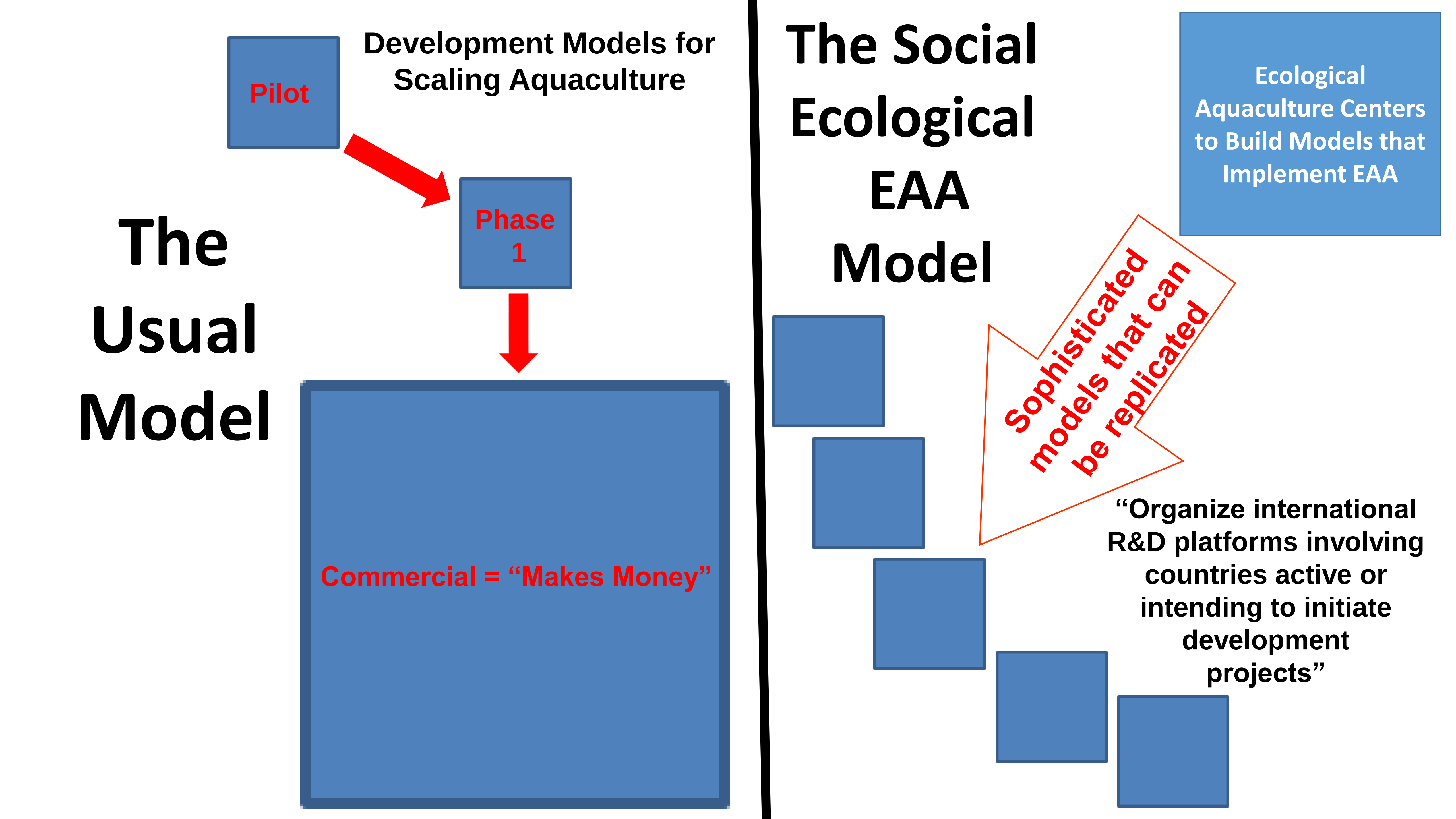
Design Charette

Transdisciplinary - Formed a Ecological Engineering, Social-Ecological Research Team

OLD - Dead Weight Moorings, Vertical Mooring Line Design



- Expensive Moorings
- Cumbersome to Deploy
- Permanent Installation
- Large Buoys
- Slack System
- Requires Large Boats = $$


Development Models for
Scaling Aquaculture
The Usual Model
Pilot
Phase 1
Commercial = “Makes Money”
The Social Ecological EAA Model
Ecological Aquaculture Centers to Build Models that Implement EAA
Sophisticated models that can be replicated
“Organize international R&D platforms involving countries active or intending to initiate development projects”

Aquacultural Engineering 90 (2020) 102086

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journal homepage: www.elsevier.com/locate/aque

Hydrodynamic characteristics of a full-scale kelp model for aquaculture applications

David W. Fredriksson[a,*], Tobias Dewhurst[b], Andrew Drach[c], William Beaver[d], Adam T. St. Gelais[e,f], Kathryn Johndrow[e], Barry A. Costa-Pierce[e,f]

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[b] Kelson Marine Co., Scarborough, Maine 04074 USA
[c] University of Texas at Austin, Austin, Texas 78712 USA
[d] Hydromechanics Laboratory, United States Naval Academy, 590 Holloway Road, 11D Annapolis, MD 21402 USA
[e] Graduate Program in Ocean Food Systems, School of Marine & Environmental Programs, University of New England, 11 Hills Beach Road, Biddeford, Maine 04005
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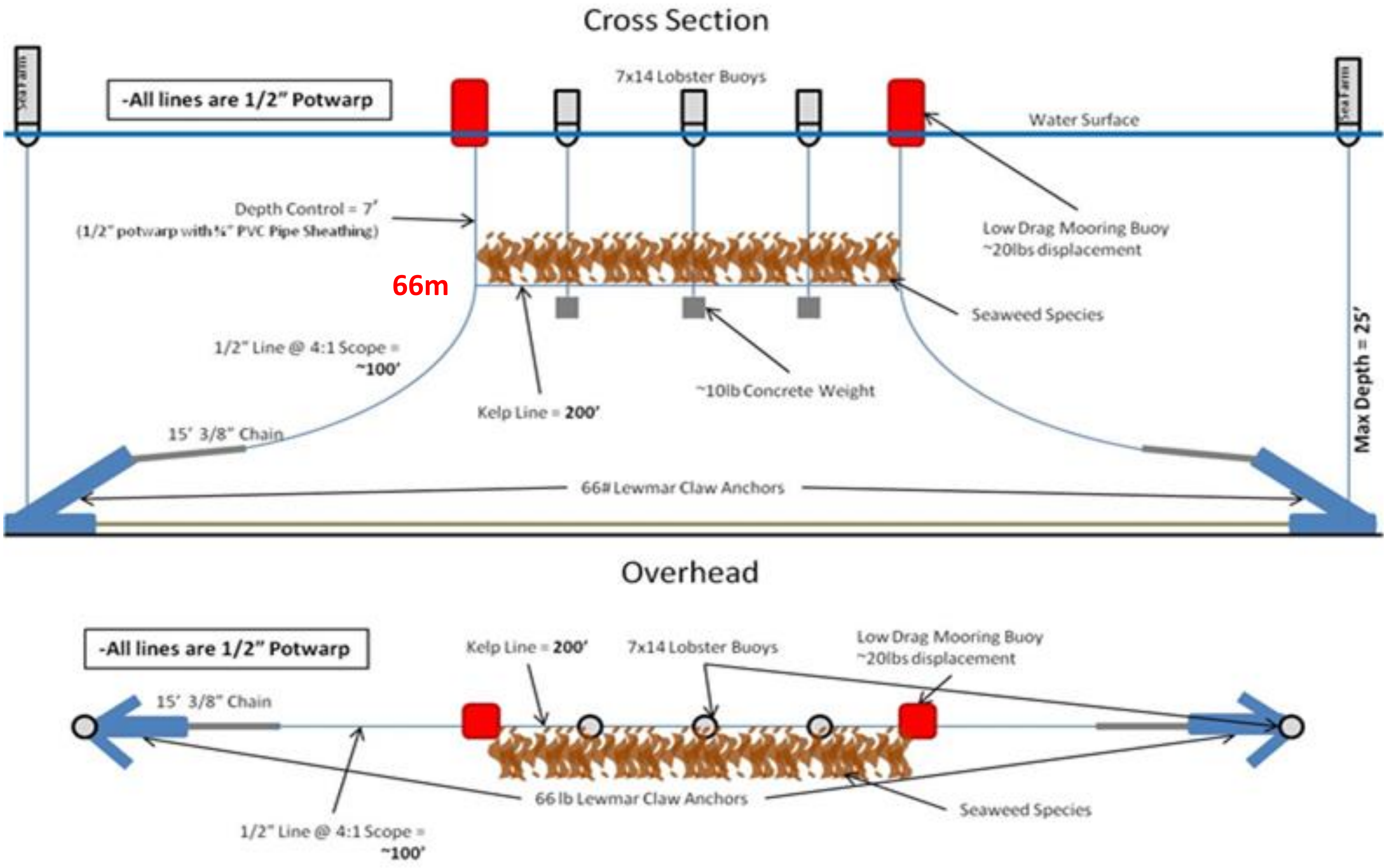
Mooring tension assessment of a single line kelp farm with quantified biomass, waves, and currents

David W. Fredriksson[1*], Adam T. St. Gelais[2], Tobias Dewhurst[3], Struan Coleman[4], Damian C. Brady[2,4] and Barry Antonio Costa-Pierce[5,6]

[1]School of Marine Science and Ocean Engineering, University of New Hampshire, Durham, NH, United States, [2]Aquaculture Research Institute, University of Maine, Darling Marine Center, Walpole, ME, United States, [3]Kelson Marine Co., Portland, ME, United States, [4]School of Marine Sciences, Darling Marine Center, University of Maine, Walpole, ME, United States, [5]Faculty of Biosciences and Aquaculture, Nord University, Bodø, Norway, [6]Ecological Aquaculture Foundation, LLC, Biddeford, ME, United States


Cross Section
-All lines are 1/2" Potwarp
7x14 Lobster Buoys
Water Surface
Depth Control = 7'
(1/2" potwarp with ¾" PVC Pipe Sheathing)
Low Drag Mooring Buoy
~20lbs displacement
66m
Seaweed Species
1/2" Line @ 4:1 Scope =
~100'
~10lb Concrete Weight
Kelp Line = 200'
Max Depth = 25'
15' 3/8" Chain
66# Lewmar Claw Anchors
Overhead
-All lines are 1/2" Potwarp
Kelp Line = 200'
7x14 Lobster Buoys
Low Drag Mooring Buoy
~20lbs displacement
15' 3/8" Chain
66 lb Lewmar Claw Anchors
Seaweed Species
1/2" Line @ 4:1 Scope =
~100'

Farm in a Box

200' (66 m) culture lines
18' (6 m) Maritime Skiff
Crew of 2...Total deployment time < 0.5 hour

Mobile gear all removed during high fishing season

Supplies and materials - All locally available and familiar to commercial fisheries

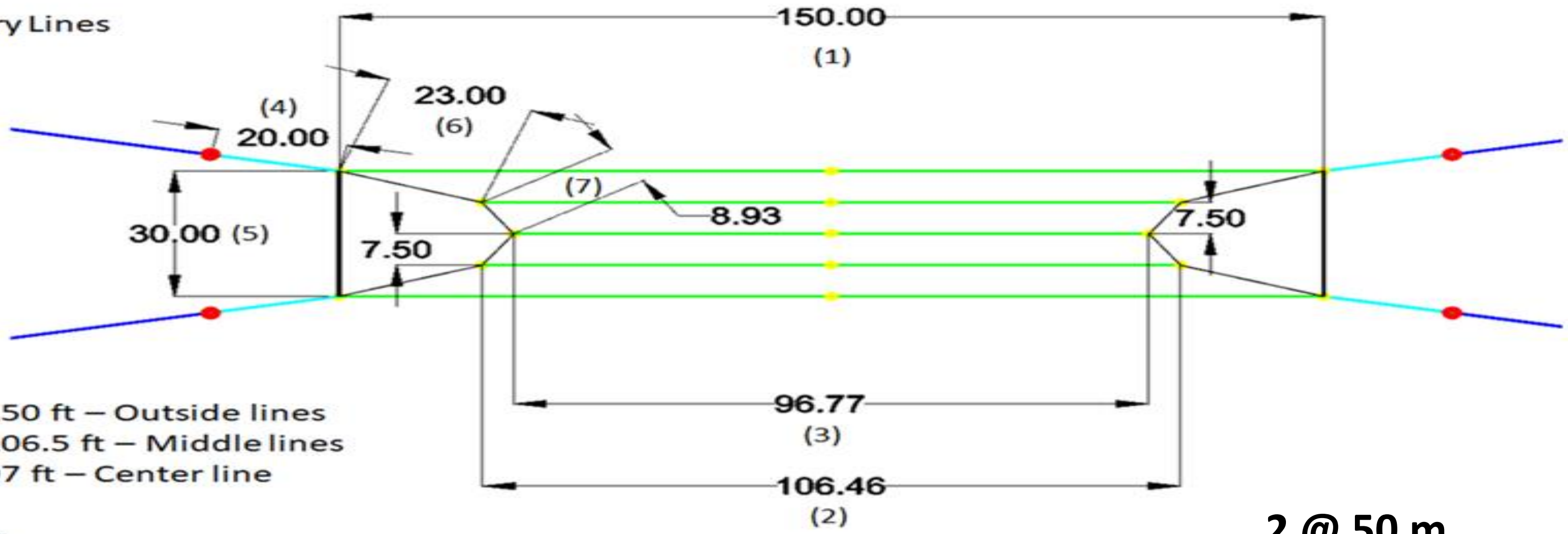
Total cost < $600 REUSABLE

- **Five Years of Success**
- **Cash on harvests...**
- **High education value = Easy tech transfer**

Produces ~ 1000 kg wet wt/line ~15-16 kg/m of Sugar Kelp

Farm in a Truck

a) Grow out and Catenary Lines



Green Grow-out Lines

1. (2) 1” nylon at 150 ft – Outside lines
2. (2) 1” nylon at 106.5 ft – Middle lines
3. (1) 1” nylon at 97 ft – Center line

2 @ 50 m

2 @ 35 m

1 @ 33 m

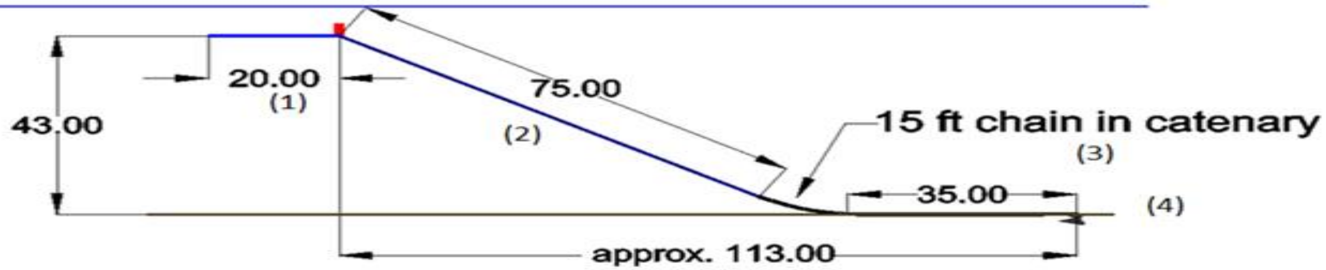
Light Blue Load-cell lines

4. (4) 1” nylon at 20 ft

Black Catenary Lines

5. (2) 1” nylon at 30 ft – Open span lines
6. (4) 1” nylon at 23 ft – Outside catenary lines
7. (4) 1” nylon at 9 ft – Inside catenary lines

b) Anchor leg components



Anchor leg components

1. (4) 1” nylon at 20 ft – Load-cell lines
2. (4) 1” nylon at 75 ft – Anchor lines
3. (4) 5/8” longlink chain at 50 ft
4. (4) 110# claw anchor

frontiers
in Sustainable Food Systems

ORIGINAL RESEARCH
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Engineering A Low-Cost Kelp Aquaculture System for Community-Scale Seaweed Farming at Nearshore Exposed Sites *via* User-Focused Design Process

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FINAL COMMENTS
RECOMMENDATIONS

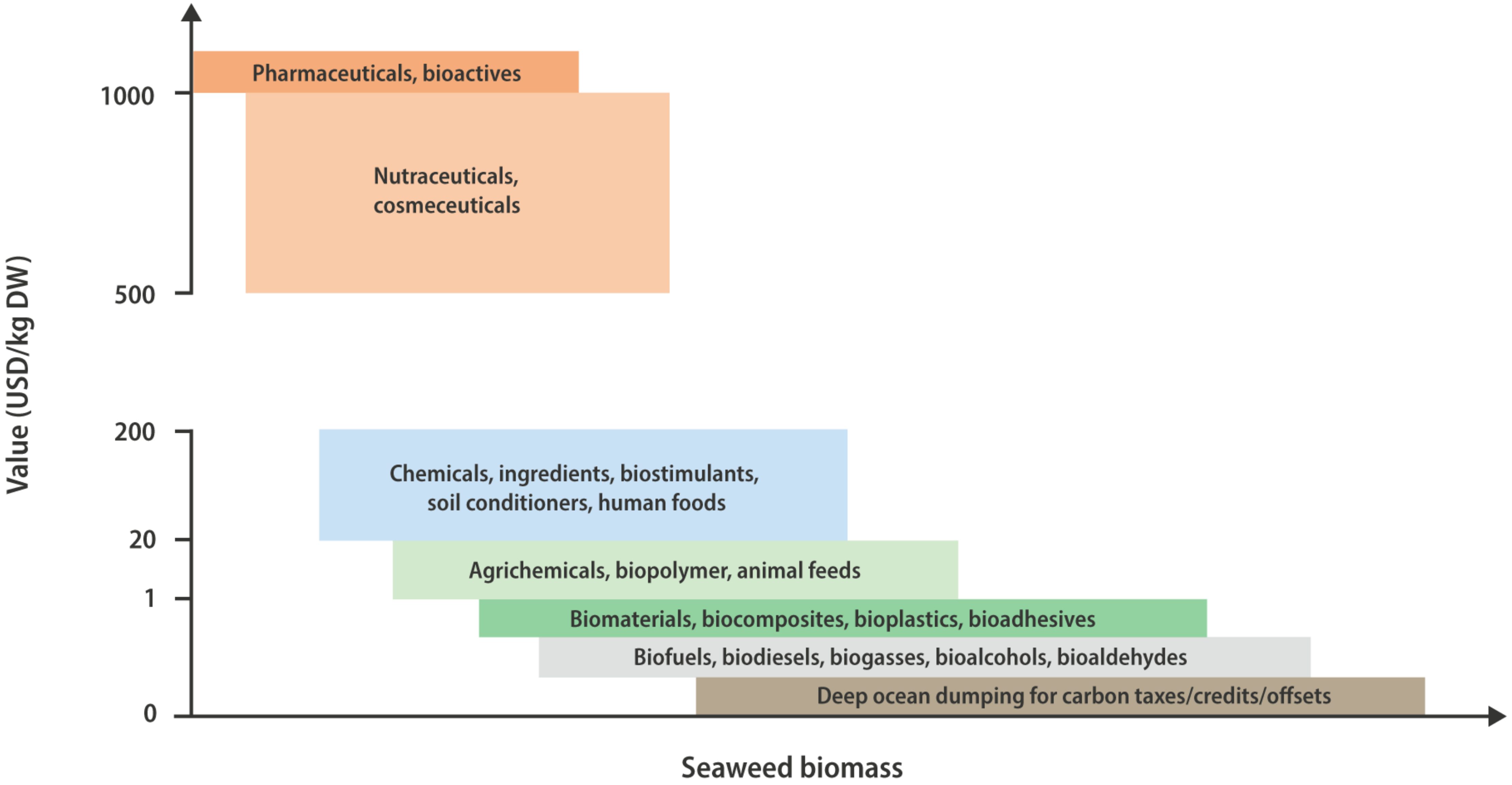
Seaweeds as a precious diverse gift to Humanity.
Seaweeds are Treasures. **They are not Trash.**

Seaweeds are ***not easy***.
"You better know their biology, ecology, physiology, biochemistry, etc. before trying to cultivate them".

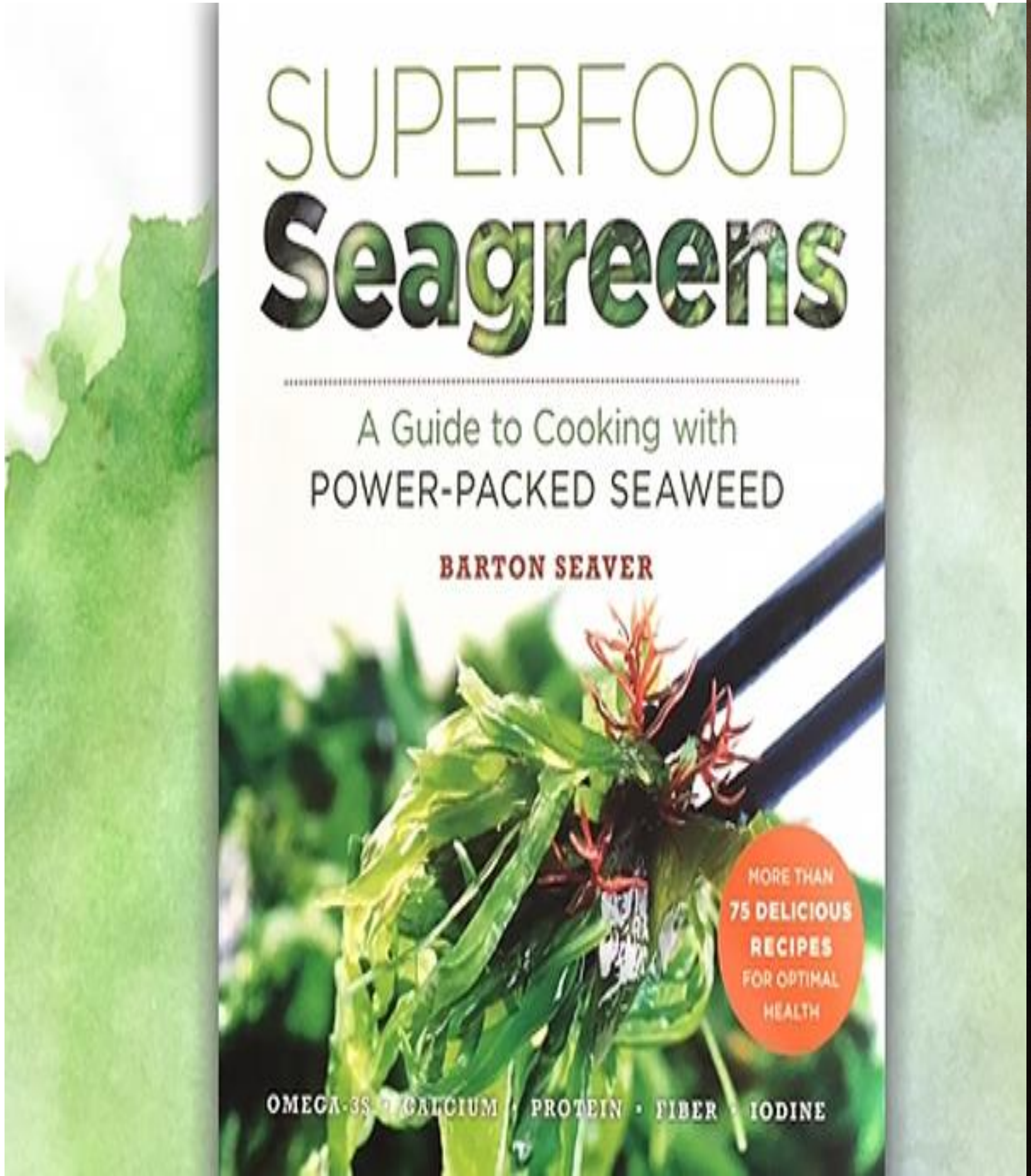
Seaweeds ***can be integrated*** with many aquaculture, agriculture and treatment systems

Seaweeds can have major roles in carbon & nitrogen absorption
TRANSFORMATION…NOT SEQUESTRATION

Seaweeds have tremendous potential in human health, agriculture (food Productio in general) and rural economic development. ***Replace Your Imports! Scale Out! Benefit Your Fishermen/Farmers!***



Chopin et al. (2024)


SUPERFOOD
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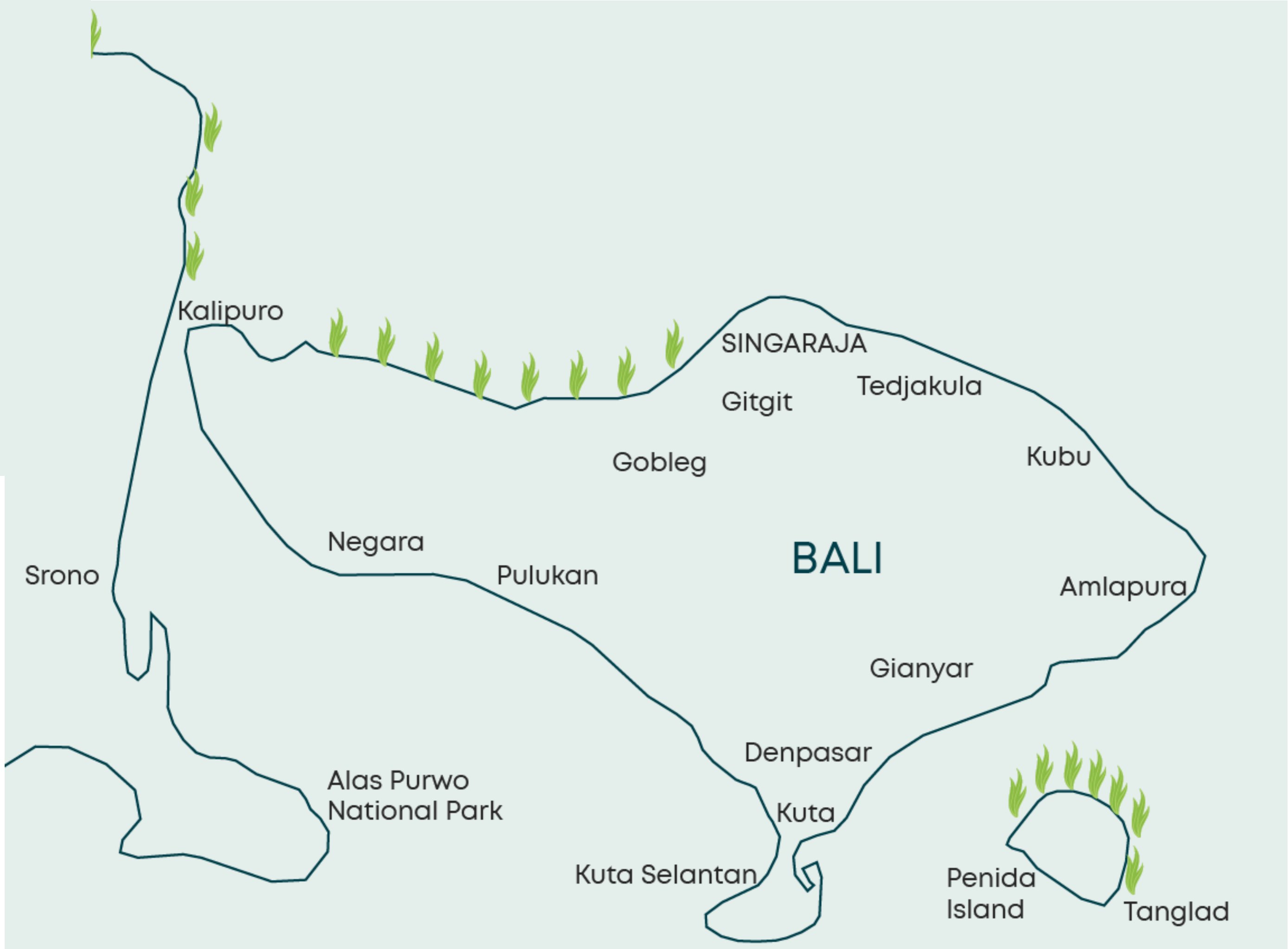
Cavi·art
Seaweed-Caviar
Cavi·art
Seaweed-Caviar
Cavi·art


atlantic
SEA FARMS
SEA-CHI
raw kelp
MILD KIMCHI
NET WT. 15 OZ. (425g)
atlantic
SEA FARMS
SEA-BEET
KRAUT
raw kelp SAUERKRAUT
NET WT. 15 OZ. (425g)
atlantic
SEA FARMS
FERMENTED
SEAWEED
SALAD
NET WT. 15 OZ. (425g)


OCEAN
APPROVED
atlantic
SEA FARMS
sustainably rope-grown by independent fishermen in the
clean, cold waters of Maine.
READY-CUT thaw & eat
KELP
3–4 OZ. PACKS NET WT. 12 OZ. (340g)
KEEP FROZEN

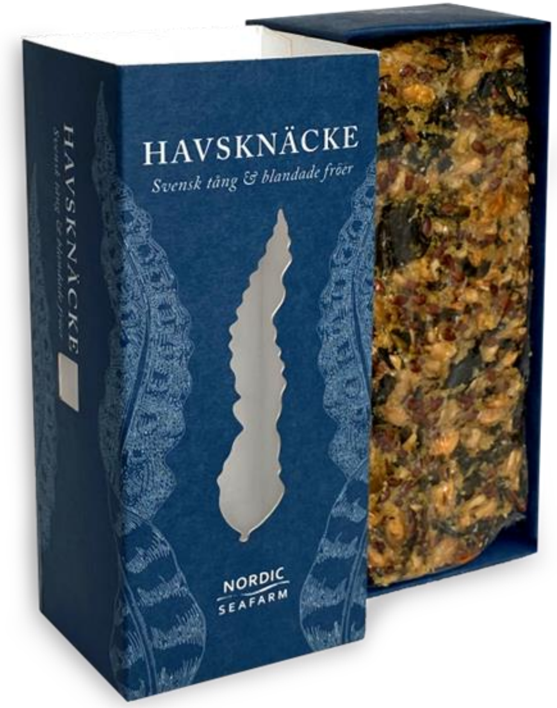
SEA6 ENERGY

Bangalore, India
Bali, Indonesia



NORDIC
SEAFARM

https://nordicseafarm.com/



Foods
Biomaterials
Animal feeds
Fertilizers

EU-funded project SEABIOPLAS

Seaweeds from sustainable aquaculture as feedstock
for
biodegradable bioplastics

More Opportunities

- Genetic Improvement – NIBIO Norway
- Systems Ecology – Fisheries/Aquaculture
  Social Ecological Systems



P. Dobbins, WWF

Aquaculture → Fishery??


MARSHALL WHARF
MW

CELEBRATE!


BARREN'S
Sugar Kelp
FLAVORED VODKA
BLUE BARREN
40% ALC. BY VOL. 80 PROOF 750 ML

Have FUN!