# Ocean-focused $CO_2$ Capture and Storage Technology Development Efforts at ARPA-E

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# ARPA-E Mission

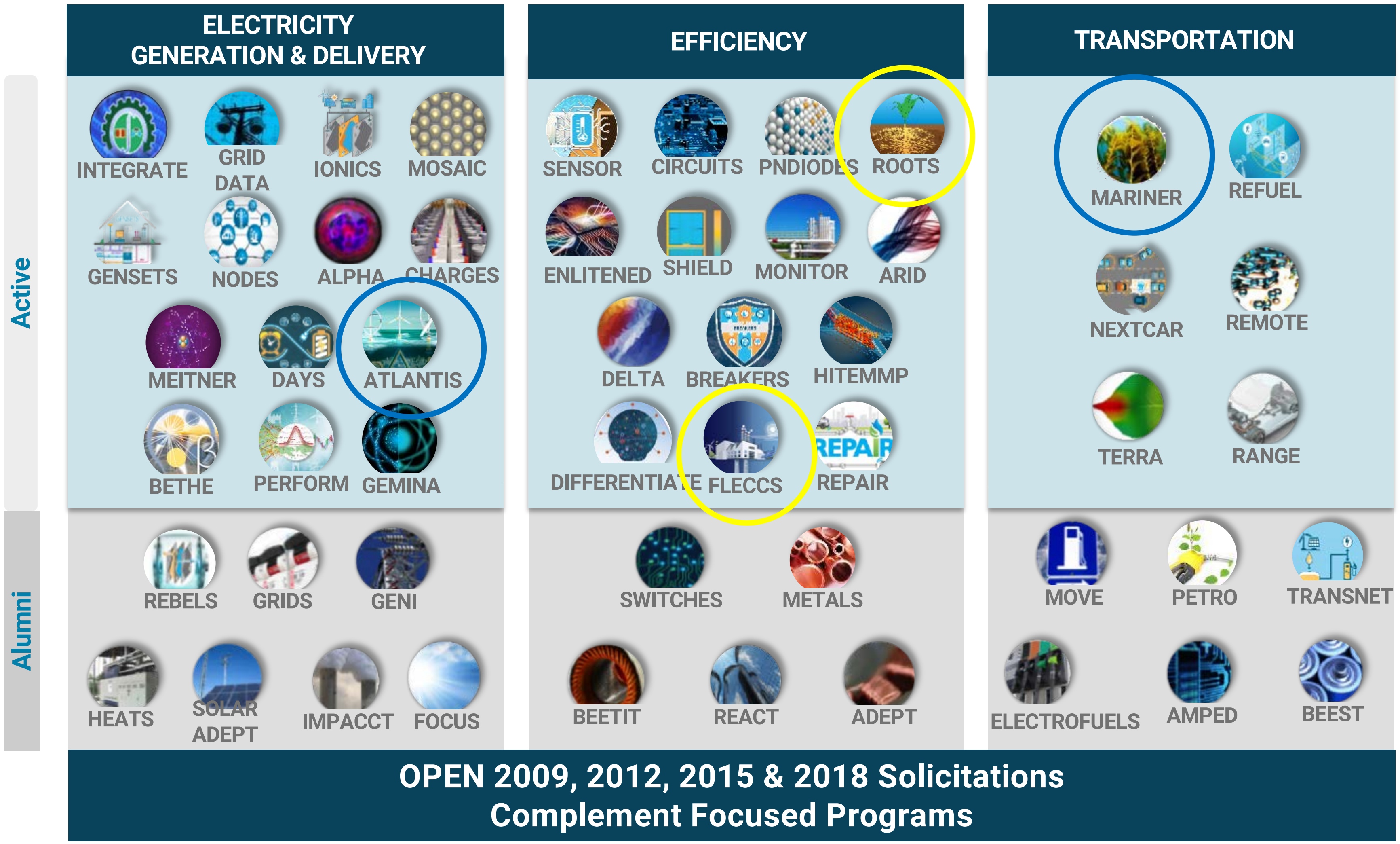
**Goal 1:** To overcome long-term and high-risk technological barriers in the development of energy technologies that…


**Goal 2:** To ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies.

## Means:

- Identify and promote revolutionary advances in fundamental and applied sciences;
- Translate scientific discoveries and cutting-edge inventions into technological innovations; and
- Accelerate transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty.

# More than $2.4 billion for 950+ Projects since 2009



# Recent Direct Ocean Capture (DOC) Funding at ARPA-E

- In October 2020, ARPA-E announced $3 Million of funding for 3 projects focused on DOC under the *Innovating Through Unconventional Ideas* Program (https://arpa-e.energy.gov/news-and-media/blog-posts/arpa-e-innovating-through-unconventional-ideas)

- **California Institute of Technology – Pasadena, CA**

  DEVELOPMENT OF AN OFF-SHORE, STAND-ALONE SYSTEM FOR EFFICIENT CO2 REMOVAL FROM OCEANWATER ($850K)

- **U of North Dakota Energy & Environmental Research Center – Grand Forks, ND**

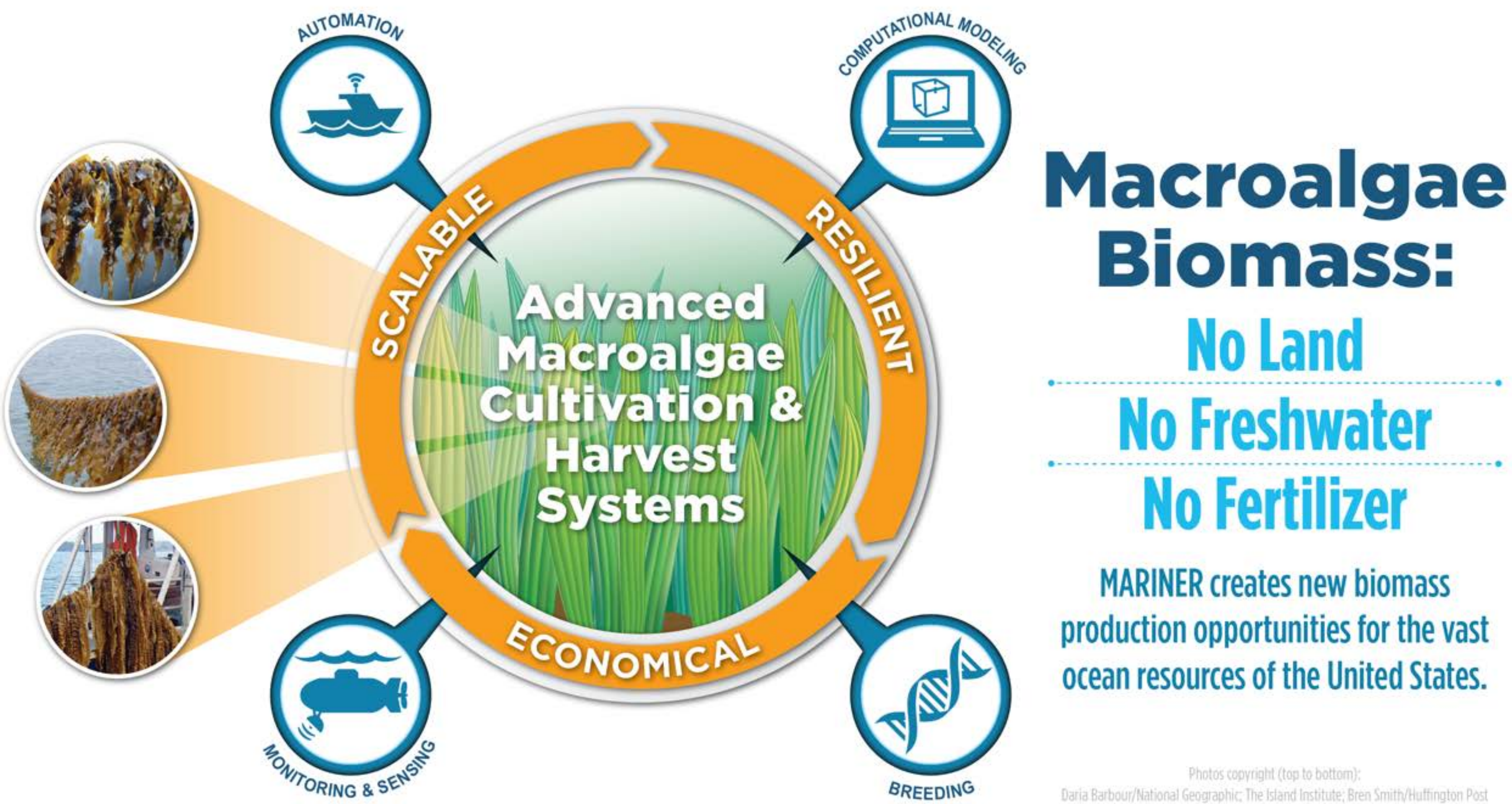
  HYDROLYTIC SOFTENING OF OCEAN WATER FOR CARBON DIOXIDE REMOVAL ($500K)

- **Massachusetts Institute of Technology – Cambridge, MA**

  ELECTROCHEMICALLY MODULATED $CO_2$ REMOVAL FROM OCEAN WATERS ($650K)

# ARPA-E's MARINER Program

**M**acro**A**lgae **R**esearch **I**nspiring **N**ovel **E**nergy **R**esources




- **Launched in 2016**
- **US$50+ Million**
- **20+ Projects**
- **Close cooperation with NOAA on Marine Spatial Planning tools**

# Macroalgae (aka seaweed) – the quintessential ocean crop




- **~15,000 different species growing in a wide range of geographies**
- **Fast growth rate**
- **Mostly carbohydrate & protein**
- **Amenable to cultivation & harvest**

# 1 Ton of Macroalgae (dry) ≅ 1 Ton of $CO_2$ captured

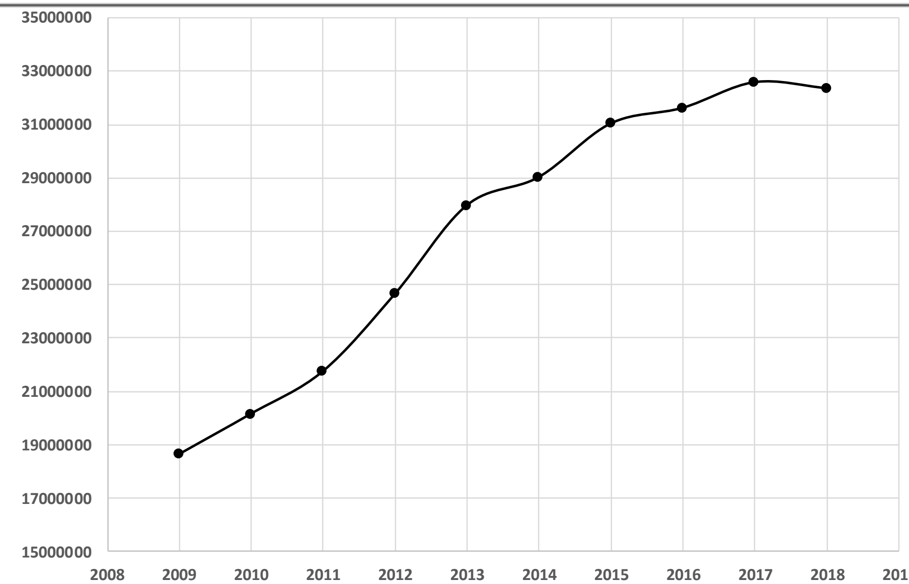
| | Conservative | Medium | Optimistic |
|---|---|---|---|
| Dry weight yield (t/ha) | 10 | 30 | 50 |
| Carbon Content (% dry weight) | 25% | 27% | 30% |
| $CO_2$ captured (t/t biomass) | 0.92 | 0.99 | 1.10 |
| **$CO_2$ captured in (t/ha)** | **9** | **30** | **55** |
| **Area to capture 1 Gt $CO_2$ ($km^2$)** | **1,091,000** | **337,000** | **182,000** |
| Cost of biomass production (US$/t dry weight) | 200 | 130 | 80* |
| **Cost of capturing 1 t of $CO_2$ (US$)** | **218** | **131** | **73** |

~ 1.6% of U.S. EEZ

Numbers presented in this table, while in the right ball park, are primarily for illustrative purposes

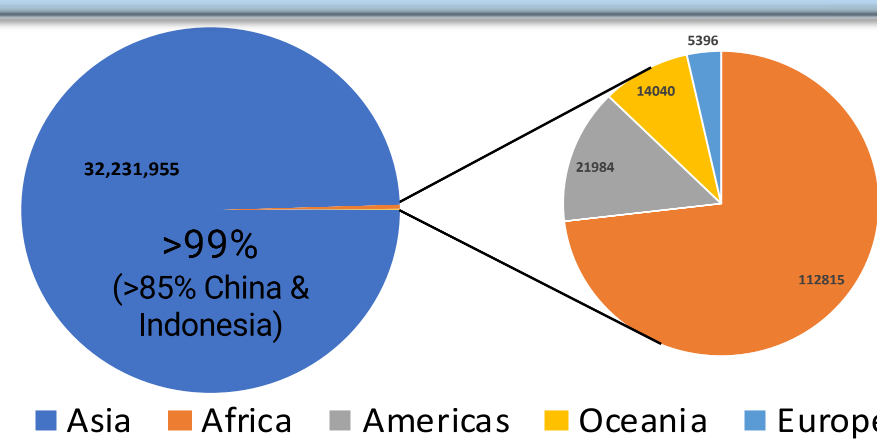
* ARPA-E MARINER cost target

# Global Production of Seaweed: 32.4 Million Wet Tons in 2018




Production nearly doubled over last 10 years

**World Wide Aquatic Plant Production 2009-2018 (Wet Tons)[1]**

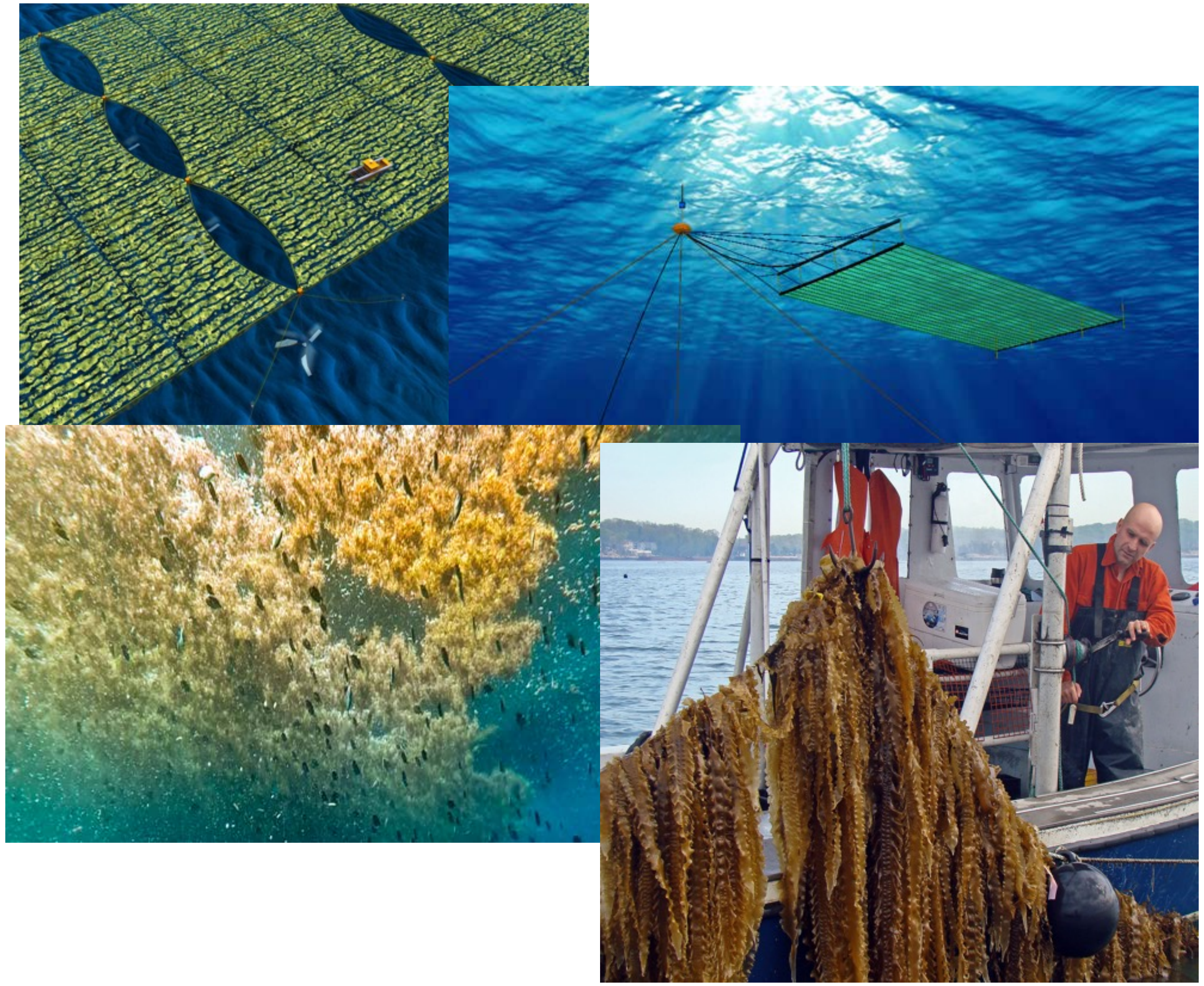



**Asia dominates production**



[1]Data taken from *2018 FAO Yearbook Fishery and Aquaculture Statistics: "http://www.fao.org/fishery/statistics/en"*

# What does it take to reach energy/climate scale?

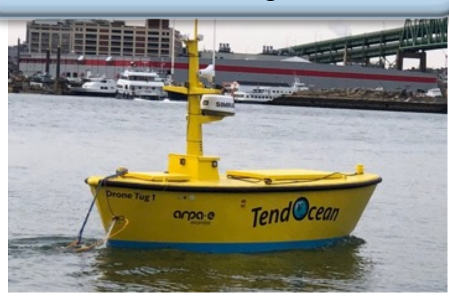


- Move off-shore and survive/operate in open-ocean conditions
- Accessing “free” nutrients predictably and reliably
- Maximize biomass yield by optimizing productivity of individual plants and whole farm system
- Highly energy-efficient operation and harvesting through advanced automation & remote monitoring

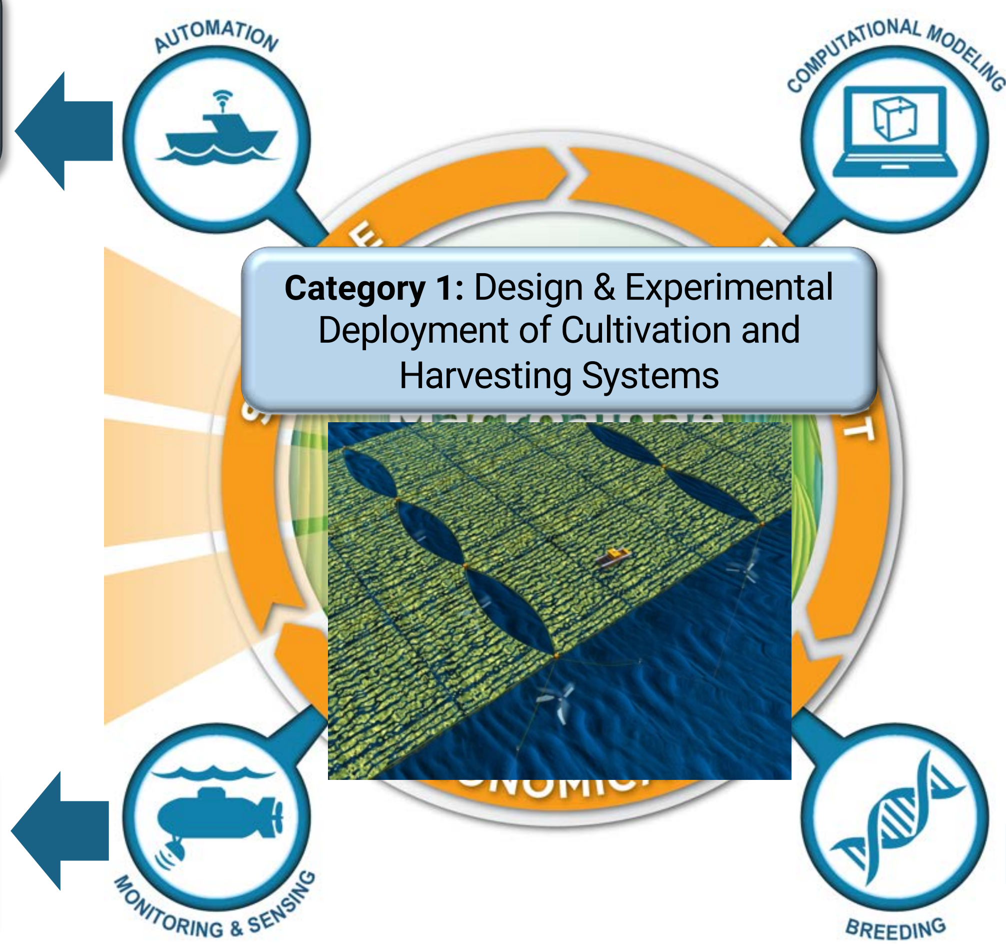
# MARINER Program Structure – Taking a systems perspective

## Integrated technical categories to enable rapid innovation

**Category 2:** Design & Experimental Deployment of Critical Component Technologies

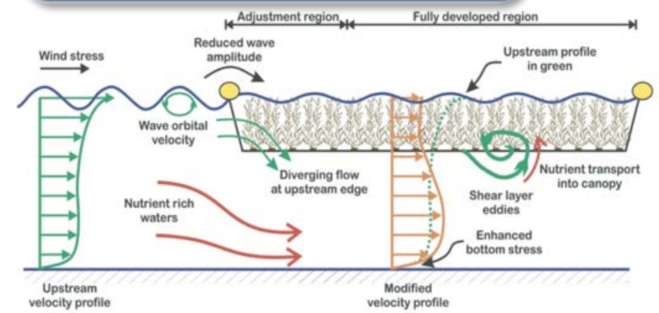


**Category 4:** Design & Deployment of Aquatic Monitoring Technology and Tools




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

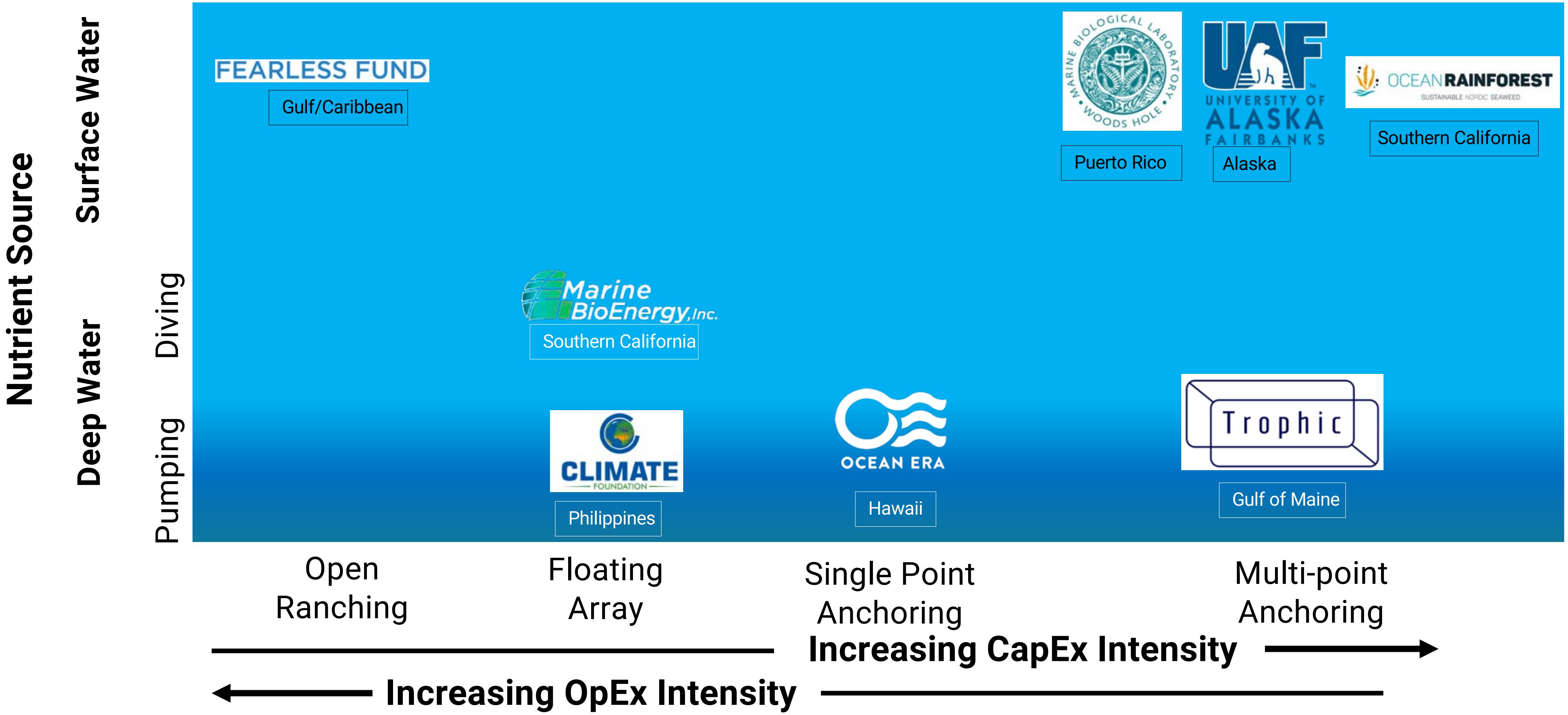
**Category 3:** Development & Validation of Computational Modeling Tools




**Category 5:** Research & Development of Breeding and Genetic Tools

**Cost Target:** \$80/DMT **Scale Target:** >1,000ha per farm, >100,000ha per technology

# Diverse cultivation approaches to anchoring and nutrients

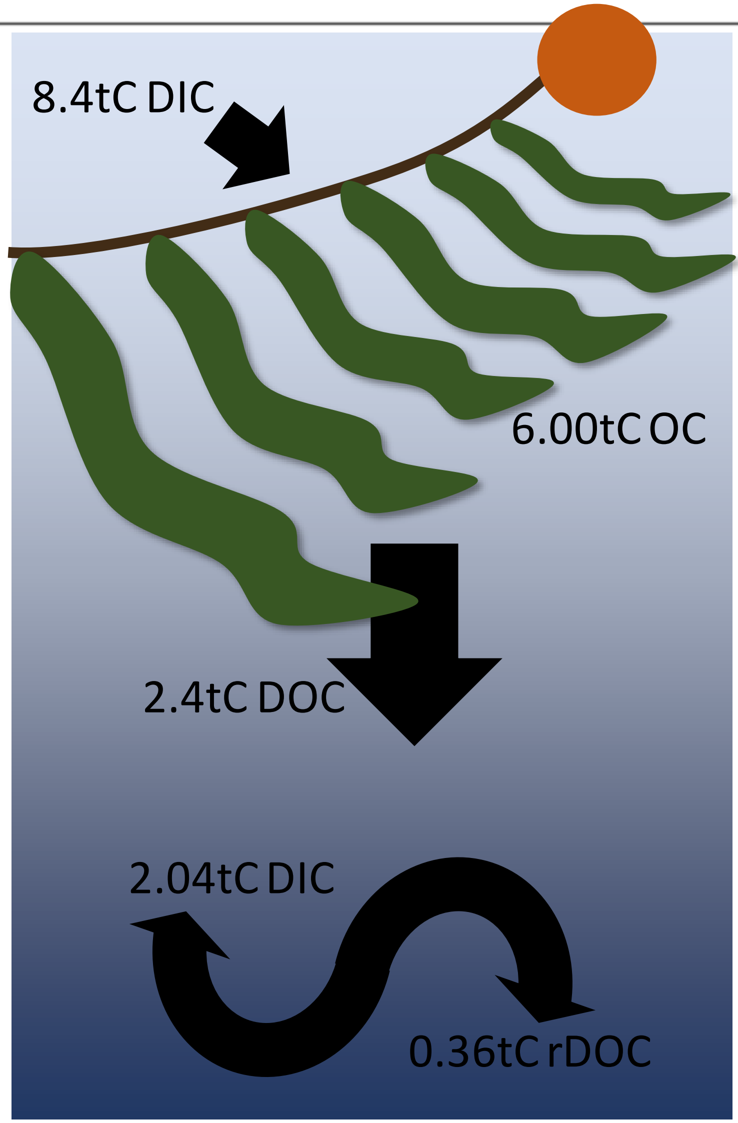



All projects listed are part of ARPA-E MARINER program, except Climate Foundation*
*Climate Foundation uses the term *Marine Permaculture*™ for its seaweed cultivation technology

# From $CO_2$ Capture to Sequestration

- Cultivation-associated carbon sequestration
- Deep ocean sinking of macroalgae
- BECCS
- *Biochar/Hydrochar*
- *Conversion into chemicals used in durable goods*

# Cultivation-associated carbon sequestration




**No carbon translocation to soil system, but refractory Dissolved Organic Carbon**

## Assumptions:

- 20 dry t/ha/yr
- 30% C in solid content
- 40% of NPP released as DOC
- 15% of DOC is refractory

## Results:

- 1.32 t $CO_2$/ha sequestered as rDOC
- 66 kg $CO_2$ sequestered as rDOC per dry t harvested

Based on data by Hughes et al. 2012

# Deep ocean sinking of macroalgae

Translocation of whole macroalgal biomass to the deep ocean (>1,000m) by sinking. Requires negatively buoyant macroalgae, either by crushing of pneumatocysts or weighing down of material

**Benefits**

– Can sequester carbon for hundreds or thousands of years
– Minimizes transport requirements of macroalgae back to shore

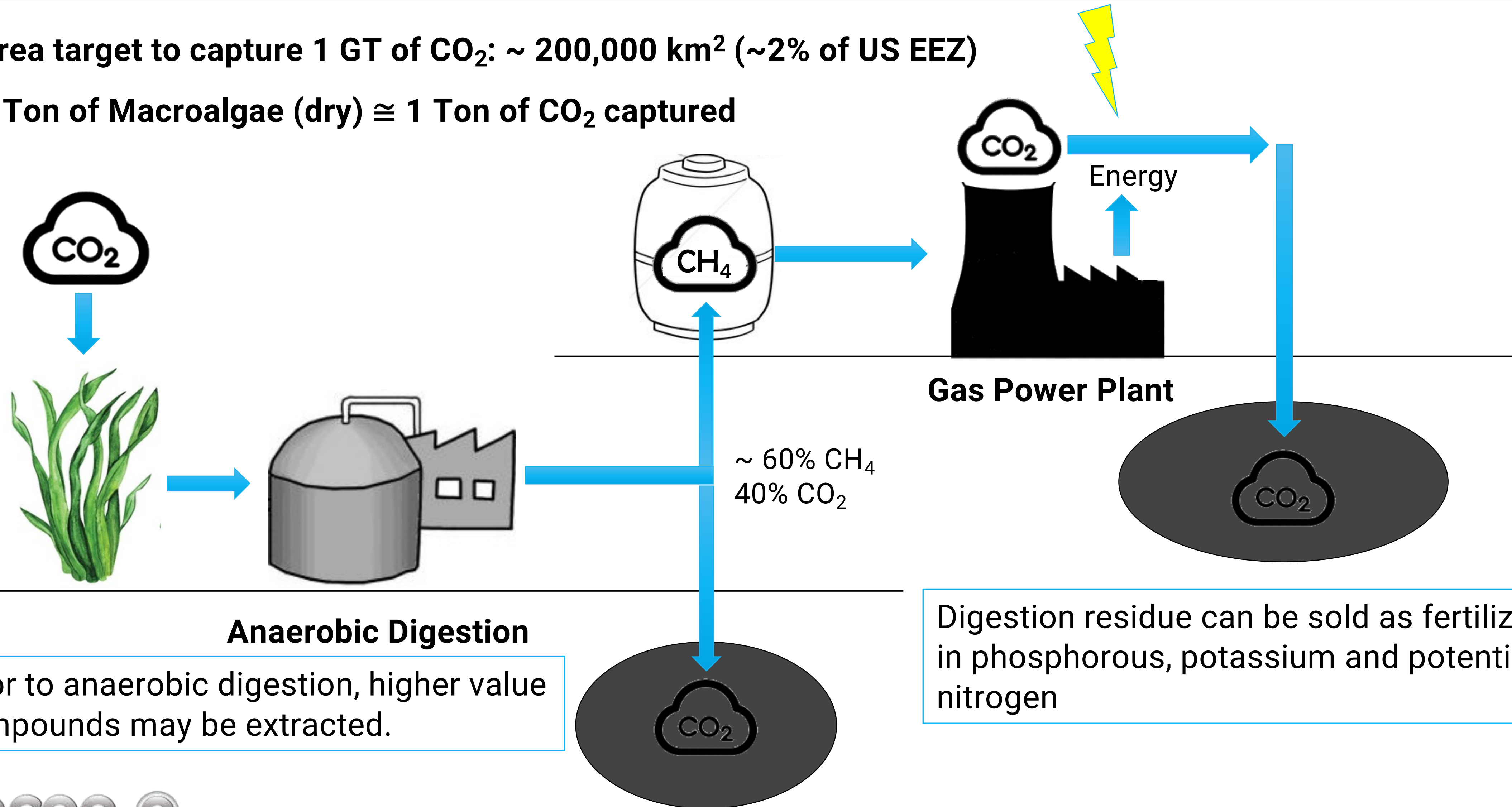
**Challenges/Uncertainties**

– Effect of enhanced macroalgal deposition on ocean ecosystems is not well understood
– No direct product opportunity – relies on carbon tax/payment

# BECCS via a Macroalgae Biorefinery

**Area target to capture 1 GT of $CO_2$: ~ 200,000 km$^2$ (~2% of US EEZ)**

**1 Ton of Macroalgae (dry) ≅ 1 Ton of $CO_2$ captured**




Prior to anaerobic digestion, higher value compounds may be extracted.

Digestion residue can be sold as fertilizer rich in phosphorous, potassium and potentially nitrogen

# Thank you! Any Questions?

## ARPA-E MARINER Program Team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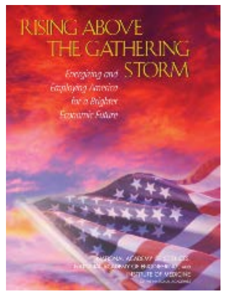
U.S. DEPARTMENT OF ENERGY

https://arpa-e.energy.gov

# Supplemental Slides

# History of ARPA-E

In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.




*American Recovery & Reinvestment Act* **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects

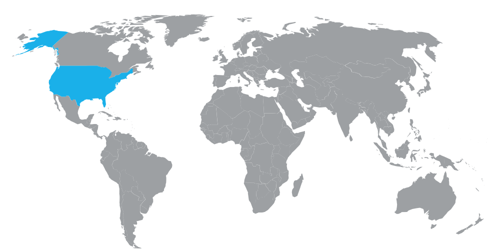
2007

2009

2020

*Rising Above the Gathering Storm* **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

*America COMPETES Act* **Signed** – authorizing the creation of ARPA-E



**850+** Awards
**54** Programs

Current Funding:
**$425M**
(FY20)

# ARPA-E Impact Indicators 2020

Since 2009 ARPA-E has provided
**$2.4 billion**
in R&D funding to more than **950 projects**

**166 Projects** have attracted more than
**$3.3 billion**
in private-sector follow-on funding

**86 companies**
formed by **ARPA-E projects**

**229 projects**
have **partnered with other government agencies** for further development

**4,021**
peer-reviewed **journal articles** from ARPA-E projects

**609 patents**
issued by U.S. Patent and Trademark Office

As of September 2020

# Details on recent ARPA-E DOC funding

- **California Institute of Technology – Pasadena, CA**
- **DEVELOPMENT OF AN OFF-SHORE, STAND-ALONE SYSTEM FOR EFFICIENT CO2 REMOVAL FROM OCEANWATER - $850,000**
- California Institute of Technology aims to develop an off-shore, stand-alone system for low-cost, efficient CO2 removal from ocean water. The project's main objectives are to demonstrate a (1) high operating current density and low power electrodialyzer stack and (2) membrane contactor to facilitate unprecedented rapid removal of CO2 from ocean water. These combined innovations will significantly reduce the volume of ocean water that needs to be processed. They will also significantly reduce the capital and associated system costs. The proposed system aims to provide a viable pathway to achieve CO2 removal from ocean water at <$100/ton and could be potentially scaled up to multi-gigaton CO2/year capacities.
- **University of North Dakota Energy & Environmental Research Center – Grand Forks, ND**
- **HYDROLYTIC SOFTENING OF OCEAN WATER FOR CARBON DIOXIDE REMOVAL - $500,000**
- Hydrolytic softening is a lower-cost process to remove $CO_2$ from the oceans. It has similarities to processes at conventional water treatment facilities, which mix hydrated lime to "soften" water by precipitating dissolved inorganic carbon as calcium carbonate. In hydrolytic softening, however, instead of a consumptive use of lime, the calcium carbonate is decomposed. This releases $CO_2$ gas for sequestration or industrial use and regenerates the lime for continued cycles of carbon removal. Hydrolytic softening can reduce energy input costs for $CO_2$ removal by 77% compared to state-of-the-art methods based on sodium chloride salt splitting using bipolar membrane electrodialysis.
- **Massachusetts Institute of Technology – Cambridge, MA**
- **ELECTROCHEMICALLY MODULATED $CO_2$ REMOVAL FROM OCEAN WATERS - $650,000**
- The Massachusetts Institute of Technology proposes to use electrochemical modulation of a proton gradient within electrochemical cells to initially release the $CO_2$ in seawater, and then to alkalize the water before it is returned to the ocean. This battery-like electro-swing approach does not require expensive membranes or addition of chemicals, is easy to deploy, and does not lead to formation of byproducts. Innovative electrode configurations will be employed to reduce overall transport and electrical resistances while still enabling large quantities of water to be treated efficiently. Relatively compact $CO_2$ capture processes with promising low energetics, powered by renewable solar or wind resources, could be assembled for deployment on platforms or cargo ships.

# Why do we care about macroalgae?

- By 2050: ~9 billion people = **30% more energy** & **50-100% more food**
- Biomass is critical for both and provides important **flexibility for low-carbon energy**.
- May not rely on terrestrial biomass alone, due to other **land use needs**, **freshwater challenges**, and **climate change uncertainties**
- U.S has the world's largest Exclusive Economic Zone; with **abundant light**, **water**, and **nutrients**
- **Untapped ocean opportunity** to produce **energy**, **food**, and **feed** from ocean farmed seaweeds!

# U.S. Macroalgae Production: Small, but Growing

| Estimated Edible Seaweed Farmed 2015-2019 (Wet lbs) | | | | | |
|---|---|---|---|---|---|
| Source | 2015 | 2016 | 2017 | 2018 | 2019 |
| Maine | 15,000 | 24,000 | 45,000 | 54,000 | 325,000 |
| Alaska | Not Available | Not Available | Not Available | 30,000 | 180,000 – 200,000 |
| All Other | 10,000 – 15,000 | 10,000 – 20,000 | 15,000 – 30,000 | 20,000 – 40,000 | 45,000 – 75,000 |
| Total | 25,000 – 30,000 | 30,000 – 40,000 | 60,000 – 75,000 | 100,000 – 125,000 | 550,000 – 600,000 |

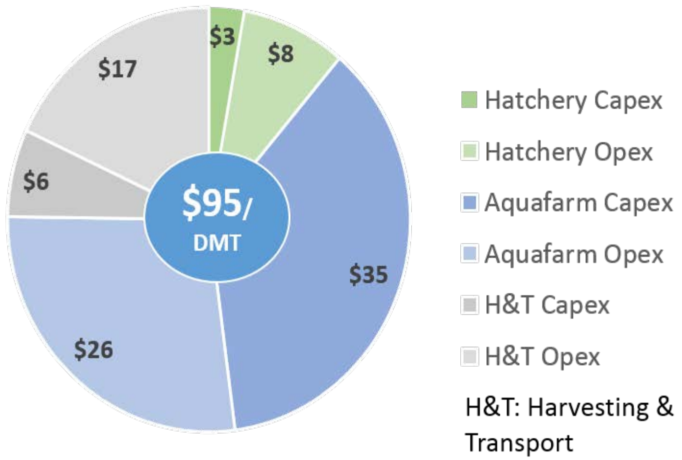
*Source: Pentallect Inc. and EPR research; Maine DMR*

**Recent Trends in Alaska:**

- Seaweed Farming Workshops held in cities across the state.
- 16 new seaweed farm applications over 610 acres submitted in 2020.
- Largest farmer (SeaGrove Kelp) plans on 5000 ton capacity by 2023.

# Initial TEA identified Yield, Scale, Farm CapEx as Cost Drivers

A.

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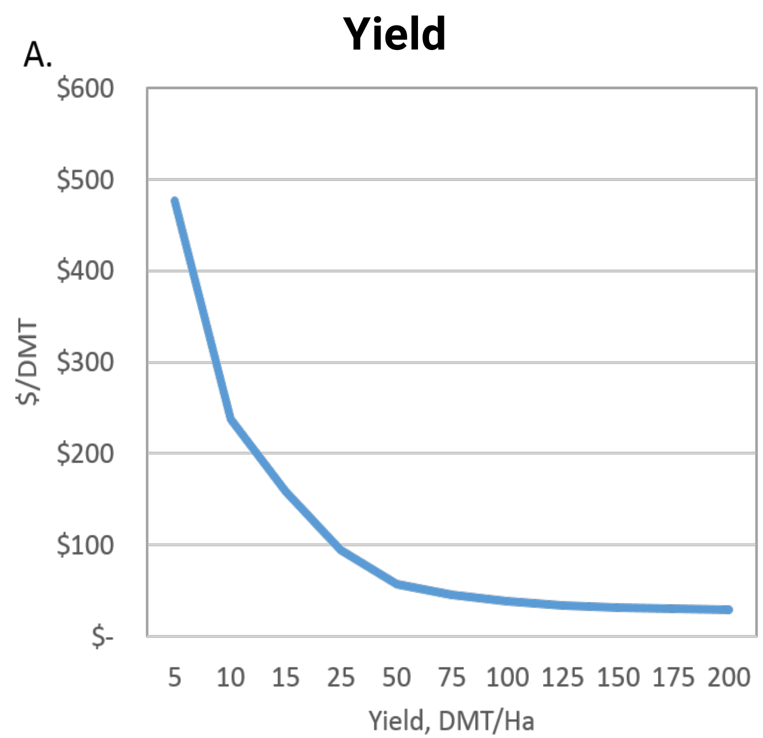
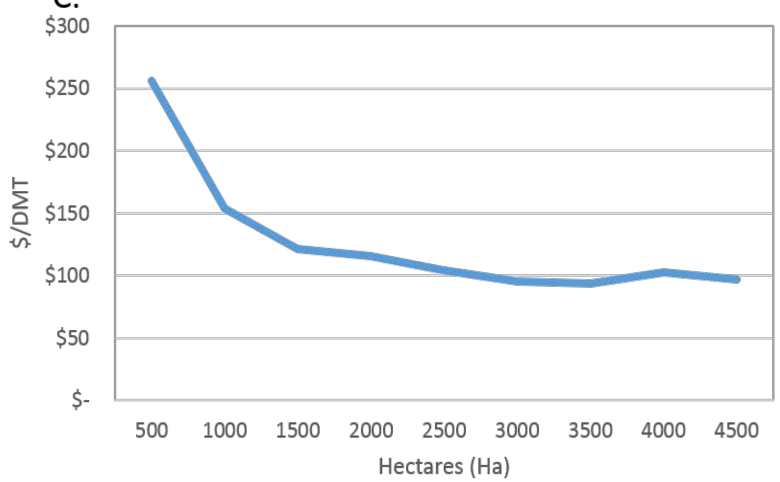


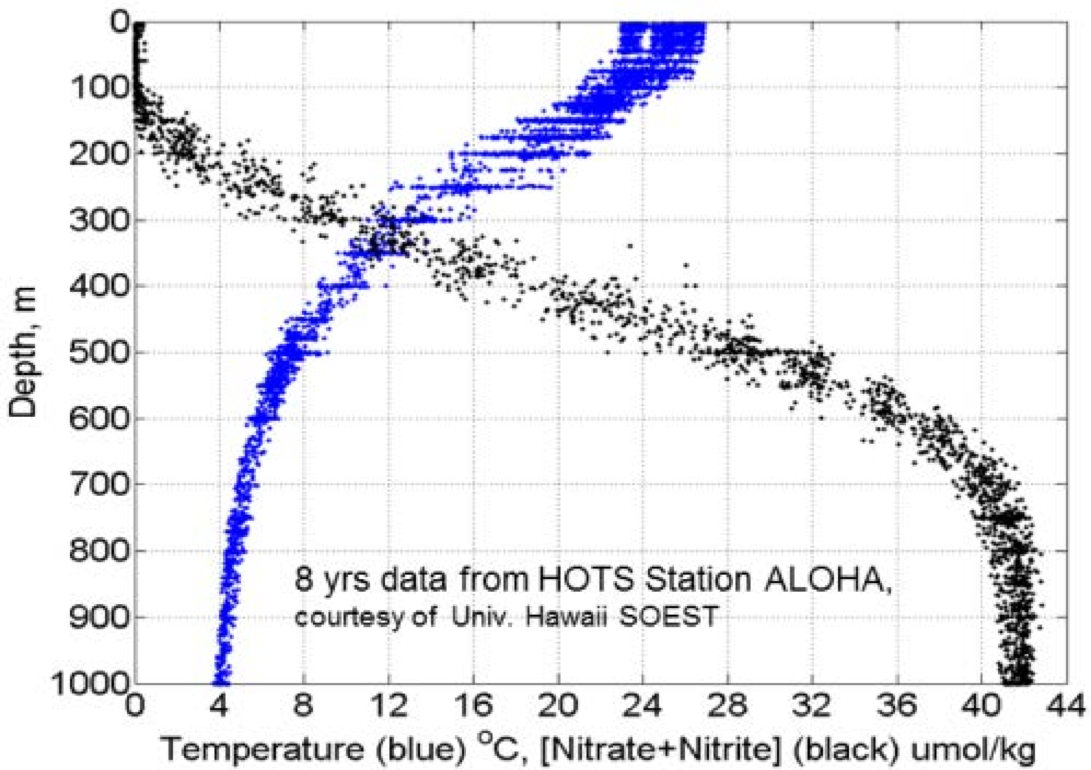

**Scale**

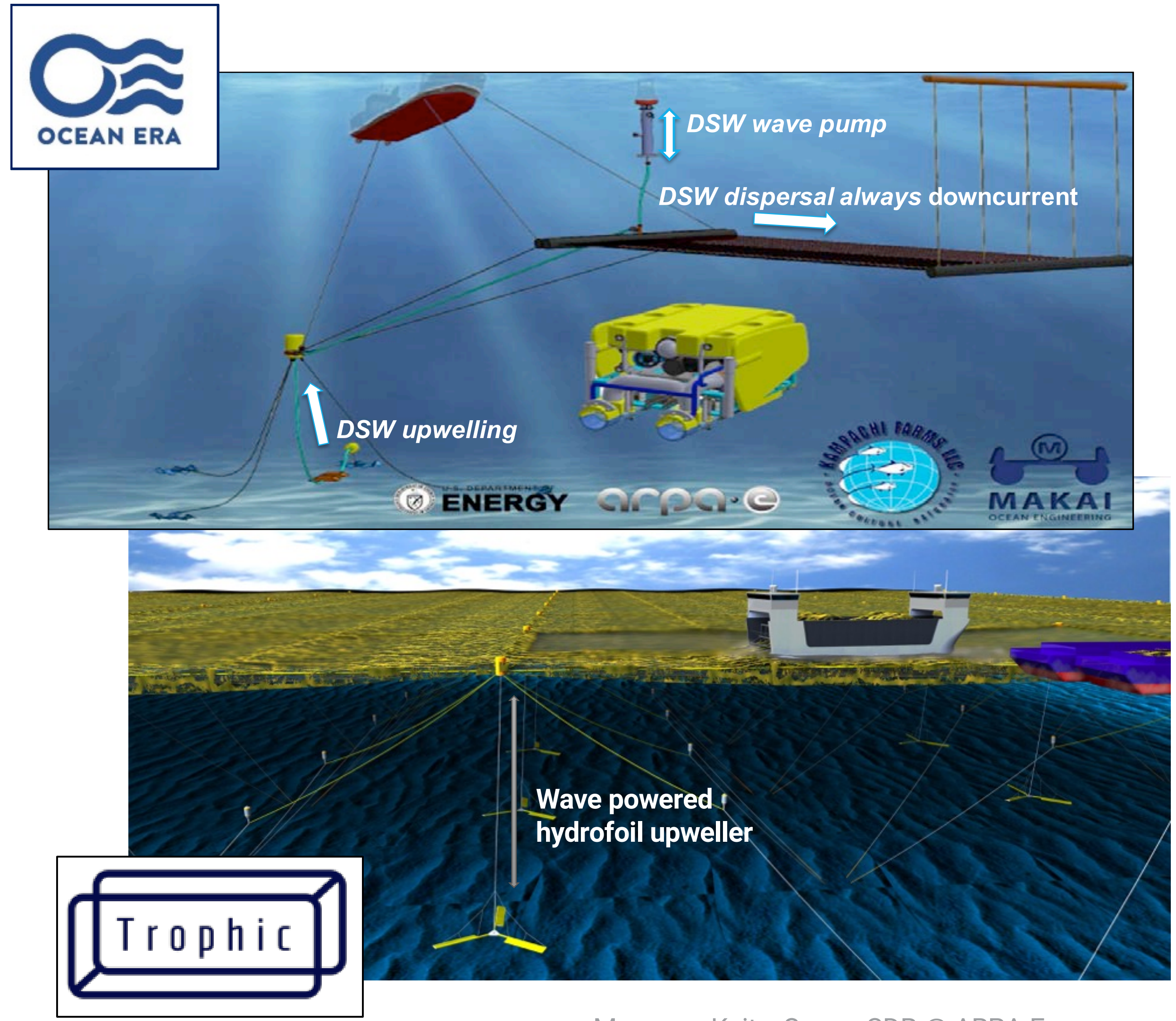
C.



# Accessing Deep Water Nutrients: Upwelling to the Surface

In many places the surface waters **do not contain enough nutrients** to support macroalgae cultivation

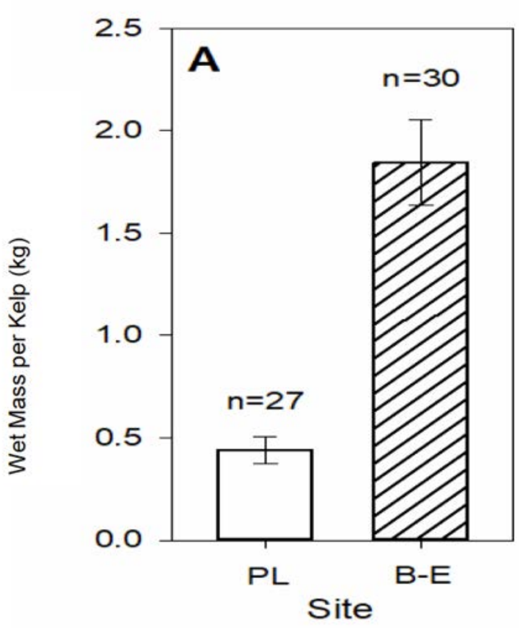


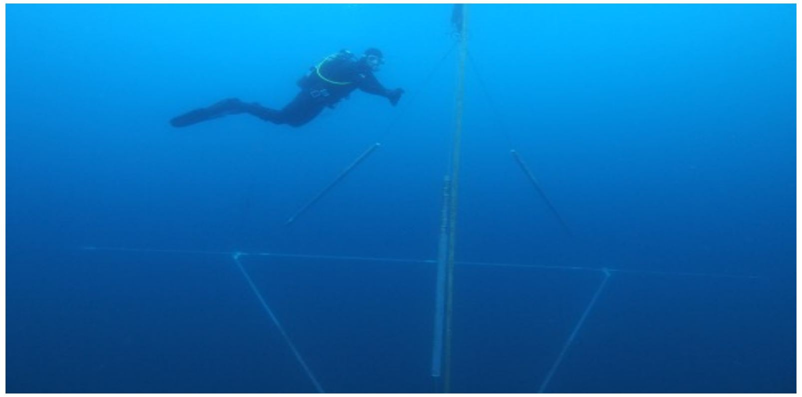



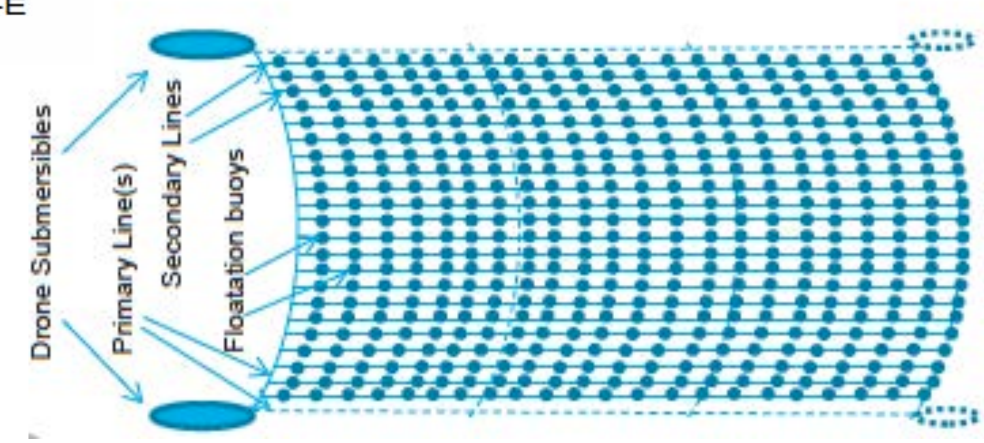
# *Marine Bioenergy*: Diving for Nutrients - Untethered


***Macrocystis* cycled to 80m depth 90x over 100 day period**

Biomass yield
~ 4x greater in depth cycled than in control






Marine BioEnergy, Inc.

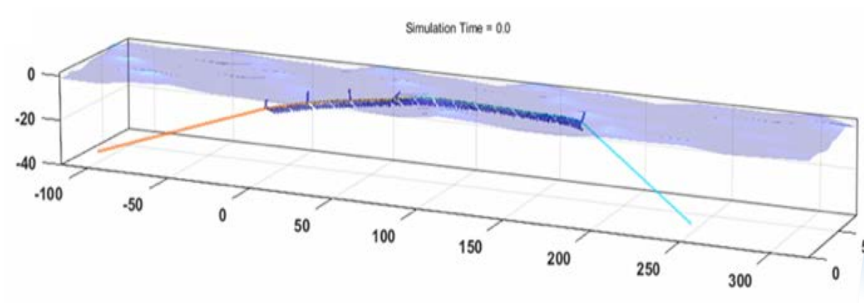
# Advanced Modelling Tools for Farm Design

UNE UNIVERSITY OF NEW ENGLAND

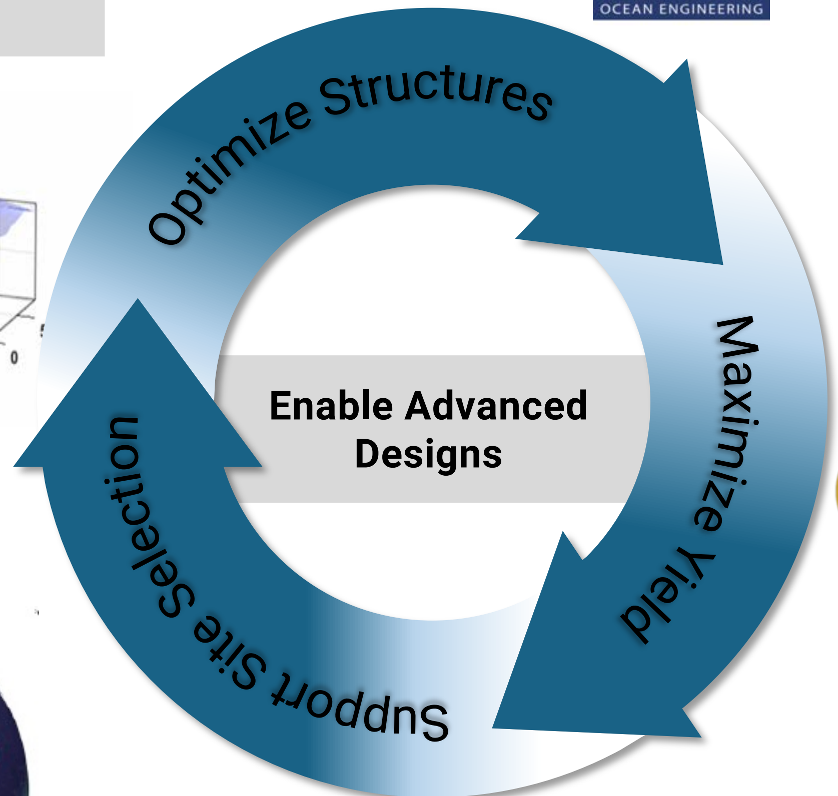
MAKAI OCEAN ENGINEERING

UC IRVINE

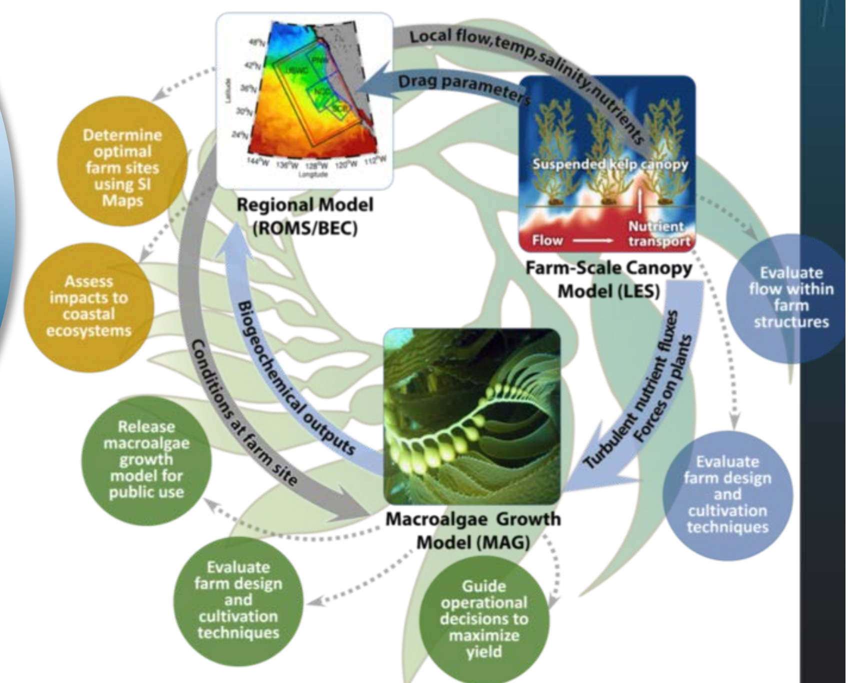
## Simulation of Farm in Ocean Environments



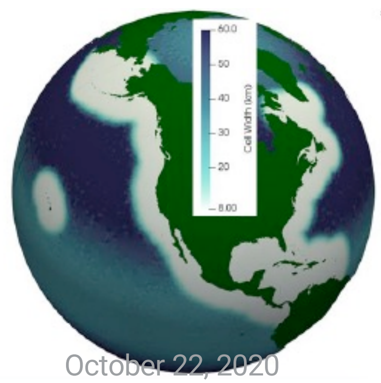

## Regional Current and Biogeochemical Analysis




## Nutrient Flux & Algal Growth Modeling




Pacific Northwest NATIONAL LABORATORY

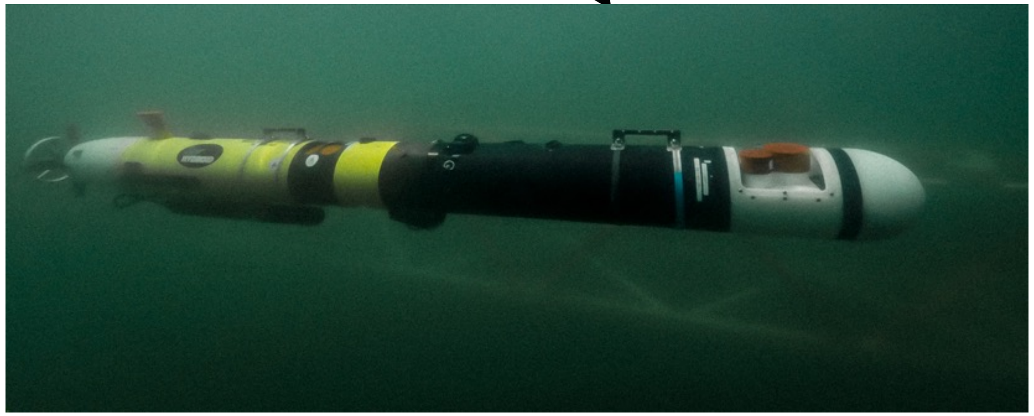


arpa·e CHANGING WHAT'S POSSIBLE

# Better farm and crop monitoring capabilities

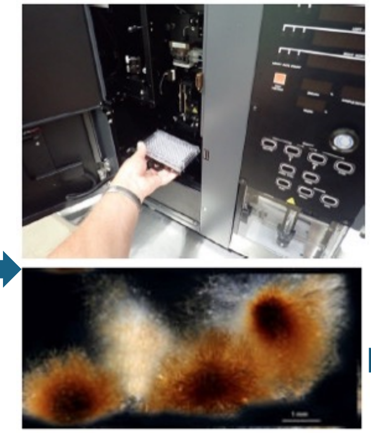
From above…

…and below the Surface.

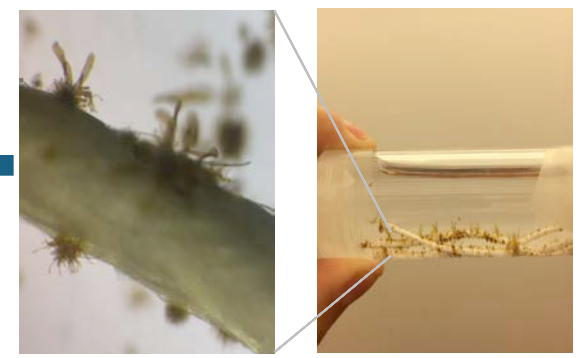


# Development of Breeding and Genetic Tools

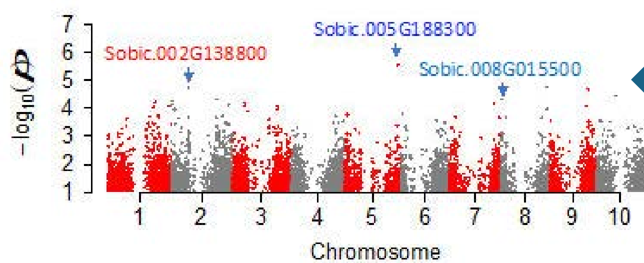
Collected a wide range of natural diversity



Isolation of individual gametophytes



Field deployment of seedlings




*GWAS on field phenotypes to identify significant genetic markers*

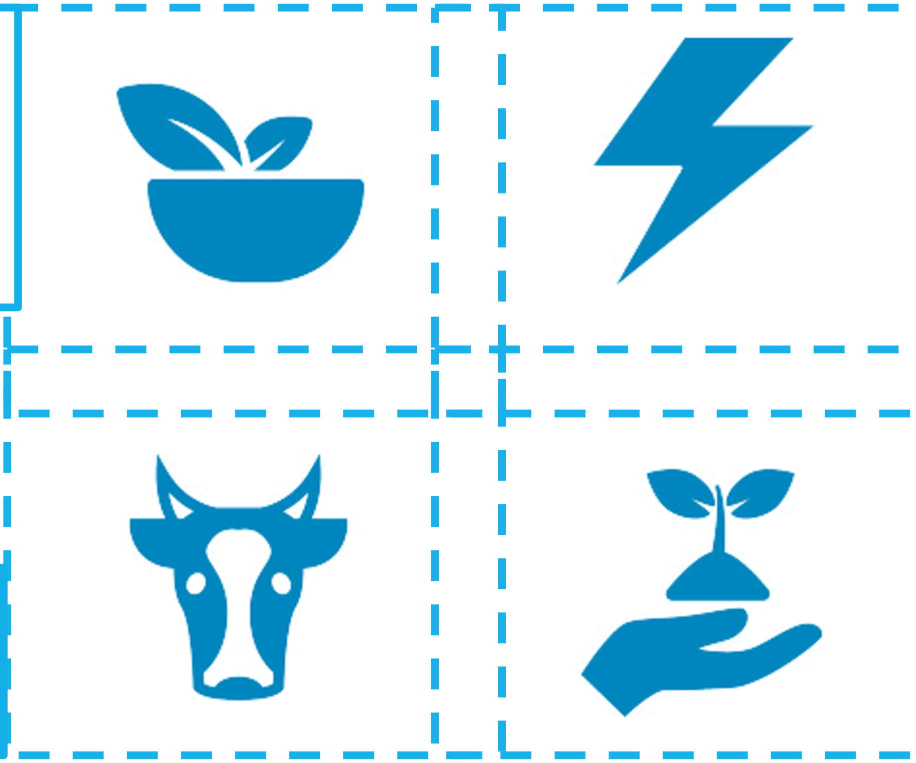
WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

UNIVERSITY of WISCONSIN UWMILWAUKEE

# Access to expanding market opportunities critical to achieve scale

**Human**
- Whole foods
- Nutraceuticals
- Proteins
- Hydrocolloids

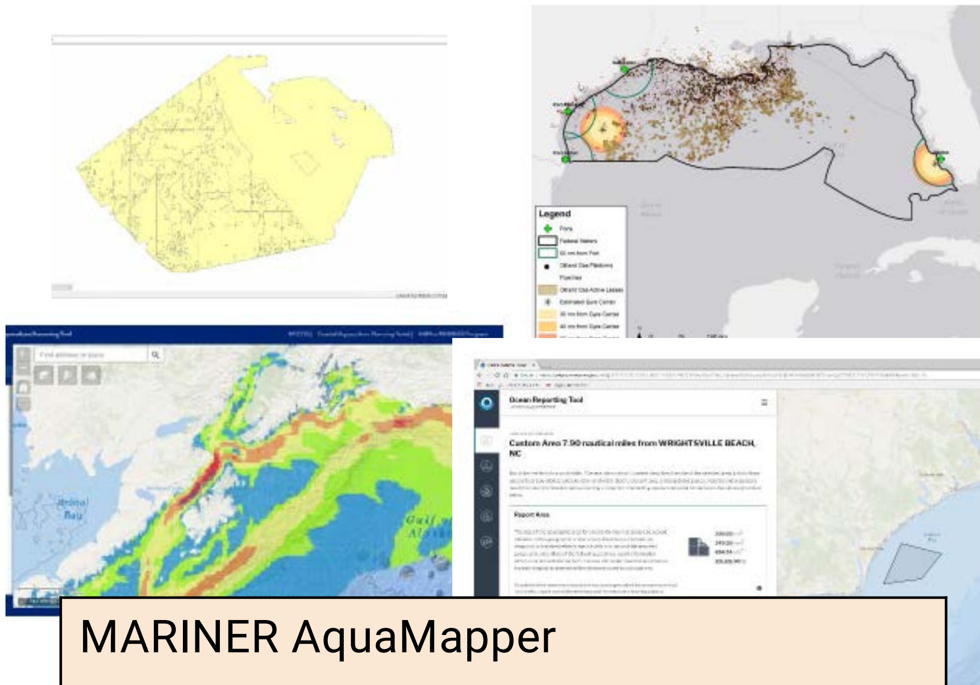
**Energy and Industrial Products**
- Biogas via anaerobic digestion*
- Biofuel via HTL or fermentation
- Chemicals and Intermediates



**Animal Health & Nutrition**
- Ruminants
- Monogastrics

**Ecosystem Services**
- Nutrient reuptake
- Local deacidifcation
- Wave attenuation
- Carbon storage
- Fertilizers*

# NOAA – Developing Site Selection Tools for Mariculture Industry

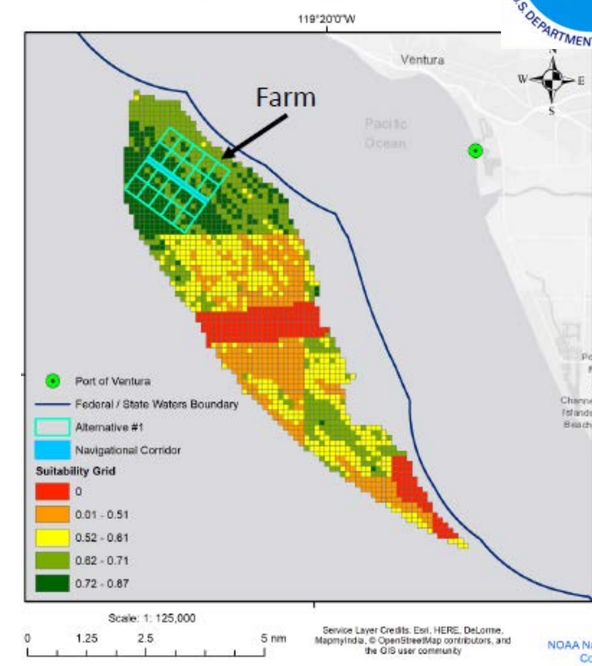


| |
|---|
| MARINER AquaMapper |
| Regional Databases |
| Scalability Analysis |
| **Ocean Reports Tool** |

Ocean Reports

4 million

The number of square miles of U.S. ocean space that can be analyzed in 1 second using OceanReports




**Site Selection and Permitting Support for Category 1 Teams**

https://noaa.maps.arcgis.com/apps/webappviewer/index.html?id=4f12cbde0c22488196dda69d495116cc

# Biochar/Hydrochar

- Production of stabilized carbon via pyrolysis
- Macroalgal biochar has shown to enhance crop yield when applied to certain soils
- Requires dry biomass
- Not a meaningful solution at large scale, due to prohibitive amounts of energy needed for drying due to low solids content of fresh macroalgae (10-15%)

- Hydrothermal carbonization or liquefaction may be more efficient, because it does not require drying. However, resulting hydrochars tend to be much less stable than biochars.