Pacific Northwest
NATIONAL LABORATORY

PNNL-32776

Marine Renewable Energy Applications for Restorative Ocean Farming: Kelp

FY21 Seedling Final Report

April 2022

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Executive Summary

Kelp farming and kelp forest restoration have both been proposed as a solution to locally decrease the impacts of ocean acidification and eutrophication, often with co-benefits to other forms of aquaculture and mariculture. Compared to global markets, the kelp industry in the United States is still in its early phases, with the first commercial kelp farm founded in Casco Bay, Maine in 2010 (then Ocean Approved, now Atlantic Sea Farms). Since then, interest and effort in kelp production have been increasing, with farms now present in Maine, New Hampshire, Connecticut, Rhode Island, Massachusetts, New York, Washington, and Alaska. The largest kelp farm in North America is now located off of southeastern Alaska. Many research projects are underway in the United States to explore benefits of 3D ocean farming, tackle logistical problems of working in the ocean (ARPA-E MARINER), autonomous farming (NTNU AMOS, ARPA-E MARINER), and explore viable end uses for kelp products (Running Tide, Sea Grant).

In seaweed farming, to remove the stored carbon or excess nutrients from the system, the biomass needs to be harvested at the optimal time to avoid the release of CO_2 that comes with decomposition. Timing of the harvest is also important for maximum crop yield, which can vary based on the final product. Additional monitoring needs can include a variety of water quality metrics, growth measurements, and visuals to ensure the health of the farm, compliance with permits, support operations and maintenance functions. The variables measured may vary by the desired end use of the product, location of farm, and operational design. Monitoring these parameters requires specialized devices that can be costly and challenging to maintain. Monitoring devices often face power and logistical constraints that could prevent kelp farmers from adopting these technologies or receiving accurate, efficient monitoring to assess ecosystem benefits and valuation. Marine energy has been identified as a possible power source for these devices. This project investigates the power needs for conducting kelp farm environmental monitoring compared with the available marine energy resource to evaluate if locally generated ocean energy could provide a solution to these monitoring challenges and benefit kelp farmers.

This process was structured as follows:

1. Define what data are needed for farmers and their communities through desk research and interviews with end users.
2. Identify sensors and power requirements currently in use or available for commercial purchase.
3. Analyze current kelp and other mariculture farm locations for the potential marine energy resource.
4. Analyze farm designs and associated structures to make recommendations for marine energy design.
5. Quantify value that investment in sensors could provide in terms of carbon credit or data possibilities, such as additional revenue streams.

115 kelp farms across the United States were analyzed for overlap with marine energy resources, and wave energy was identified as the most promising resource. The farms with the greatest wave energy resources are found in Alaska and the West Coast. Farmers that responded to our outreach typically employ small-scale monitoring operations and have very low power needs, based on the devices identified and parameters measured. No power pain points were identified for the farms presently in operation. However, it is expected that the number and size of farms will increase as the market grows, and the potential for co-location of

kelp farms with marine energy for monitoring may need to be revisited. In addition, the development of alternative markets for monitoring, including sale of aggregate data or use of monitoring to validate carbon credit sales, could increase the value of monitoring data over time and require additional power. A case study approach in partnership with key farmers is recommended to begin exploring this potential for integration, and could be leveraged in scoping or testing future DOE prizes for ocean observing. This approach would also enable refinement of the boundaries for the ideal resource availability, balancing power potential with safe working conditions and ideal growing conditions, to advance the marine energy and kelp aquaculture industries in parallel on a path to commercialization.

1.0 Introduction

1.1 About Kelp

Kelp are large, brown macroalgae that are part of the Class Phaeophyta and the Order Laminariales. They are typically found in cool, temperate to subpolar waters, with global distribution (Figure 1). They are known as habitat engineers, naturally forming dense canopy for numerous species of fish, marine mammals, and invertebrates at many life stages. There are a few main species of kelp that are currently considered commercially important in the United States: *Nereocystis luetkeana* (bull kelp), *Saccharina latissima* (sugar kelp and skinny kelp), *Alaria marginata* or *esculenta* (winged or ribbon kelp), *Laminaria digitata* (oarweed), and *Macrocystis pyrifera* (giant kelp) [1], [2] (Figure 2).

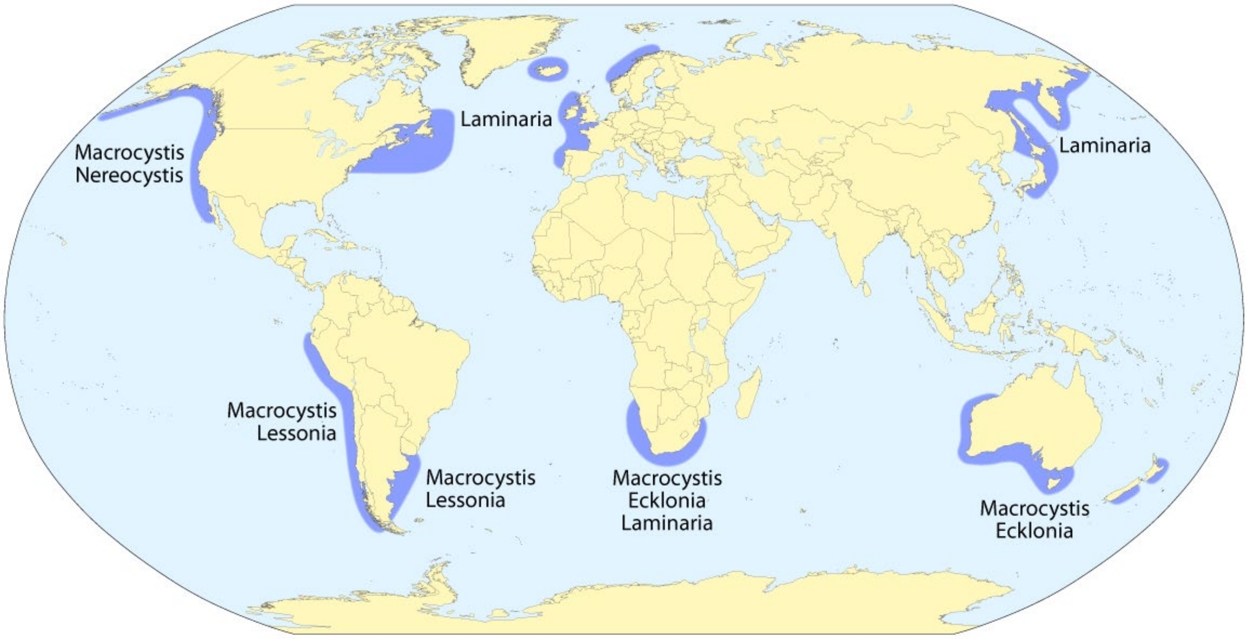


Figure 1. The global distribution of kelp species. Courtesy of Maximilian Dörrbecker.

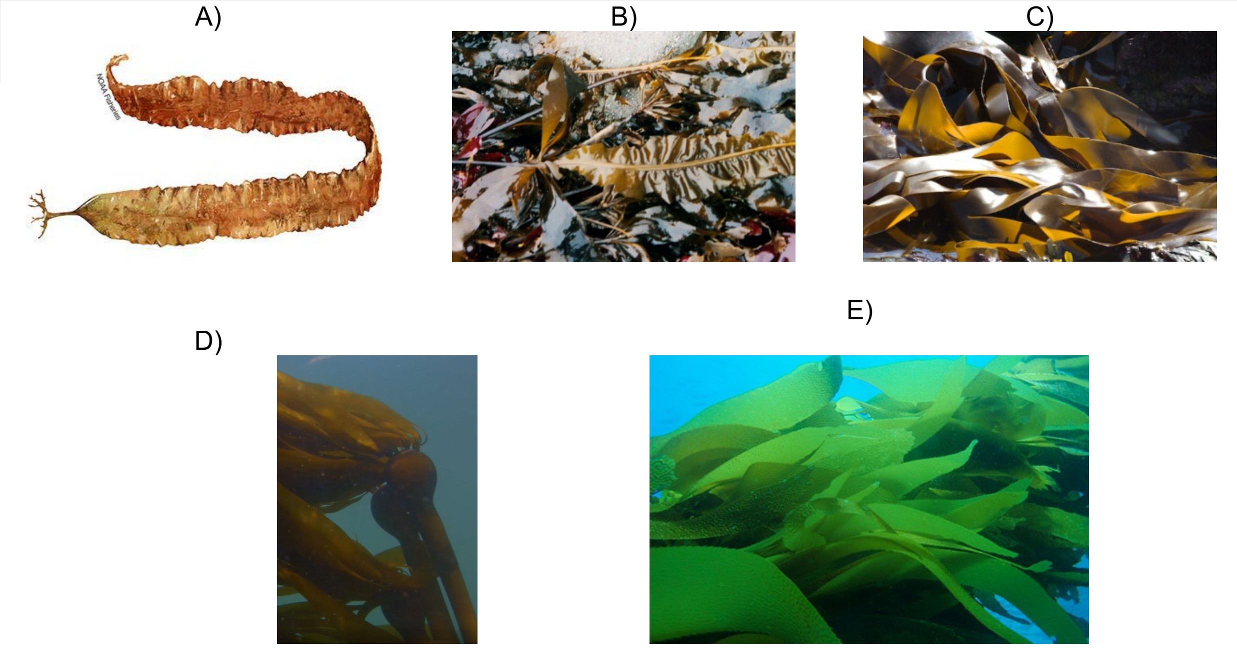


Figure 2. Commercially important kelp species in the United States. A) *Saccharina latissima* (sugar kelp and skinny kelp), Credit: NOAA Fisheries. B) *Alaria marginata* or *escuelenta* (winged or ribbon kelp), Credit: Dolly Garza, Alaska Sea Grant. C) *Laminaria digitata* (oarweed or horsetail kelp), Credit: The Seaweed Site [3]. D) *Nereocystis luetkeana* (bull kelp), Credit: NOAA. E) *Macrocystis pyrifera* (giant kelp), Credit: NOAA.

1.1.1 Benefits and Value

There are numerous benefits of kelp, both as a natural habitat and as a farmed product. Kelp and seaweeds are known for their ability to sequester carbon, locally reduce ocean acidification and nitrogen pollution, create habitat for fish and other marine species, and provide economic benefits.

The carbon capture potential of farmed kelp and status of knowledge is explored by Ocean Visions in their roadmap [4]. This roadmap highlights that for cultivated macroalgae to contribute to carbon dioxide removal, the carbon needs to be sequestered, either through intentional sinking, sedimentary burial below the farm, production of bioenergy with carbon capture and storage, or creation of long-lived products. The permanence of carbon sequestered in these kelp products throughout the lifecycle is not fully known, though this is an area of active research. It is clear that kelp and other macroalgae contribute to global carbon sequestration [5]–[7], and this information has been incorporated into ecosystem service valuations (e.g., [8]).

Kelp grown as part of multitrophic mariculture has been shown to provide a “halo effect”, locally improving water quality and protecting shellfish from ocean acidification, as well as uptake of excess nutrients at finfish farms [9]–[12]. The presence of kelp at farms also provides habitat for species not specifically harvested, boosting wild stocks for fisheries and other protected species [13]. Additional ecosystem benefits have also been documented by NOAA [14]. Compared to land-based agriculture, kelp farming takes up no valuable land, uses no freshwater or fertilizers, and is relatively low-tech. Large quantities of kelp can be produced in few acres of open ocean over a single season. This kelp is rich in nutrients, plant-based protein, and unique flavors.

Kelp have also been investigated as an off-season income for fisherman and fish processors in Alaska [1]. Rinker et al. (2021) found that it is feasible to utilize idle fish processing facilities for kelp, and that co-processing of the combined fish and kelp waste for biofuel feedstock could provide significant economic benefit for Alaskan communities. Additional economic benefits have been identified for seaweed aquaculture more broadly, including food security, poverty reduction at appropriate operation scales, and generation of new income streams from specialized, high-value products [15].

1.1.2 Products

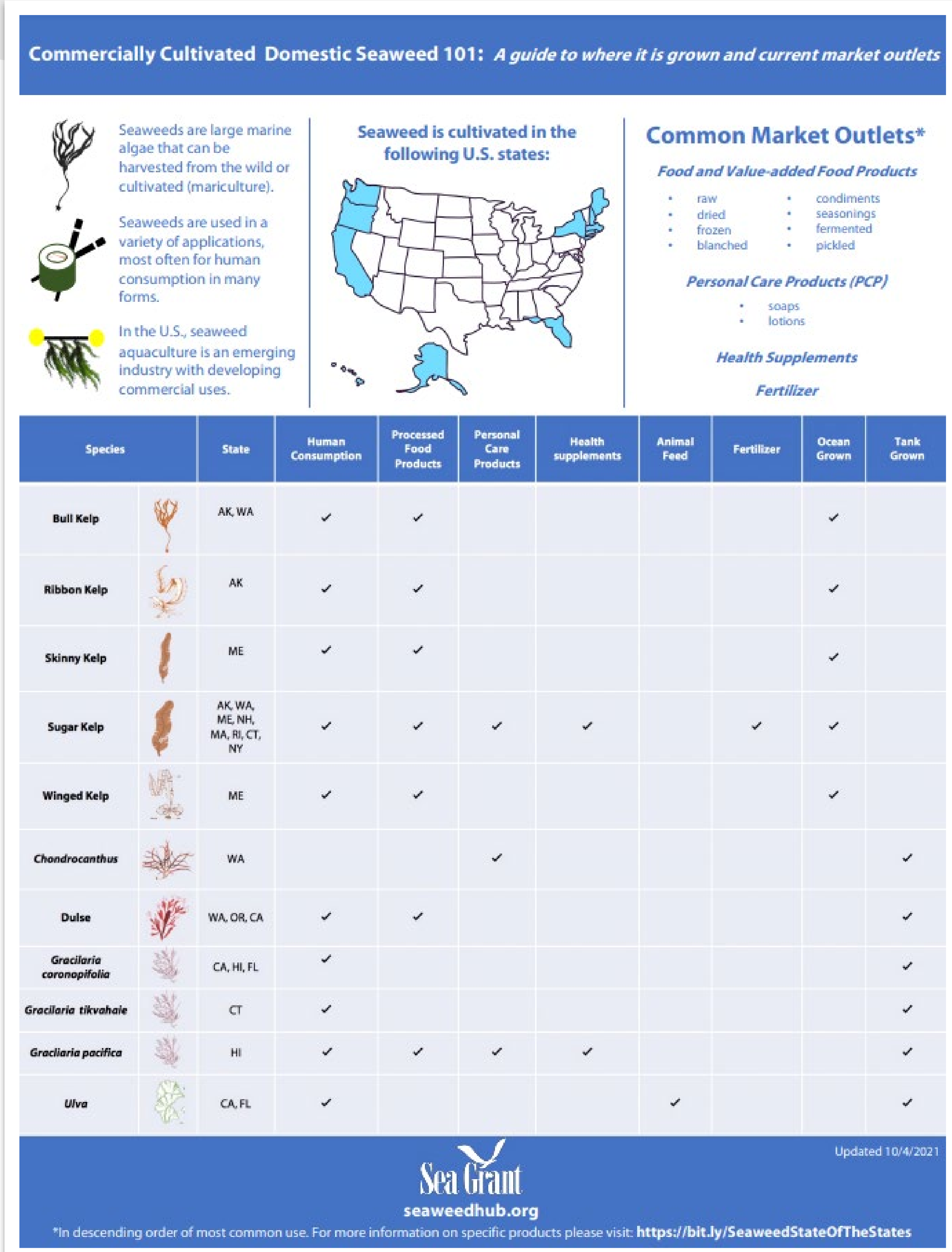
Once grown (either cultivated or wild-harvested), kelp can be used for a variety of products. Examples of these products are described below.

- Biofuels [16], [17]
- High value commercial products – carrageenan, alginate, iodine (cosmetics, stabilizers, thickeners, pharmaceuticals) [18]–[21]
- Food – salsa, jerky, kimchi, noodles [20], [22], [23]
- Fertilizer / biochar - additional nutrient bioextraction, including nitrogen and phosphorus [24], [25]
- Livestock / fish food supplement – additional benefit of methane reduction [26]–[30]
- Textiles [31], packaging [32], bioplastics [33]
- Building materials [34], [35]

Non-product uses of farmed kelp can include leaving it in place (typically for restoration purposes), growth as part of a mariculture farm, or intentional sinking to export the captured carbon to the deep ocean.

1.2 Status of the Industry

Despite numerous benefits, ease of production, and low costs, kelp aquaculture is a relatively small industry compared to land-based agriculture worldwide. This varies by region and country, but overall, the kelp industry in the United States is growing and promising, with many research investments looking at scale, products, monitoring, and carbon capture. Figure 3 shows the general distribution of seaweed cultivation in the United States (including several species of kelp) and product uses, compiled by Sea Grant.



Commercially Cultivated Domestic Seaweed 101: *A guide to where it is grown and current market outlets*

Seaweeds are large marine algae that can be harvested from the wild or cultivated (mariculture).

Seaweeds are used in a variety of applications, most often for human consumption in many forms.

In the U.S., seaweed aquaculture is an emerging industry with developing commercial uses.

Seaweed is cultivated in the following U.S. states:

Common Market Outlets*

Food and Value-added Food Products

- raw
- dried
- frozen
- blanched
- condiments
- seasonings
- fermented
- pickled

Personal Care Products (PCP)

- soaps
- lotions

Health Supplements

Fertilizer

Species	State	Human Consumption	Processed Food Products	Personal Care Products	Health supplements	Animal Feed	Fertilizer	Ocean Grown	Tank Grown
Bull Kelp	AK, WA	✓	✓					✓	
Ribbon Kelp	AK	✓	✓					✓	
Skinny Kelp	ME	✓	✓					✓	
Sugar Kelp	AK, WA, ME, NH, MA, RI, CT, NY	✓	✓	✓	✓		✓	✓	
Winged Kelp	ME	✓	✓					✓	
Chondrocanthus	WA			✓					✓
Dulse	WA, OR, CA	✓	✓						✓
Gracilaria coronopifolia	CA, HI, FL	✓							✓
Gracilaria tikvahaie	CT	✓							✓
Gracliaria pacifica	HI	✓	✓	✓	✓				✓
Ulva	CA, FL	✓				✓			✓

Updated 10/4/2021

Sea Grant

seaweedhub.org

*In descending order of most common use. For more information on specific products please visit: **https://bit.ly/SeaweedStateOfTheStates**

Figure 3. Seaweed cultivation in the United States. [36]

1.3.1 Distribution in the United States

Under another DOE project, funded jointly by the Advanced Manufacturing Office and Water Power Technologies Office, PNNL developed a 'Kelp Asset World Survey' published in March 2021 to understand how and where kelp is being grown worldwide [1]. From this, it was determined that over 99 percent of all kelp grown in the world is cultivated in eastern Asia, specifically in China, North and South Korea, and Japan.

The American seaweed and kelp aquaculture industry is much younger compared to Asian countries, but the industry is growing rapidly [37]. As of July 2021, there were 155 permitted or pending approval kelp sites in the United States (Figure 4, for a complete list by each state, and sources for updated information, see **Appendix A**). These farms are concentrated in southeast Alaska (Figure 5) and New England (Figure 6), though there are a few sites along the West Coast (Figure 7) with more to be expected.

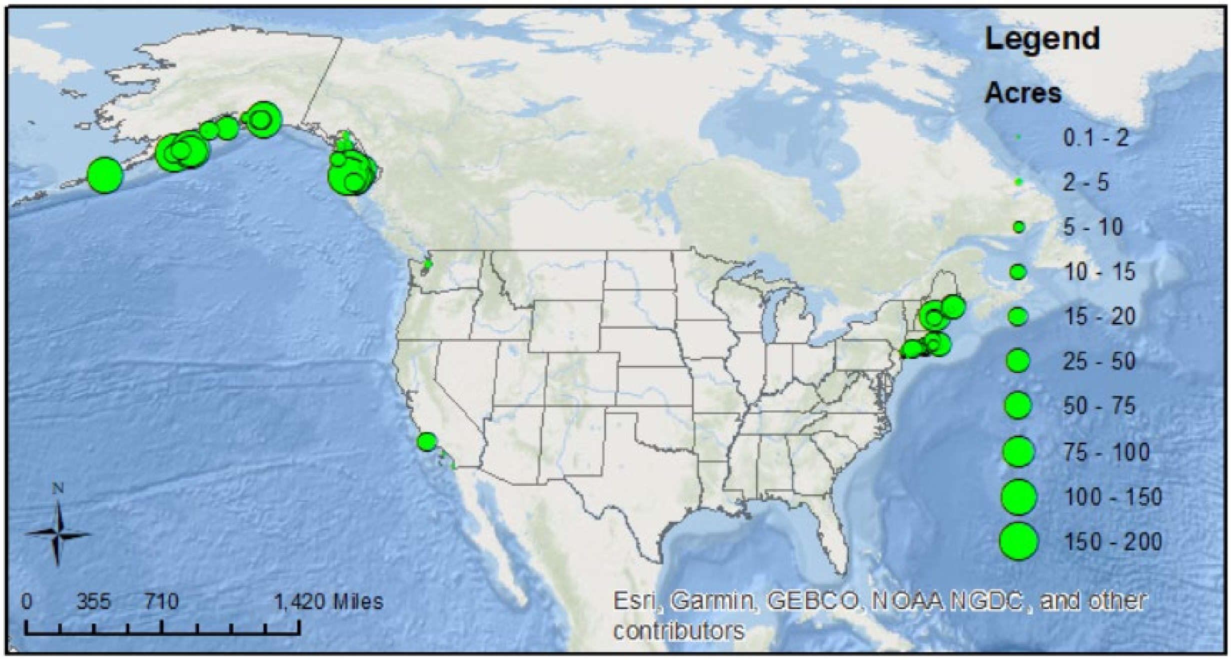


Figure 4. Kelp farms in the United States. Green circles indicate permitted or submitted site applications (n = 115), with size relative to acreage. Data sources described in **Appendix A**.

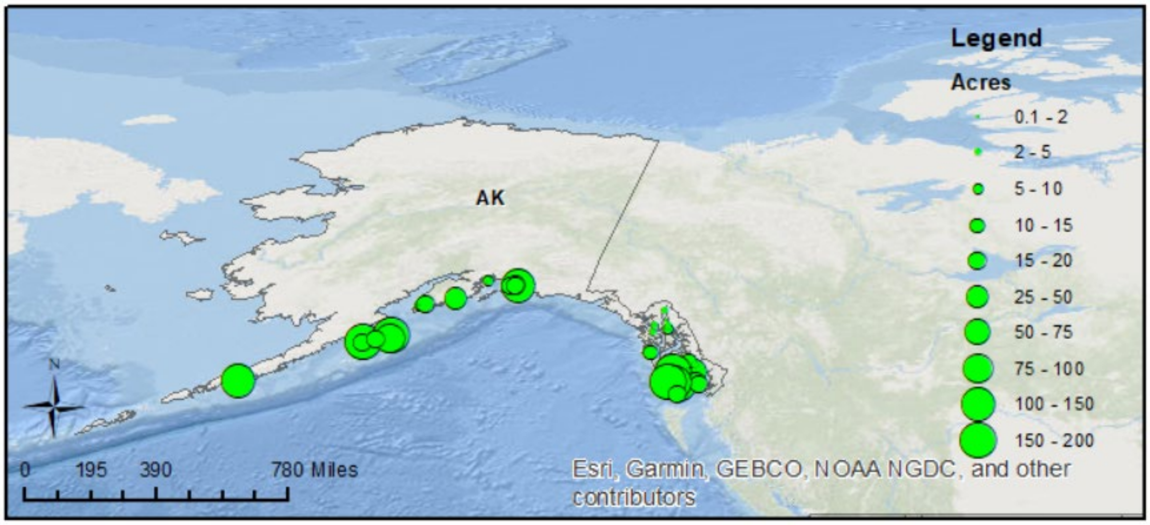


Figure 5. Closer look at kelp farms in Alaska. Updated information available from [ADFG map application](#).

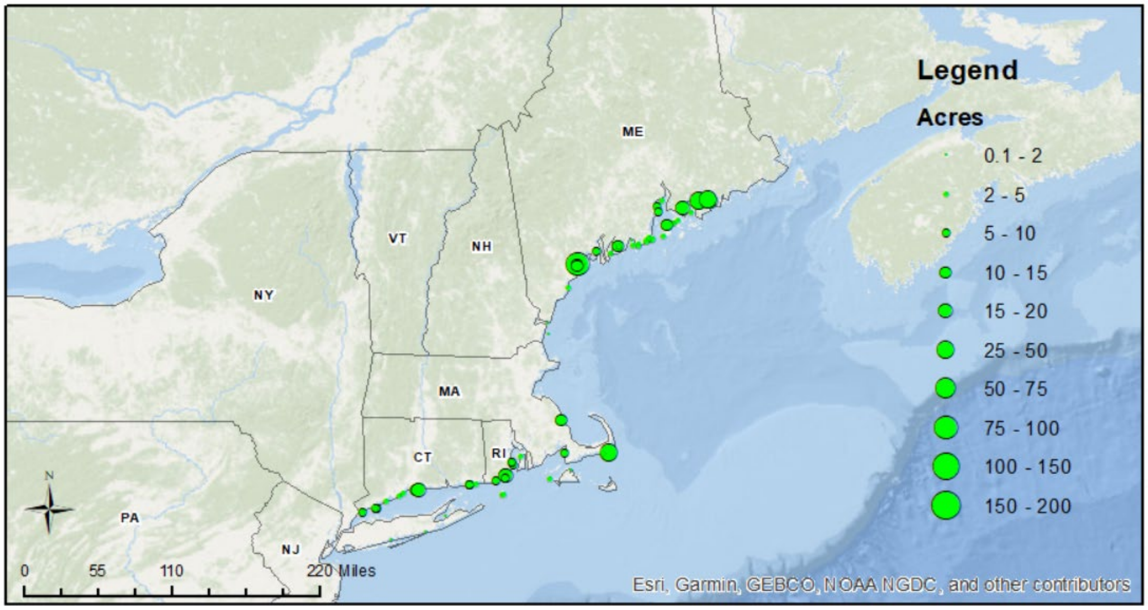


Figure 6. Closer look at kelp farms in New England. Data sources include Maine DMR Aquaculture Map, Northeast Ocean Data, CTECO Aquaculture Mapping Atlas, NY and CT's Shellfish and Seaweed Aquaculture Viewer, MA-ShellfAST Viewer, and RIDEM Marine Fisheries Maps.

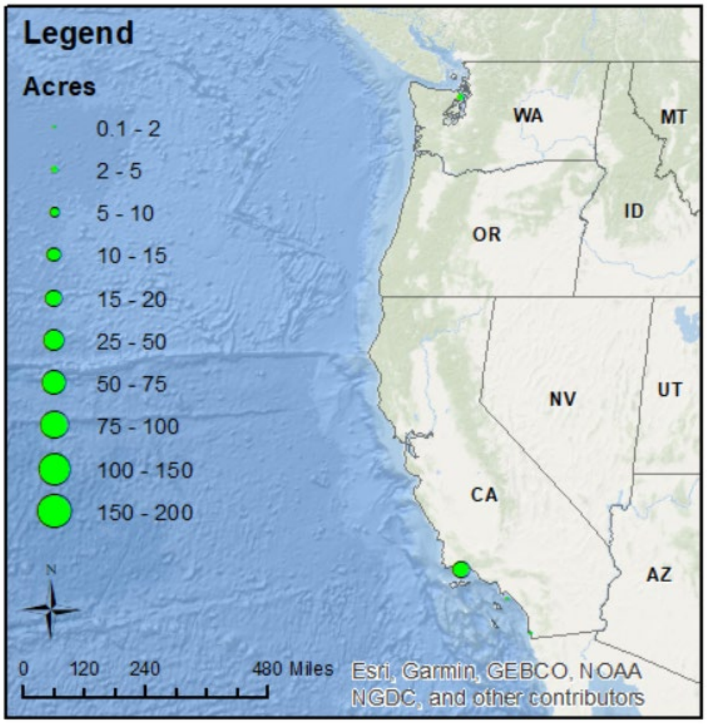


Figure 7. Closer look at kelp farms on the West Coast. Data sources described in **Appendix A**.

1.3.2 Siting Kelp Farms

The selection of a site for a kelp farm is determined both by biological need, maintenance logistics, competing uses, scale of operation, and regulatory ease. Most information currently available in the United States is for small to mid-size farms that are locally operated. Siting very large farms at great distance from shore will have different or additional considerations.

The Ocean Approved Kelp Farming Manual [38] recommends the following attributes for farm site selection in New England waters:

- Adequate current (1-2 knots during peak ebb and flood)
- Sufficient nutrients
- A protected lee from winter storms or ice flows
- Limited existing use for fisheries
- Bottom conditions good for mooring (recommend mud holes)
- Depth greater than 18 feet at mean low water
    - To reduce kelp touching bottom and biofouling
- No essential or protected habitat for endangered species, or significant flora and fauna on the bottom
- 1000 feet from public piers and beaches
- 1000 feet from riparian owners
- Growing in areas open to harvesting shellfish help assure clean water
- An area that allows for a long, narrow farm for ease of work, construction, and maintenance
- Calm wind and waves during harvest season (March-May)

The Alaska Sea Grant manual [39] recommends similar attributes, including:

- Clear, nutrient rich seawater
- Appropriate wave or current for the species being cultivated
- Adequate sunlight, temperature, and salinity
- Accessibility for regular visits

This manual has since been updated for Alaska (http://akaquaculturepermitting.org/siting-your-farm/) with a mapping tool, state and federal siting guidance for permit requirements, and additional recommendations for assistance in completing applications.

GreenWave has also developed a Site Evaluation Workbook [40] as a tool to help prospective farmers consider access, social and biophysical attributes, and regulatory considerations for siting. Several manuals also exist outside of the United States, including the United Kingdom Seaweed Cultivation Manual [41] and the EnAlgae Best Practice Guidelines [42]. Numerous species specifics handbooks exist, including for *Laminaria digitata* [43] and bull kelp [44]. Species specific environmental requirements can be found within these handbooks or on websites like MarLIN (UK - https://www.marlin.ac.uk/) or AlgaeBase (https://www.algaebase.org/).

Relevant information for co-locating kelp farms with marine energy is shown in Table 1.

Table 1. Guidance on siting kelp and seaweed farms relevant to co-location with marine energy.

Source	**Species**	**Wave energy-relevant recommendations**
Ocean Approved Kelp Farming Manual (2013) [38]	*S. latissima*, *L. digitata*, *A. esculenta*	Adequate current, 1-2 knots during peak ebb and flood Protected from winter storms Calm wind and waves during harvest season (March to May)
Alaska Sea Grant Manual (2017) [39]	*S. latissima*, *A. marginata*	Appropriate wave or current for the species cultivated
UK Seaweed Cultivation Manual (2016) [41]	General	Flow sufficient to bring in fresh nutrients and CO_2, and prevent biofouling. *Alaria esculenta* is well adapted to exposed, high flow sites
EnAlgae Best Practice Guidelines [42]	General	Max swell of 2m for nearshore sites Max current of 3 knots/1.5m/s
Cultivating Laminaria digitata (2011) [43]	*L. digitata*	Mid to high currents, 5-10cm/s
Bull Kelp Cultivation Handbook (1991) [44]	Bull kelp	Wave heights above 1-2 ft become difficult to work in Site in an area protected from long wind fetch
MarLIN	*L. digitata*	Flourishes in sites with strong water currents (1 – 6 knots)
	S. latissima	Flow rate effects blade morphology, such that blades from wave exposed sites are narrower, more wrinkled, and have shorter stipes Can tolerate fairly strong water currents

In addition to these recommendations, many web and mapping tools have been developed in the United States to aid in siting aquaculture farms. All of these tools are collated in the Coastal Aquaculture Planning Portal [45] and notably include:

- Alaska Ocean Observing System Mariculture Map
- Coastal Resilience Mapping Portal

- Connecticut Aquaculture Mapping Atlas
- Maine Aquaculture Map
- Marine Aquaculture Story Map
- Marine Cadastre
- Northeast Ocean Data
- Washington State Coastal Atlas

1.3.3 Farm System Construction and Design

There are various kelp farm designs in operation today. This section will describe the basic components of design with the intent of identifying potential locations for integration with marine energy within a farm.

Many kelp farms in the United States utilize a series of submerged, parallel longlines to grow kelp. The lines are moored to the seabed at each end and supported by additional buoys and weights spaced along the line to maintain desired depth and stability (Figure 8, 9). Marking buoys are also used (and often required by regulations) to aid in navigation and safety with competing uses on the water.

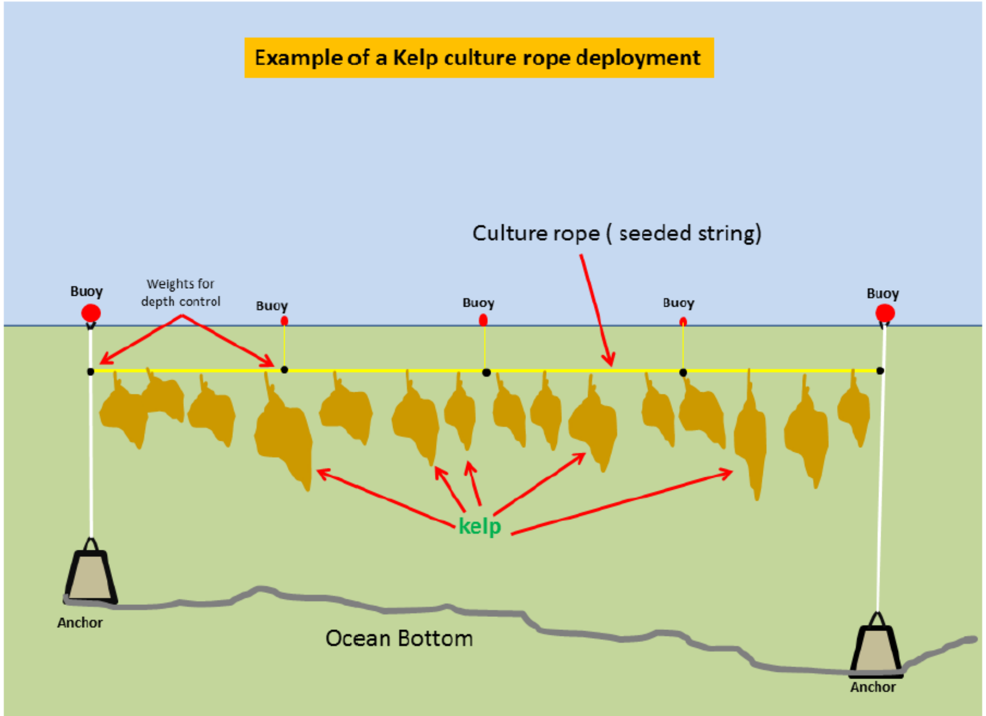


Figure 8. Example design of a horizontal kelp farm. Figure from the Alaska Sea Grant Manual [39].

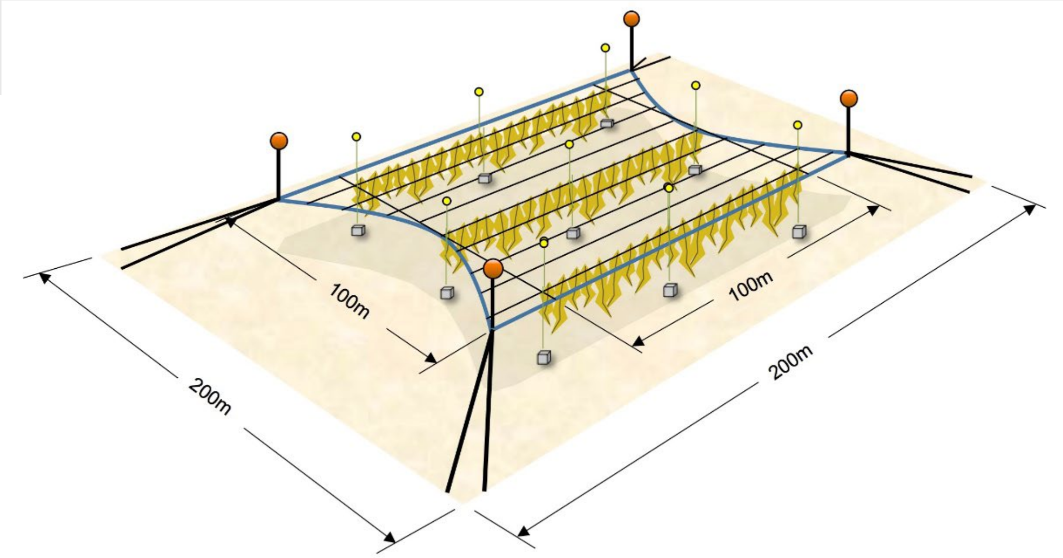


Figure 9. This kelp farm design was developed for use in Long Island Sound by C.A. Goudey & Associates and illustrates spacing of multiple longlines in a farm area. [46]

The dimensions of the farm are carefully determined for efficiency in materials, seeding, harvest, and crop yield, as well as species-specific considerations related to light, nutrients and buoyancy. Long, narrow farms have been found to be most efficient by Ocean Approved (now Atlantic Sea Farms), the first commercial seaweed farm in the United States [38]. Some farms are considering adopting a vertical farming approach (e.g., Alaska's Best Shellfish), though most farms currently in operation have a horizontal design.

1.3.4 Investments in Kelp Aquaculture and Marine Energy

Many groups in the United States and internationally are investing in large scale kelp aquaculture and specifically the nexus with marine energy. One of the most notable examples is the ARPA-E MARINER (Macroalgae Research Inspiring Novel Energy Resources) program, which started in 2017 with a primary focus on biofuels, and auxiliary projects on marine energy. Projects under the MARINER program that link marine energy and kelp monitoring include:

- Ocean Energy from Macroalgae by Fearless Fund
- Nautical Offshore Macroalgal Autonomous Device (NOMAD) by Pacific Northwest National Laboratory
- Monitoring Macroalgae Using Acoustics and UUV (KelpBot) by Woods Hole Oceanographic Institution
- Scalable Aquaculture Monitoring System by UC Santa Barbara

The United States Department of Energy and the Water Power Technologies Office in particular are interested in exploring how marine energy can power emerging markets like kelp farming and other climate mitigation strategies that utilize the ocean as a carbon sink [47].
The Sea Grant network has developed a national Seaweed Hub to coordinate seaweed aquaculture in the United States. At a state level, Washington Sea Grant, Connecticut Sea Grant, Maine Aquaculture Innovation Center and the Alaska Mariculture Initiative all have significant projects related to developing the kelp aquaculture industry in the United States. There are also numerous local-scale projects (e.g. Puget Sound Restoration Foundation Sugar Kelp Ocean Acidification Project; Running Tide), often partnered with academic institutions or other agencies.

There are also several international projects in this area. Oceans 2050 is conducting a 15-month study to quantify carbon sequestration by seaweed aquaculture by sampling sediments at farms in multiple countries, including Atlantic Sea Farms in the United States. Norway has been a leader in the kelp aquaculture space with several projects, including a project on autonomous monitoring by NTNU AMOS and the MACROSEA knowledge platform. MARIBE under the European Horizon 2020 project also has a topic partnering a wave energy array with a seaweed farm to create a calm sea area for aquaculture operations, with energy exported to the grid.

1.3.5 Challenges

There are several challenges to the development of the kelp aquaculture industry in the United States. The Sea Grant Seaweed Hub conducted a Needs Assessment [48] in January 2021 to document these challenges for the industry and identified production systems and regulatory and permitting concerns as a major barrier. From a legal and regulatory perspective, the path to permitting has not been traditionally easy, although things are expected to change with a new proposed nationwide permit from the United States Army Corps of Engineers. Many farms are located in state waters, often with multiple competing uses and occasionally access issues due to private properties. The economic barriers stem from high upfront investments, low access to developing markets and processing facilities, and the financial risk inherent in growing single crops, especially with the ongoing threat of climate change.

2.0 Monitoring Kelp Farms

Monitoring at kelp farms varies greatly based on the scale of the farm and planned end products. For example, growing macroalgae for biofuel requires precise monitoring for optimal harvest in order to get the greatest yield from processing. Growing kelp for human food products also requires monitoring to ensure health and safe consumption. But growing kelp as a part of a multitrophic farm to remove excess nutrients or for carbon capture may require a different type of monitoring, as the kelp itself is not the primary end product, but the effectiveness of uptake is key to understand.

2.1 Why Monitor

Monitoring at a kelp farm may or may not be required for permits to ensure environmental protection or product quality. For example, water quality samples are required for analysis in Alaska to ensure safety of human consumption, testing for contamination and bacterial or fungal loads, while kelp farmers in Maine have indicated that there are no requirements for monitoring and most sampling or analysis is for academic purposes. Regardless of requirement, monitoring water conditions and quality throughout the growing season provides useful data to inform future decisions [17], and even if kelp farmers are not conducting monitoring themselves, they often utilize data collected by others (e.g., research laboratories in the same water body, state monitoring for recreational shellfish harvesters, etc.).

An additional benefit of monitoring is that it enables continuous, secure farm operations. Kelp can become detached from lines in storms and even low tech equipment needs to be attended to be productive [49]. Monitoring can also serve a security purpose, deterring vandalism or theft. Monitoring the carbon offset potential of kelp in addition to health and status monitoring can allow farmers to make timely decisions about their harvest, as well as to value the services they are providing to the ecosystem. This could also allow for the sale of carbon credits or offsets as a supplemental income source to support further farm projects and development. While this concept has not been practiced yet for kelp, research is underway to assess the feasibility of carbon credit sales for certain kelp products, based on the permanence of the carbon captured by the kelp [50].

In order for the carbon credits to be traded (typically representing 1 metric ton of CO_2), a certification body needs to assess the timeline of sequestration. There are a variety of certification standards and schemes with varying levels of rigor and requirements for entry, for example:

- Gold Standard Climate+ https://www.goldstandard.org/take-action/certify-project
- Verra Verified Carbon Standard https://verra.org/project/vcs-program/
- Climate Action Reserve https://www.climateactionreserve.org/how/voluntary-offset-program/
- American Carbon Registry https://americancarbonregistry.org/carbon-accounting/standards-methodologies/american-carbon-registry-standard
- Plan Vivo https://www.planvivo.org/register-a-project
- Climate, Community and Biodiversity Alliance Standards https://www.climate-standards.org/ccb-standards/
- Green-e Climate Certification https://www.green-e.org/programs/climate
- Carbon Neutral Certification https://www.carbontrust.com/what-we-do/assurance-and-certification/carbon-neutral-certification

While terrestrial carbon credits are common, marine or blue carbon credits make up much less of the overall carbon market. Gold Standard and Verra both have methodologies targeted at blue carbon protection and restoration projects, but they are much newer. Verra launched a Seascape Carbon Initiative in 2021 to improve the blue carbon market and includes kelp and seaweed farming, though little progress has been documented. In addition to carbon markets, some private companies are investing in restoration projects or carbon capture projects that are not certified. For example, e-commerce company Shopify has committed $5M as part of their Frontier Portfolio to explore new permanent carbon removal technologies, which includes investment in Running Tide towards validation of their kelp carbon sequestration methodology [51]. As a newer frontier, marine carbon capture through seaweed farming may take time for certification bodies to develop the standards needed for certifications and sales in this area to move forward, but this is a topic that is front-of-mind for certification bodies as well as those working in blue carbon industries [52].

Lastly, there are some possibilities for farmers to directly profit from monitoring data. GreenWave is piloting a Kelp Climate Fund that will pay farmers for their monitoring data in order to aggregate and track the impact of kelp farming across North America [53]. As of March 2022, they estimate a yield of 566,400 pounds, 90 acres of kelp planted, 14,160 pounds of carbon removed, and 1,122 pounds of nitrogen removed from just five enrolled farms in Alaska, Rhode Island, New York, and Maine [53].

2.2 Parameters

There are numerous possibilities for parameters that could be monitored at or around kelp farms. The Ocean Approved Kelp Farming Manual [38] recommends monitoring water temperature, salinity, turbidity, nitrogen levels, and growth rate of kelp. The Alaska Sea Grant manual [39] recommends collecting data and maintaining records on water temperature, salinity, water clarity, and nutrient levels. Participation in GreenWave's Kelp Climate Fund requires growth measurements (length, weight) to calculate carbon and nitrogen removal [53]. Additional parameters that can be measured include:

- Dissolved oxygen [49], [54]
- Growth rate (biomass and size) [55], [56]
- Genetic diversity [57]
- Nutrient / carbon absorption [5], [58], [59]
- Sugar content (for biofuels) [56]

Examples of the parameters that can be measured at and around kelp farms are detailed in Table 2.

Table 2. Parameters measured at kelp farms. Frequency column indicates roughly how common a parameter measurement is relative to other parameters (**** most common, * least common).

Parameter	Frequency	Example sensors	Definition and uses
Acoustic backscatter	**	EK80	Used to measure relative biomass or abundance of kelp, or to detect kelp in contrast to other habitat features (e.g., [60]).
Bathymetry	****	Altimeter, echosounders	Depth and topography of the seafloor. Used in siting kelp farms based on species specific depth requirements.
Canopy composition	**	Hyperspectral drones, ADCP, RGB UAV imagery	Aerial techniques to measure area and distribution of kelp forests or farms. Automated methods available [61]
Chlorophyll	**	YSI sonde and sensor (fluorometer), CCM-200, chemical extraction, spectro-photometer	Typically measured in a laboratory. Kelp utilize chlorophyll for photosynthesis, so this measurement can be used to assess samples of tissue. Chlorophyll can also be measured in water and represents the concentration of suspended phytoplankton, which can allow for detection of harmful algal blooms [62]
Conductivity	****	CTD, Optode	Ability of seawater to conduct electricity. Conductivity is related to salinity, as it is the concentration of dissolved salts (ions) that transmit electricity.
Current direction and velocity	***	Drogues, GPS	Measures of current and velocity are needed in siting and monitoring water speeds around a farm site.
Dissolved organic matter (DOM)	**	SeaOWL	DOM can be released as kelp respire and break down throughout their lifetimes [63]–[65]. It can also be present in the environment (e.g., nutrients) and can contribute to growth.
Marine mammal presence	**	Video camera, human observers	Observation to report marine mammals within the site. Video could also be used for security purposes.
Nitrates	**	Nitrate meter, ion-selective electrode, SUNA, EXO Sonde, Aquaread sensor	Nitrates are a set of compounds that contain nitrogen and oxygen molecules. Kelps utilize nitrates as a key nutrient. High nitrate presence can also be an indicator of pollution.
Oxygen concentration and saturation (dissolved oxygen [DO])	***	Optode, AdvantEDGE HF Scientific, Omega, Orion field multiprobe	Though not much is known about the direct effects of hypoxia on macroalgae, DO is required for kelp and other marine animals for respiration [54]. Hypoxic conditions can lead to fish kills or shellfish die offs, affecting the broader ecosystem.
pH	***	Hanna portable meters, Orion field multiprobe, SAMI pH system, SeaFET systems, other	Measure of how acidic water is. Ocean acidification is a concern for many mariculture species.
Photosynthetically active radiation (PAR)	*	PAR sensor, silicon photovoltaic detector	PAR is the portion of the light spectrum used by kelp for photosynthesis. Measuring PAR enables evaluation of the effect of light on kelp growth.
Salinity	****	CTD, Optode, refractometer	Salt concentration of the seawater. Salinity tolerance of kelp varies by species (e.g., [66]) and can contribute to diversity [67]. Salinity is typically measured through electrical conductivity.
Temperature	****	CTD, Optode, HOBO loggers	Warmth of seawater. Kelp typically grow in cool water ranging from 5 - 20˚C. Temperature has been shown as a driver of morphological characteristics [68], reproductive patterns [69], and C:N ratios [70].
Turbidity	**	Hand-held nephelometer, Secchi disc	Measure of water clarity, related to total dissolved or suspended solids. Affects light penetration, which is required for growth.

2.3 State of the Art – Farmers, Researchers, Devices

A variety of monitoring devices have been leveraged or coopted for use in monitoring kelp farms for maintenance of the farm, timing for optimal harvest, health and product quality, and ongoing research. Several of these devices currently used at United States farms or research sites are described in Table 3. Note that individual farms contacted are not reported due to expressed desires for confidentiality and anonymity.

Table 3. Monitoring devices at U.S. kelp farms. Information from direct outreach to U.S. kelp farmers, supplemented by web searches on device. Frequency column indicates roughly how common a device is specific to aquaculture monitoring (**** most common, * least common or custom).

Device / platform	Frequency	Sensors	Data collection and availability	Power needed	Infrastructure needs
REMUS 100	**	Customizable	Data available upon vehicle recovery	Rechargeable batteries	Deployment, autonomous or operated
Aerial drone	**	Camera, video	Live transmission	Rechargeable batteries	Shore-based operator
CTD	****	Conductivity (salinity), temperature, depth	Casts or continuous	mW, can be wired or battery (replaceable AA), very low power	Moored, integrated (AUV or profiler), or cast
Video Camera	***	Video	Live transmission or recorded	Varies by active time, 12V charge or cabled	Moored, integrated (AUV), towed by boat, or diver
HOBO Pendant data loggers	***	Temperature, light	Continuous	Batteries – 9V	Moored
Refractometer	**	Salinity (based on specific gravity)	Sample collected	Batteries (3V) or integrated with device power	Handheld or integrated (profiler)
Orion field multiprobe	***	DO, pH	Continuous, timed, or individual samples	Batteries (AA) or universal cable	Mounted or handheld
Video plankton recorder, Scripps Plankton Camera (and others)	**	Plankton composition	Continuous or time series frames along routes, live transmission	Battery or cable to ship	Towed by boat
PSRF moored buoys	*	pCO_2, pH, temperature, salinity, density, DO, chlorophyll, turbidity, current	Timed (6 min)	Solar and battery onboard	Ship required for deployment, then moored
SeaBird SeapHOx sensors	**	pH, DO, temperature, salinity, density	Timed (10 min)	Battery (1 year life)	Integrated with moored buoy
SAMI pH systems	**	pH	Timed	Battery	Integrated with moored buoy
Custom built durafet-based sensors	*	Temperature and pH	Data available to download on recovery	3V battery for durafet, 9V for data logger	Deployed on lines and retrieved after 3 months
Niskin bottles	***	DIC, oxygen, nutrients, alkalinity	Water samples for offsite analysis	NA	Ship time for collection

Some farms also utilize monitoring data obtained by the state or other monitoring organizations such as NOAA for recreational shellfish harvesting or general ocean observation data. Additional physical sampling is done at many farms for research or monitoring purposes that require an in-person site visit as opposed to a deployed sensor. Examples include: carbon and nitrogen sampling via excised blades and laboratory analysis; holes punched to measure growth rates, standing biomass and erosion rates; water sampling for additional biogeochemical attributes; or samples testing for pathogens and other human food quality needs.

In general, monitoring done at small farms in the United States is minimal with low power needs. Some larger farms are interested in the future investing in more autonomous, continuous sampling which would require more power. Several farms indicated that their monitoring systems were proprietary, and were reluctant to share even basic information. Farms that responded to our outreach effort utilize data from a variety of sources to make decisions, often leveraging existing data collection efforts that were publicly available or made available in collaborations.

A few detailed case studies of monitoring projects around kelp farms are summarized below.

2.3.1 Woods Hole Oceanographic Institution

Researchers at Woods Hole Oceanographic Institution have been developing and using monitoring devices in their KelpBot program since 2017 when they were awarded $2 million from the ARPA-E MARINER program. Two unmanned AUVs have been developed, Snoopy and Darter, with a variety of acoustic, optical, and environmental sensors [55]. Each AUV is an upgraded REMUS 100 [71], mounted with equipment that can include: echosounders (DAQ Box LC-EDB, based around the BlueRobotics Ping 120 kHz echosounder; Simrad EK80 on Snoopy only), split beam sonar, sidescan capabilities, Go Pro, KelpCam 360 degree camera system with laser scaler (Darter only), fluorometer, CTD package, and nitrate sensors (P. Teixeira, personal communication).

From their ARPA-E project page, and as shown in Figure 10, “The system will routinely survey and quantify key parameters such as infrastructure health, macroalgae growth rate, and nutrient content of the water. An upward/downward split-beam acoustic echosounder will use sonar technology to monitor the longline array used to grow the macroalgae, quantify growth on the longlines, and detect fish/zooplankton in the water column. Environmental sensors include a nitrate sensor (nutrients) and a package for collecting temperature and salinity data. A panoramic camera system will be used for close inspection of infrastructure and anomalies, with images available to operators within 24 hours of capture. Real-time processing of acoustic data, fed back into the autonomy system, will be used to map infrastructure and navigate the UUV relative to longlines for macroalgae sensing. Ultimately the UUV-based system will be able to operate in real conditions offshore and over large areas without human intervention.” [72]

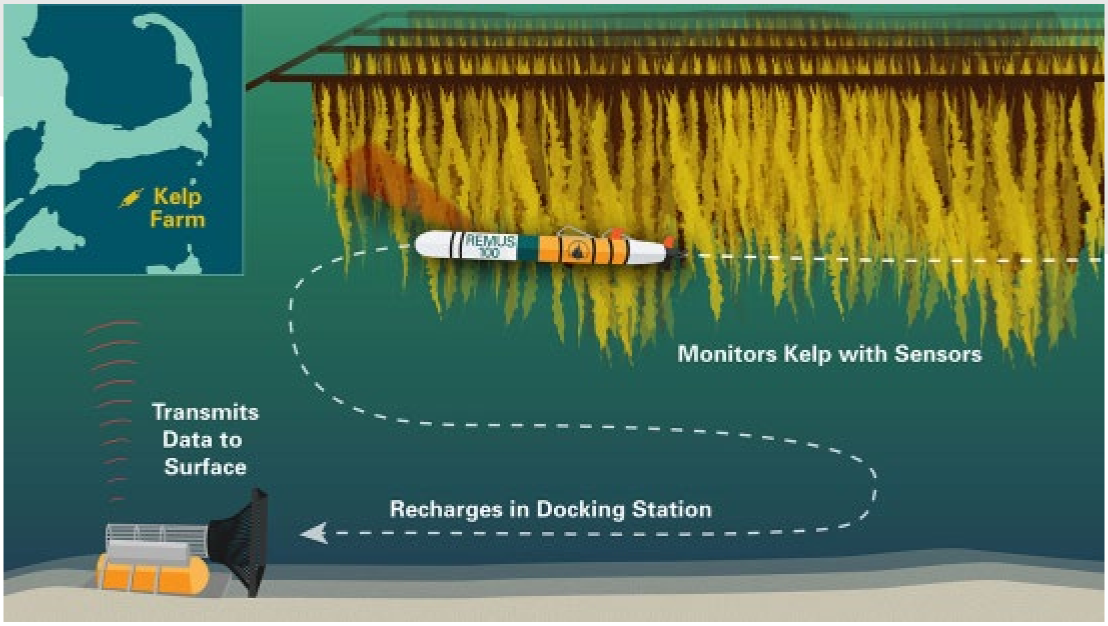


Figure 10. Overview of KelpBot program REMUS. Illustration by Natalie Renier, Woods Hole Oceanographic Institution.

2.3.2 UC Santa Barbara

The Earth Research Institute team at UC Santa Barbara in California is developing a Scalable Aquaculture Monitoring System with a $2 million ARPA-E MARINER project. The team is using aerial drones (DJI Phantom 4 Pro with color camera, Matrice 200 with a five-band Micasense Multisensor, Matrice 600 pro with a Headwall Nano-Hyperspec sensor) to monitor floating giant kelp on the West Coast. They are also using UUVs, including a REMUS 600 unit, to monitor subsurface biomass and other environmental data. These data will be used to determine the optimal harvest time, ensuring that the sugar content of kelp is at its maximum. The goal of the UCSB team is to provide a suite of data products for farms of any size to be able to monitor from outplant to harvest [73].

2.3.3 Hood Canal Puget Sound Restoration Fund Project

A partnership between Hood Canal Mariculture, Puget Sound Restoration Fund, Washington Sea Grant, University of Washington, NOAA, and funding from the Paul G. Allen Family Foundation enabled permitting of the first kelp farm in Puget Sound, WA. This farm conducted significant research from 2015-2019 on the mitigation of ocean acidification by kelp and its effects on shellfish aquaculture. Two moored buoys were installed at the site for the duration of the project, carrying sensors for pCO_2, pH, temperature, salinity, density, DO, chlorophyll, turbidity, and current velocities (Figure 11). Results of this monitoring enabled the development of models to assess the effect of kelp on seawater chemistry and evaluate candidate sites for kelp farms, though these models are yet to be published and publicly available. While this research was unable to measure differences between the kelp farm and surrounding sites due to residence time of seawater and other biological factors, this provides an example of the application of significant monitoring efforts.

Figure 11. Monitoring buoys at an experimental farm in Hood Canal, Washington. Credit: John Mickett, APL UW [74].

2.3.4 Coastal Observing Buoy

Maine Aquaculture Innovation Center and Prescott Engineering are developing an environmental monitoring buoy that integrates with existing farm infrastructure [75]. While this project is focused on shellfish, the parameters measured with the buoy and the overall goal of a low-cost, multi-sensor platform fits well with the status of the kelp aquaculture industry.

2.3.5 Carbon Wave Glider

The Pacific Marine Environmental Laboratory carbon group has collaborated with Liquid Robotics and Saildrone to develop a carbon monitoring wave glider that can measure dissolved carbon dioxide in addition to temperature, salinity, and other environmental conditions [76], [77]. The carbon wave glider is powered by wave energy for propulsion and solar panels to power the sensors and communications [78]. This device provides one of the few examples of autonomous monitoring devices that are fully powered by renewable energy.

3.0 Opportunities for Marine Energy

Alaska and the New England states have the most established kelp industry in the United States, and have significant potential marine energy resources (Figure 12), though very different contexts for implementation and infrastructure. New England states are characterized by large population centers and extensive coastal development, with demonstrated interest in grid-scale renewables (e.g., land based and offshore wind, hydroelectric power). Alaska does not have the population centers that are widespread in the New England states and, as such, has very different energy needs. With the lowest population density and spatially separated communities, a state-wide power grid integrated with renewables is not feasible. Instead, distributed power is the norm, with many communities relying on a solely diesel-powered microgrid or occasionally supplemented with hydroelectric power. In both Alaska and New England, marine energy resources are available and compatible with these disparate contexts.

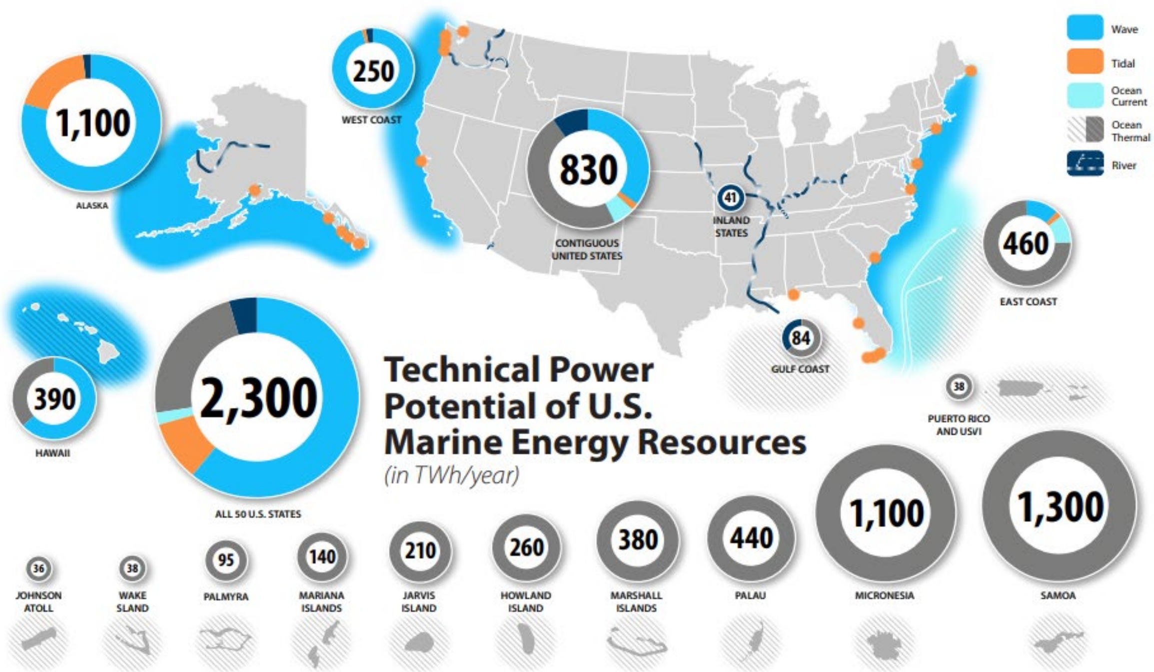


Figure 12. Marine energy resources in the United States, from [79].

Wave energy is the most common resource in the United States and also most prevalent in areas where kelp forests are located and farms are being developed. Kilcher et al. [79] found that Alaska has a technical wave resource of 890 TWh/yr, the East Coast has 55 TWh/yr (including areas not suitable for kelp in the Southeast), and the West Coast has 240 TWh/yr.

3.1 Past Work: Powering the Blue Economy Report

The Powering the Blue Economy Report [80], produced in 2019, describes opportunities for marine energy to provide power at sea or in remote communities. The report contains sections on offshore aquaculture and marine algae. The report notes that while small aquaculture sites require little power, the larger farms expected to become the future norm will need energy for "harvesting, drying, monitoring, and maintenance activities, as well as for maneuvering and buoyancy controls… These power needs could be satisfied wholly or in part via energy generated from marine energy devices by designing marine energy systems into growing and harvesting systems to provide off-grid power needs. Marine energy provides a unique advantage over other forms of energy generation by being less geographically limited at high latitudes where some macroalgae species thrive and could also provide shelter to more exposed sites by attenuating wave action while simultaneously generating power."

3.2 Past Work: Processing

Coastal Alaskan communities were a focus of a 2021 report by Rinker et al. that assessed the connections between kelp products and marine energy [1]. This report identified clear opportunities for marine energy in the processing phase of kelp, in particular, for biofuels. While this report does not address monitoring at kelp farms, the multiple linkages between renewable energy and kelp production suggest that on-site marine energy could provide power for multiple uses, if designed appropriately. The report also identified that the possibilities and benefits are highly location-specific, and that energy transmission distance plays a large role in the feasibility of marine energy for processing or other uses.

3.3 Past Work: Wave Resource Characterization

Significant work has been done to characterize the marine energy resources available in the United States, as well as efforts to harness these energy resources. The most recent work can be found on the National Renewable Energy Laboratory's Marine Energy Atlas (https://maps.nrel.gov/marine-energy-atlas). Models developed by Pacific Northwest National Laboratory provide high resolution information on wave resources on the West Coast, East Coast, and Hawaii, with information on Alaska coming soon. Past work has been done for the entire U.S. at slightly lower resolution (U.S. Wave Model 2011). Average annual results from these available modeling efforts in areas relevant for kelp cultivation are shown in Figure 13,14 and 15.

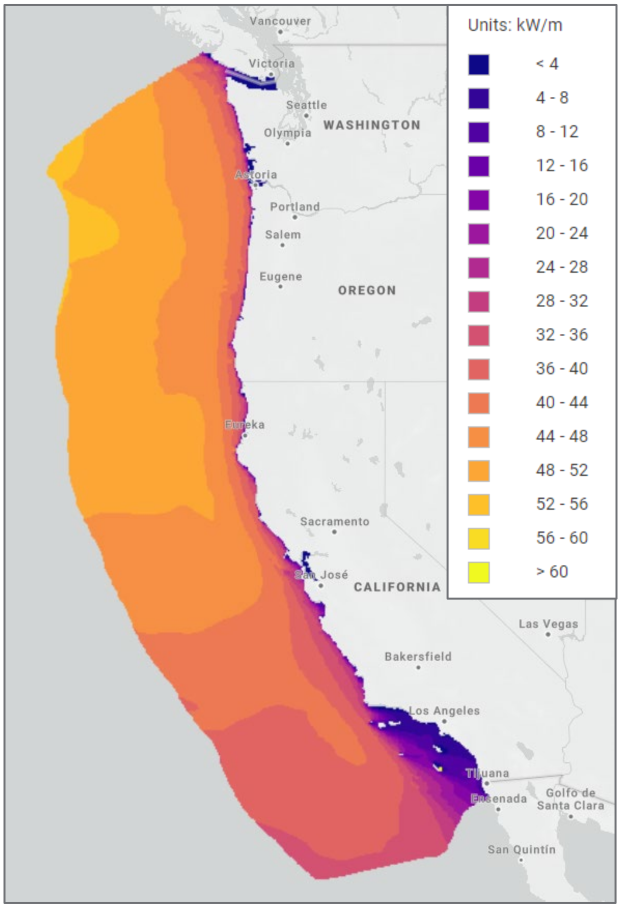


Figure 13. Annual average omnidirectional wave power - West Coast Wave Model (2020). From Marine Energy Atlas.

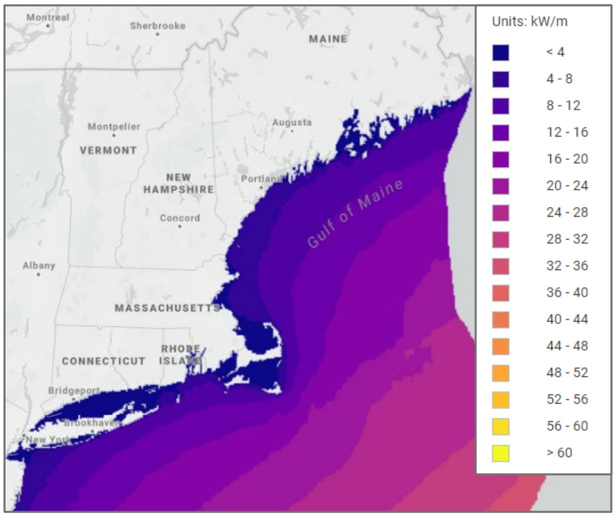


Figure 14. Annual average omnidirectional wave power – Atlantic Wave Model (2021). From Marine Energy Atlas.

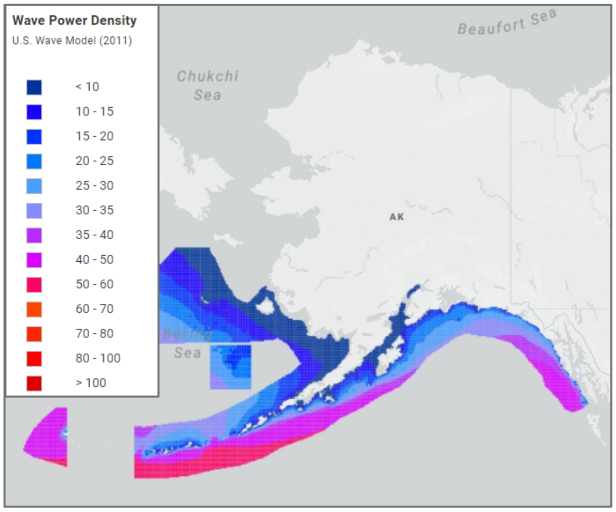


Figure 15. Annual average wave power density (kW/m) – U.S. Wave Model (2011). From Marine Energy Atlas.

3.4 Overlap of Energy Resources and Farms

Most kelp farms are located relatively nearshore for maintenance and operational needs, while most wave energy harvesting projects to date have focused more on offshore locations. Figure 16 shows an overlay of available wave power data across the United States and the location of kelp farms. Due to these operational needs, the available wave resource at coastal farm sites is typically lower than it would be if located far offshore. In addition, higher resolution models are needed to assess the coastal wave resource closer to shore, and modeling the wave climate in closer areas can be more difficult (Figure 17).

There are other metrics used to assess wave power that may also be relevant for assessing suitability for energy harvest at kelp farms [81], but this report focuses only on annual average omni-directional wave power (OWP, also referred to as wave power density, both reported in terms of kW/m) as a measurement of total power available and general wave climate of a site.

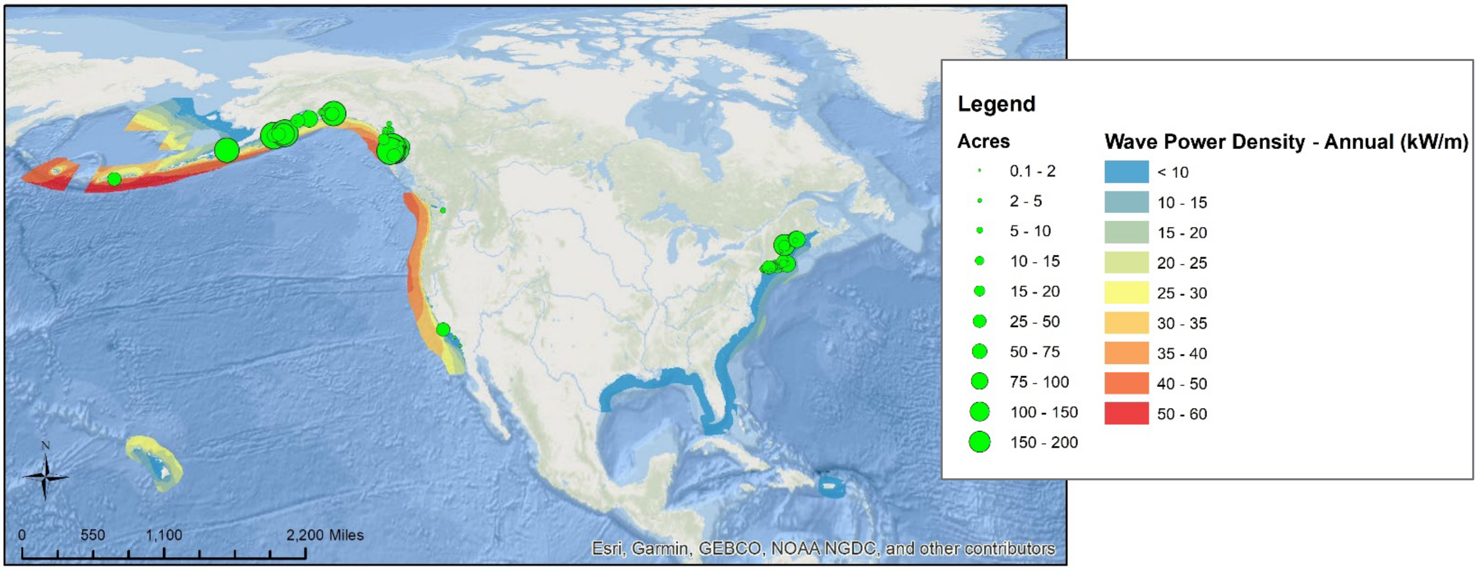


Figure 16. Overlap of U.S. wave energy resource and permitted/pending kelp farms. A list of current kelp farms by location and capacity is available in **Appendix A**. Wave resource data are average annual wave power density from the Wave Energy Resource Assessment [82], accessed from Marine Energy Atlas.

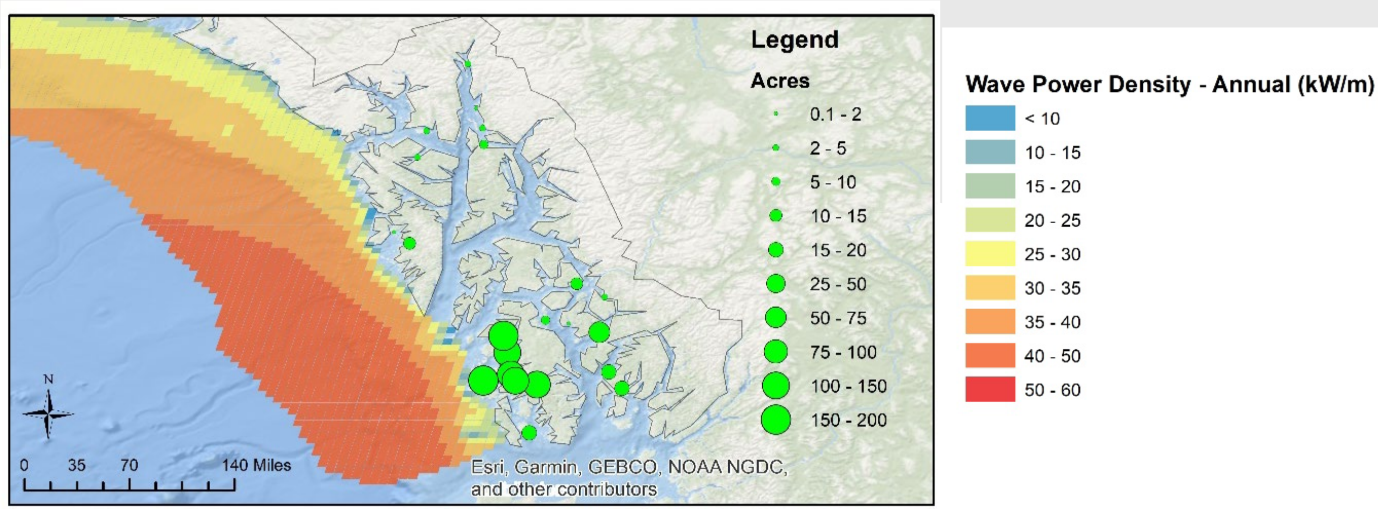


Figure 17. Close up example on farms in Southeast Alaska, showing that the resolution of modeling is too low to match farm locations especially inshore. Updated data are expected to be available for this area soon on Marine Energy Atlas that may resolve this issue for some sites.

It is expected that larger farms have higher energy needs for monitoring, general operations, and processing their products. Figure 18 shows the relationship between power at a site and the farm size.

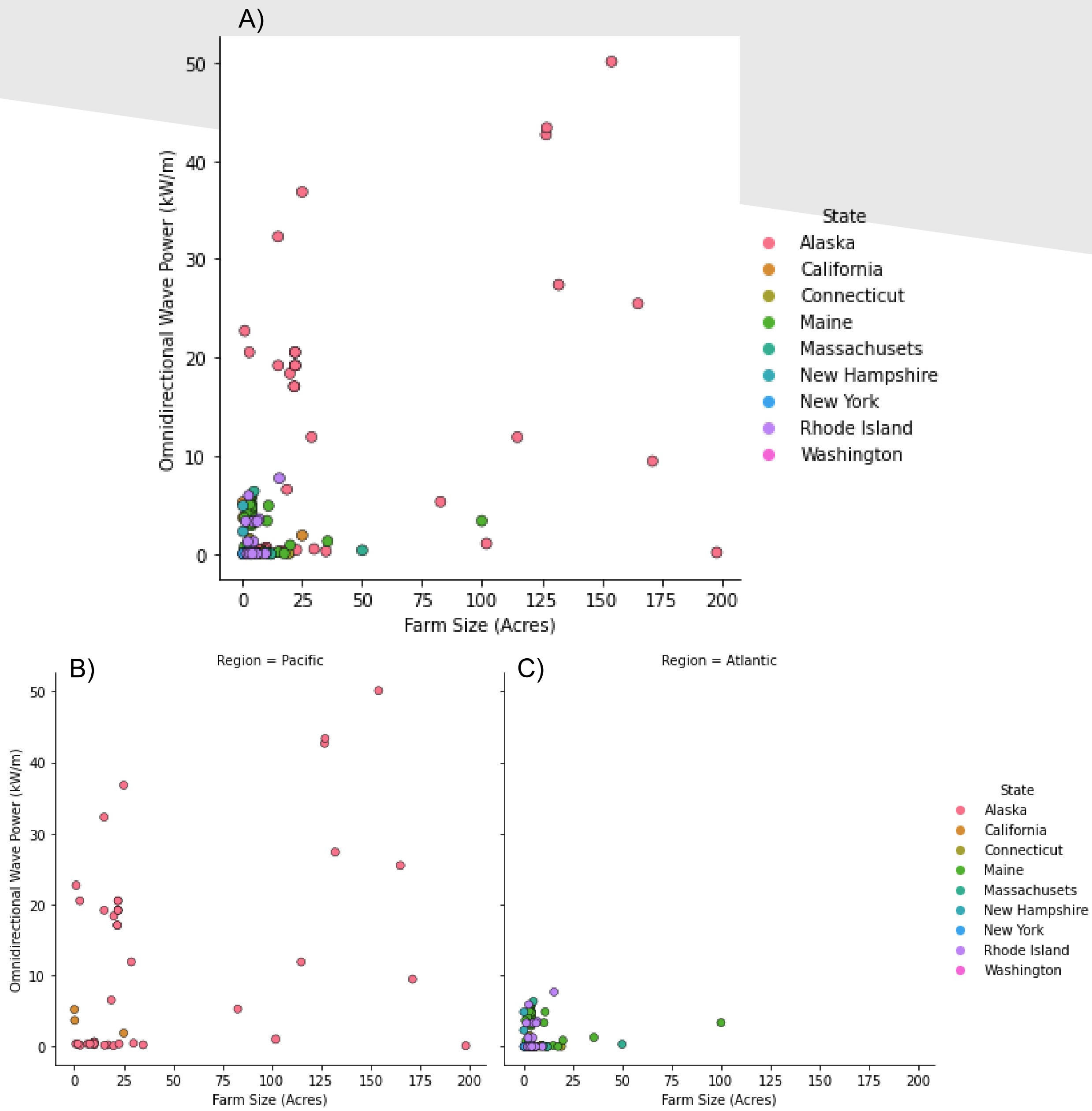


Figure 18. Relationship between farm size and average annual power availability. A) Combined, B) Pacific, C) Atlantic. Power data compiled from U.S. Wave Model (2011) for Alaska, Atlantic Wave Model (2021) and West Coast Wave Model (2020) accessed on Marine Energy Atlas for the closest centroid to each farm listed in **Appendix A**. Note that the power data are missing for 26 inshore farms.

Both the power and acreage of farms between the Pacific and Atlantic are significantly different (Figure 19, 20) based on a two-sample t-test assuming unequal variance.

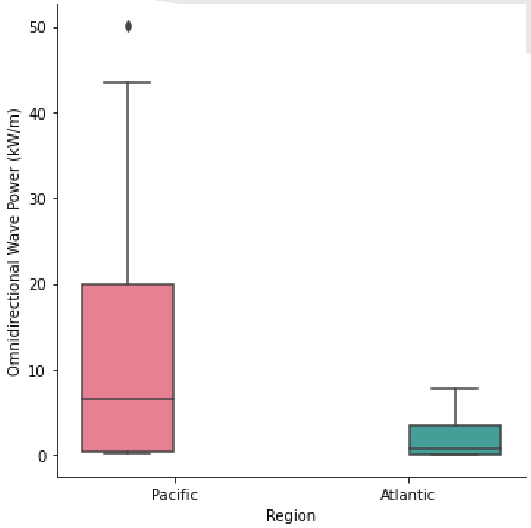


Figure 19. Average annual power distribution at farm sites across the United States (n = 129). Significantly different between Pacific and Atlantic ($p < 0.01$).

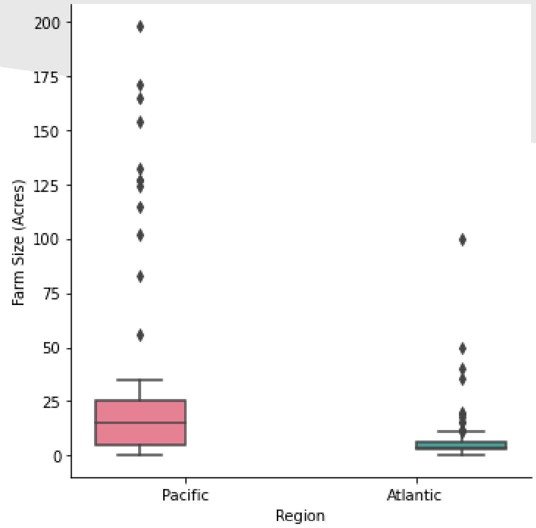


Figure 20. Farm size distribution across sites (n = 155). Significantly different between Pacific and Atlantic ($p < 0.01$).

To interpret what these results mean for the potential for marine energy development in conjunction with kelp aquaculture, it is important to understand how the power availability relates to the energy that could be harvested and used in particular settings. It is typically assumed that the power captured by a wave energy converter is proportional to the average OWP, such that a site with larger OWP will be able to generate more power than a site with a small OWP [81]. However, the true power available for harvest depends on numerous site-specific factors, including seasonality, ratio between maximum power and average power, water depth, directionality, and spectral characteristics of the wave climate [81]. Particulars of WEC design and efficiency, which could vary based on these additional characteristics, can also impact the total energy harvest.

A global classification of wave resources has been developed by Martinez and Iglesias (2020) [83]. Table 4 shows general classification of power (in terms of kW/m) that is relevant for harvest, as well as key other factors for utilization. Despite many farm sites falling in the Class I and Class II categories, these locations could still provide enough resource for the low power needs at kelp farms. Low power harvesting remains an interest of the Powering the Blue Economy Initiative, especially as it applies to particular U.S. markets under the Power at Sea theme.

Table 4. Wave resource classification, adapted from [83].

	Power Range (kW/m)	Description
Class I	<10	Little interest for wave energy harvest
Class II	10-20	Limited resource
Class III	20-40	Interest for wave energy exploitation
Class IV	40-80	Substantial resource, supplemented by westerly winds and cyclones
Class V	>80	Typically occurring in Southern Ocean, not practical for harvest due to distance.

3.5 Power Needs at Farms

From our outreach effort to kelp farmers in the United States, the overall power needs are quite low for most small farm operations. In addition to the power needed at farms for monitoring devices, which is often minimal, energy can be needed for the following aspects of operation:

- Fuel for boats, consumption depending on horsepower and location
- Solar/wind or generators (fuel) if there is a dwelling associated with the farm
- Automated system to raise/lower lines
- Floating cabins for temporary housing
- Lighting for safety, navigation, security, or dwellings

These power needs vary greatly from farm to farm based on size of operation, level of automation, staffing / on-site presence, distance from shore operations, and more.

3.6 Characteristics of Kelp Farms and Structural Integration with Marine Energy

Siting a wave energy device with a kelp farm, assuming sufficient resource available, is logistically simple. Kelp farms already require numerous buoys, cables, and markers that are anchored in relatively shallow water. A wave energy device could be modular, and connected to separate monitoring buoy or power bank, or integrated into an all-in-one monitoring and energy harvesting device, depending on how the wave device might interfere with the instrumentation. Alternatively, a wave-powered AUV could be used for monitoring needs, easily deployed from shore or dock to monitor nearshore farms. Boat access for deployment of relatively small devices is naturally available, as the farms are typically serviced by human-operated boats. There is no need for very large, high power devices (at least at present in the United States), as the energy needs at kelp farms are low and it is unlikely that the resource available nearshore would provide sufficient power to warrant something of that scale.

As both the kelp farming industry and the marine energy industry in the United States are in their early phases, there is opportunity for co-development of technologies that scale with farm needs. A key consideration for this development is adaptability and compatibility with existing systems in order to fit a variety of end user needs. Additionally, it is unlikely that kelp farmers would consider paying premium prices for marine energy powered monitoring devices, as this is currently not a major power pain point or area of significant financial investment. At least in the early phases, to encourage adoption, pilot projects for monitoring in conjunction with aquaculture will likely need to be subsidized to balance out costs.

As the kelp industry is likely to move towards larger scale, farther offshore kelp farms, these questions will need to be revisited to assess the different needs and design considerations for integration of larger monitoring programs with additional autonomy and power needs that marine energy could fill.

4.0 Conclusion

There is potential for marine energy and kelp aquaculture to co-develop in the United States in the monitoring space. However, at present, there are no key pressures forcing alternative energy solutions for monitoring at kelp farms. It is unlikely that kelp farmers would be willing to pay higher prices for marine energy powered monitoring devices, without a clear need or power pain point. Current operations utilize low power technology for fairly minimal monitoring programs, relying on available data from other sources and periodic sampling to ensure quality. There are major differences in the monitoring needs between these small-mid scale current commercial operations in the United States, research-oriented farms, and the more theoretical offshore mega farms with autonomous monitoring needs.

Kelp farms may not need to monitor much as part of operations, but could consider monitoring more if there was a value to monitoring for carbon dioxide removal and carbon credit sales. Several organizations are considering this possibility and working to close the gaps in knowledge around sequestration quantity and permanence [53], [84]. While the potential scale for this is still unknown, in part due to the value of temporary carbon sequestration provided by the kelp, we expect further discussions on this topic that could create additional value for monitoring at kelp farms. The growth of carbon markets broadly and the potential for ocean solutions to contribute to this space could increase the value of ocean observations in kelp aquaculture, though it only exists in a research capacity at present.

Moving forward, finer scale resolution is needed to assess wave power at particular farm sites, and to assess the seasonality of wave power and suitability for use during the kelp growing season. This study focused broadly on the potential across the United States, and reveals the regions for future focus on the West Coast and Alaska. A case study approach in partnership with key kelp farmers is recommended to begin exploring the potential for integration, and could be leveraged in scoping or testing future DOE prizes for ocean observing. This would also enable refinement of the boundaries for the ideal resource availability, balancing power potential with safe working conditions and ideal growing conditions.

As the kelp aquaculture industry in the United States continues to grow, it is expected that more farms will be permitted and farm size will increase as long as markets for products grow with the supply. The potential for co-location of farms with marine energy for monitoring may need to be revisited as new farms, designs, and technologies are developed in new locations.

5.0 Lessons Learned

A few key lessons were learned throughout the process of this project. They are documented here to aid future research, reduce the risk of repeating mistakes, and share best practices.

1. **Seasonality**
   Kelp is a winter crop. In the United States, kelp is planted around September/October and harvested in spring. Contacting farmers in their busy season (either when seeding and deploying lines or harvesting) is unlikely to yield a timely response, as many of these are small operations that require all hands on deck on the boats to put out or bring in the kelp. Interviews prior to planting are recommended for future partnership work to learn about the current season plans without interfering at a busy time.

2. **Confidentiality**
   Some of the farmers we contacted were reluctant to share proprietary information. In some cases, farmers have spent a lot of time and money developing their systems, and may not be interested in sharing that information with others. While the industry is newer and there are a lot of collaborative efforts and programs, it is still a competitive business market.

3. **Extractive Research**
   It is important to be respectful of the time that kelp farmers are volunteering to assist in research. This means doing as much pre-research prior to contacting farmers as possible and developing focused questions. While some partners may be really interested in collaborating and sharing, others may feel obligated or burdened. It is important to be able to offer something in exchange for the time of others, whether that is simply appropriate acknowledgement, protection of privacy, additional resources or connections, information about future benefits from collaborating, or financial compensation.

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Appendix A – Permitted (and pending approval) kelp farms in the United States (as of July 2021).

Alaska			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Afognak Native Corporation	30	0.500	Kizhuyak Bay
Alaska Deep Seas, LLC	22.04	19.180	Sheep Bay
Alaska Ground Swell, LLC	10	0.300	Onion Bay - Port Lions
Alaska Marine Solutions LLC	123.967	NA	Twelvemile Bay
Alaska Salty Greens	3	NA	Chikoot Inlet
Alaska Shellfish Farms LLC	6.89	0.410	Halibut Cove
Alaskan Sea Greens	10	0.650	Uganik Bay
Alaska's Best Shellfish	6.2	NA	East Squaw Bay
Aleutians East Borough	10	0.650	Zachary Bay
Andersen Island, LLC	22.04	19.180	Sheep Bay
Bare Island Farms	2.98	0.220	Dry Spruce Bay
Blue Acres Alaska	10	NA	Young Bay
Blue Evolution	34.9	0.280	Middle Bay
Blue Green Enterprises	21.7	17.060	Simpson Bay
Blue Starr Oyster Co	1.39	NA	Tokeen Bay
Canoe Lagoon Oysters LLC	5.52	NA	Canoe Lagoon/Fools Bay
Clam Gulch Seafoods LLC	9.85	0.410	Jakolof Bay
Dead Humpy Creations	18.67	6.570	Woody Island
Efficient Coastal Resources	198	0.150	Larsen Bay
F/V McCrea	55.86	NA	Earnest Sound, Southwest Cove
Fisherman Fresh	28.9	11.920	Resurrection Bay
Go Big Farms	171.14	9.470	Monashka Bay
Golden Harvest Alaska	19.9	18.370	Kagalaska Strait
Hartney Bay Kelp Company	15.04	19.180	Sheep Bay
Jakolof Bay Oyster Company	7.85	0.410	Jakolof Bay
Kaawu Shelfish Company, LLC	4.94	NA	Burnt Point
Kaguk Cove, LLC	132	27.380	Kaguk Cove
Kelptastic	1	22.710	Promisla Bay
Kodiak Island Sustainable Seaweed	16.95	0.280	Popof Island
Kodiak Kelp Company	82.65	5.300	Kalsin Bay
Kodiak Ocean Bounty	19.8	0.150	Larsen Bay
LL&SJ Farm	0.89	0.410	Peterson Bay
Madre De Dios, LLC	126.72	42.670	Madre de Dios - Craig
Marble Seafoods, LLC	15.4	NA	Clover Passage/Hump Island
Megan O'Neil	10.8	NA	Sumner Strait
Native Village of Eyak	114.78	11.910	Nelson Bay, PWS
Next Level Fisheries, LLC	22	20.530	Simpson Bay
Noble Ocean Farms, LLC	22.04	20.530	Simpson Bay
OceansAlaska	24.28	NA	George Inlet - Mile 8.5
Orr Island, LLC	154	50.100	Orr Island
Polar Seafoods	15.23	0.220	Uganik Bay
Premium Aquatics, LLC (Seagrove Kelp)	127	43.380	Doyle Bay
Pristine Products	4.41	NA	near Ragged Pt
Rainy Dawn Fisheries	2.76	NA	Pleasant Island

Rainy Dawn Fisheries x2	3.15	NA	Lena Cove
Real Marina, LLC	165	25.480	Port Real Marina
Rocky Bay Oysters LLC	0.86	NA	Mosman Inlet
Royal Ocean Kelp Co.	2.89	20.530	Windy Bay
Salt Garden Farm	2.8	NA	Madan Bay
Salty Lady Seafood Co	1	NA	North Bridget Cove
Sea Garden, LLC	22.04	19.180	Sheep Bay
Sitka Sound Aquatic Farm	14.99	32.270	No Thorofare Bay
Snug Harbor Seafoods, Inc.	22.63	0.410	Halibut Cove
Spinnaker Sea Farms	1.84	0.410	Jakolof Bay
Sven's Wild Seafood Co.	21.7	17.060	Simpson Bay
Trident Seafoods Corporation	101.9	0.500	Left Hand Bay Alaska Peninsula
Trident Seafoods Corporation	25	19.180	Cook Bay, Long Island
Washington			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Blue Dot Sea Farms	5	NA	Hood Head, WA
California			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
PharmerSea	25	1.882	Santa Barbara
Sunken Seaweed	0.25	5.235	San Diego Bay
Catalina Sea Ranch	0.1	3.685	Channel Islands
Maine			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Acadia Aqua Farms, LLC.	40.36	NA	Mount Desert Narrows
Albatross Fisheries, LLC.	3.83	1.033	St. George River
Baines, Robert	3.74	5.657	Penobscot Bay
Barrows, Abigail	2.32	NA	Penobscot Bay
Bayside Mussel Farm	6.03	0.008	Penobscot Bay
Brewer, Jodi M.	3.98	0.331	Sheepscot River
Brewer, Jodi M.	0.98	0.358	Sheepscot River
Brewer, Marsden	3.96	NA	Penobscot Bay
Brewer, Robert	3.99	NA	Penobscot Bay
Cotton, John	3.67	1.219	St. George River
Damariscove Seafood LLC.	11.99	0.002	Damariscotta River
Darling Marine Center (U of Maine)	1.78	0.002	Damariscotta River
Ehle, Timothy and Isaac Lash	3.85	3.533	Muscongus Bay
Francisco, Peter	5.27	NA	New Meadows River
George C. and Lucas G. Morrill	3.87	3.725	Penobscot Bay
George C. and Lucas G. Morrill	3.93	3.529	Penobscot Bay
Great Ledge Cove Seafood, LLC.	3.57	4.991	Casco Bay
Great Ledge Cove Seafood, LLC.	3.73	3.398	Casco Bay
Henninger, Thomas	2.06	3.434	Casco Bay
Hooper, Jason and Molly	3.79	5.840	Penobscot Bay
Hunt, Stewart	3.85	2.889	Casco Bay
Hurricane Island Foundation	3.17	5.824	Penobscot Bay
Isleboro Marine Enterprises	6	0.042	Penobscot Bay
K2 Science LLC.	0.99	0.751	Muscongus Bay
Keith Butterfield	2.72	3.773	Casco Bay

Maine Fresh Sea Farms	3.6	0.002	Damariscotta River
Maine Fresh Sea Farms, LLC.	3.62	0.002	Damariscotta River
Maine Island Aquaculture	15	0.180	Marsh Cove
Miller, Keith and Ben Stendel	3.9	4.280	Penobscot Bay
Miller, Keith and Ben Stendel	3.92	4.093	Penobscot Bay
Miller, Keith and Ryan	3.85	4.598	Penobscot Bay
Miss Madisyn	3.74	1.109	St. George River
Oceans Balance, Inc.	3.93	NA	Casco Bay
Perkins, Greg	3.97	0.019	Penobscot Bay
Shearwater Ventures	3.79	4.991	Casco Bay
Shearwater Ventures, LLC.	3.83	5.002	Casco Bay
Springtide Seaweed, LLC.	20.02	0.882	Frenchman Bay
Stewart Hunt	3.9	4.795	Casco Bay
Summit Point LLC	100	3.357	Casco Bay
Summit Point, LLC.	10.38	3.357	Casco Bay
Tightrope Seafarms, LLC.	17.59	0.043	Blue Hill Bay
Train, Stephen	3.98	3.357	Casco Bay
University of New England	3.91	3.134	Saco Bay
West, James	35.62	1.289	Frenchman Bay
Wild Ocean Aquaculture, LLC.	1.99	4.147	Casco Bay
Wild Ocean Aquaculture, LLC.	0.82	3.671	Casco Bay
Wild Ocean Aquaculture, LLC.	3.03	4.991	Casco Bay
Wild Ocean Aquaculture, LLC.	11	4.893	Casco Bay
Young, Evan	2.9	0.196	Blue Hill Bay
New Hampshire			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
UNH Integrated Multi-Trophic Aquaculture (Aquafort)	0.2	4.882	Piscataqua River
Isles of Shoals Mariculture	0.2	2.282	Isle of Shoals
Connecticut			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
BRASTEC	2.98	0.042	Fairfield
Charles Island Aquaculture	3.96	0.055	Milford
Cos Cob Kelp and Shell	5.02	0.008	Norwalk
Granfield Fisheries	2.89	0.034	Milford
Greenwave	8.96	0.190	Groton
J.P. Vellotti	8.95	0.217	Groton
J.P. Vellotti	8.95	0.208	Groton
J.P. Vellotti	6.2	0.044	Norwalk
J.P. Vellotti	6.35	0.040	Norwalk
J.P. Vellotti	6.2	0.040	Norwalk
King Lobster	11.03	0.057	Branford
Mechanic St. Marina, LLC	3.03	1.542	Stonington
New York Kelp	4.83	0.039	Greenwich
Norm Bloom Kelp Aquaculture	2.87	0.040	Norwalk
Sound Ocean Farm	8.3	0.064	Branford
Thimble Island Ocean Farm	19.3	0.044	Thimble Islands

Massachusetts			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Chatham Kelp	50	0.361	Chatham
Cottage City Oysters	2	0.227	Martha’s Vineyard
Duxbury Sugar Kelp	12	0.001	Duxbury
Kelpeher Farms	2.5	0.557	Harwich
Stanley Larsen	5	6.386	Martha’s Vineyard
Ward Aquafarms	10	0.128	Megansett Harbor
Rhode Island			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Blaney	2.63	5.927	Harbor of Refuge
Blank	9.56	0.030	Narraganset Bay
Cedar Island Oyster Co	15.54	7.724	Point Judith
Cedar Island Oyster Co	3.35	NA	Point Judith
Goemer	5.04	0.118	Narraganset Bay
Grant	4.67	1.246	Block Island
Griffin	4.09	NA	Narraganset Bay
Matunuck Oyster Farm Bar	6.94	3.547	Potter
Puckett	2.28	1.246	Block Island
Richard and Pinheiro	2	0.029	Narraganset Bay
Rome Point LLC	4.58	0.031	Narraganset Bay
Walrus and Carpenter Ninigret	4.63	3.301	Ninigret
Walrus and Carpenter Ninigret	1.4	3.315	Ninigret
Walrus and Carpenter OptonHimmel	6.35	3.301	Narraganset Bay
Walrus and Carpenter OptonHimmel	1.94	0.027	Narraganset Bay
Watson	6.02	0.029	Narraganset Bay
Wescott	3	0.030	Narraganset Bay
Whilden Unlimited	4.19	0.030	Narraganset Bay
New York			
Farm Name / Permit Holder	*Size (acres)*	*Wave Power (kW/m)*	*Location*
Stony Brook University - Great Gun Oyster Farm	0.33	0.008	Moriches Bay
Stony Brook University - East End Oysters	0.33	0.032	Long Island Sound
Stony Brook University - Town of Islip	0.33	0.045	Great South Bay

Data sources for Appendix A:

- Alaska – https://adfg.maps.arcgis.com/apps/webappviewer/index.html?id=f3ca95493c1042b39e42a3ecb5dcad6a
- Washington – no map viewer, Dan Tonnes from NOAA
- California – no map viewer, Diane from NOAA
- Maine - https://maine.maps.arcgis.com/apps/webappviewer/index.html?id=b846cf37b1d64c988f89eafa085c8b7a
- New Hampshire - https://www.northeastoceandata.org/data-explorer/
- Connecticut - https://cteco.uconn.edu/viewer/index.html?viewer=aquaculture , https://nysdec.maps.arcgis.com/apps/webappviewer/index.html?id=f8799cefbb4c4751a209710d14b9ad46
- Massachusetts – https://www.arcgis.com/apps/webappviewer/index.html?id=b6e90602c8804455917e654a018a1ba0
- Rhode Island - https://ridemgis.maps.arcgis.com/apps/webappviewer/index.html?id=8beb98d758f14265a84d69758d96742f
- New York - https://nysdec.maps.arcgis.com/apps/webappviewer/index.html?id=f8799cefbb4c4751a209710d14b9ad46 Note that commercial seaweed aquaculture was not made legal in New York until December 2021. Farms shown in **Appendix A** are all research farms.

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