

**Exploring a “Silver Bullet” Climate Solution: The Development of Kelp Aquaculture in
Massachusetts**

A thesis submitted by
Grant Perry

In partial fulfillment of the requirements for the degree of
Master of Science
In
Environmental Policy and Planning

Tufts University
May 2025

Advisor: Dr. Kathryn Davies
Reader: Dr. Rebecca Shakespeare

Abstract

In recent years, there has been interest in kelp aquaculture as a climate solution. Global demand for seaweed has increased and production has grown throughout the United States. The industry has remained nascent in Massachusetts with five farms in operation in 2023. This thesis explores kelp aquaculture and its benefits, challenges, and opportunities within New England and specifically Massachusetts. The results indicate there are a wide variety of often competing economic, ecological, social, and policy-based factors that can influence the growth of the industry and its ability to grow. While kelp may be able to sequester large amounts of carbon dioxide, improve water quality, and promote economic diversification, the industry currently lacks the shoreside production necessary to decrease the value chain responsibility of the producer and increase profitability. Recommendations are made to increase profitability, streamline the permitting process, mitigate user conflicts, and improve climate resilience through the kelp industry.

Acknowledgments

I would like to express my deep gratitude to my advisor Dr. Kathryn Davies whose support, and continued feedback were invaluable to this project and helped shape its outcome (and for being open to advise a thesis about kelp in an urban planning program). I'd also like to thank my reader, Dr. Rebecca Shakespeare, for her continued support on this project. Their combined guidance has helped me to complete this thesis and resulted in a better finished product. Thank you to the UEP community, my friends, and of course my family, without whom, this degree and thesis would not have been possible.

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Chapter 1 - Introduction

Overview of Kelp

Kelp aquaculture is often seen as a “silver bullet” for many vulnerable coastal communities in popular media and in developing scientific research (Evans 2021). Kelp farming is the fastest growing aquaculture sector in the United States (NOAA 2025). According to Robidoux and Good (2023), Alaska, Maine and Hawai’i are the largest producers of kelp in the US. There are over 70 farms in operation in New England waters, with the majority located along the coast of Maine (ibid). In Massachusetts, however, kelp farming is a small industry with only five permitted commercial farms (Robidoux & Good 2023).

The United Nations Global Compact (UNGC) argues that kelp can play a critical role in addressing multiple anthropogenic changes to Earth’s oceans including climate change. Kelp has the potential to sequester carbon and absorb nitrogen and phosphorus runoff (UNGC n.d.). The UN predicts that increasing kelp aquaculture globally to produce 500 million tons (dry) would increase global food supply by 10%, assimilate 10 million tons of nitrogen, and sequester 15 million tons of phosphorus and 135 million tons of carbon (UNGC n.d.).

Beyond climate mitigation, kelp has the potential to address climate resilience for coastal communities. Aquaculture, the farming or cultivation of aquatic organisms, may complement existing marine capture fishers’ seasons and provide economic diversification to a fisher’s portfolio, thus allowing fishers to be less dependent on one type of catch such

as lobster or cod (Love 2016). This is especially true for kelp and shellfish aquaculture in the northern hemisphere (ibid). Beyond economic climate adaptation, kelp aquaculture has the potential to attenuate waves, making it a potential method to decrease wave energy from storms (Zhu et al. 2021). Kelp aquaculture has the capacity to decrease wave energy regardless of changes to tides and sea level rise (Zhu 2019). Kelp aquaculture plots consisting of 125 longlines by up to 30% and 250 longlines by up to around 50% (Zhu 2019).

¶ Kelp aquaculture can also mitigate global land use pressures by reducing the need for terrestrial crops for products such as animal feed and biofuels (Spillias et al. 2023). Climate change and biodiversity loss caused by land-use change and agricultural production could be alleviated by the supplementation of kelp (Spillias et al .2023).

A note on language: This thesis will use the terms “kelp” “seaweed” “kelp aquaculture” and “kelp farming” and occasionally “kelp industry” interchangeably. Within academic and grey literature, as well as popular media, the terms kelp and seaweed are used interchangeably, but typically refers to sugar kelp within a US context. Additionally, “farming” and “aquaculture” are used interchangeably within academic literature and popular media. The term “kelp industry” refers to all kelp production and not only an individual practice, farm, or plot.

Massachusetts Context

Massachusetts is a major contributor to the nations’ fishing industry (NOAA 2024). As of 2022, New Bedford, Massachusetts has been the port with the highest value in the country for 22 consecutive years (NOAA 2024). In 2022, New Bedford landed \$443.2 million

worth of product out of a total of \$690 million in the commonwealth (NOAA 2024). In 2022, Massachusetts was the second highest grossing fishery in the United States second only to Alaska at two billion USD (ibid). Scallops account for the largest portion of Massachusetts landings at around 348,000,000 pounds followed next by Ocean quahog at 91,000,000 pounds (Massachusetts Division of Marine Fisheries 2021). Massachusetts also lands large quantities of lobster, oysters, and groundfish (ibid).

Kelp farming is not new to Massachusetts. As early as 1847, Irish immigrants in Scituate, Massachusetts were harvesting wild “Irish Kelp,” *Chondrus crispus*, in dories at low tide well into the 20th century even up until the 1990s (Toomey 2019). Today, there are roughly 5 kelp farms operating within the state landing roughly 9,500 wet pounds of kelp in 2023 (Robidoux & Good 2023). The largest farm, Chatham Kelp, is located off the coast of Cape Cod (Fishermen’s Alliance 2020). Another farm, Duxbury Sugar Kelp, opened in 2023, however it is unclear if they are still operating. It is unclear where the 5 currently operating farms are located based on available information. Based on farms that have either operated in the past or are currently in operation, they appear to be mostly clustered around the South Shore and Cape Cod. Additionally, Woods Hole Oceanographic Institution has referenced some farms near the Cape and Martha’s Vineyard (Woods Hole Oceanographic Institution 2019). Official landings are not reported by the state and are only available if the farmer voluntarily reports their production (Robidoux & Good 2023). After the kelp is produced and landed, it goes onto processing, which in the kelp value chain, is typically done by the consumer (Heidkamp et al. 2022). Kelp is processed into a wide assortment of products, either by the producer or a separate processor, and can be

sold for a variety of products including, but not limited to food for human consumption, fertilizer, livestock feed, biofuel, and cosmetics and plastics (Heidkamp et al. 2022; Fasahti et al. 2022; Couteau and Coiffard 2016; Ayyakkalai et al. 2024; Roque et al. 2021). In 2023, reported landings were processed for human consumption and fertilizer products (Robidoux & Good 2023).

Kelp farms in the United States typically use a farming method known as “3D farming” to maximize productivity on their plots. The seaweed is grown on longlines seeded with kelp (seeded string) that are suspended below the water and attached to two mooring balls on each end of the line (NOAA 2025). Typically, this “longline” system is repeated in parallel lines over the plot. Other types of kelp farms for nearshore production rely on rafts or netted farms where kelp is grown in tidal areas and easily accessible from the shore (Prasad Behera et al. 2022). It is important to note that this thesis is written largely from the perspective of a longline kelp farm due to its popularity in the United States.

Climate Change and Fisheries

Anthropogenic climate change has created an uncertain future for many marine based fisheries around the world. Changes to Earth’s oceans such as warming waters and ocean acidification pose significant threats to Massachusetts fishing communities dependent on the sea for their livelihoods (Howes et al. 2015). For example, Cape Cod’s namesake, the Atlantic Cod, has already been impacted by warming waters in the Gulf of Maine, with some shifts in species range resulting from rapidly warming ocean temperatures (Pershing et al. 2015)

Two of the most significant problems facing fisheries in the New England region are increasing water temperatures, and ocean acidification (Pershing et al. 2015; Siedlecki et al. 2021). In 2023, the average sea surface temperature for the Gulf of Maine was around 1.9F warmer than normal temperatures (GMRI 2024). Increased sea surface temperatures lead to poleward shifts in species ranges (Poloczanska et al. 2016). In a region like Cape Cod and the Gulf of Maine, the geography of the gulf prevents some northward migration leading to species migration to deeper waters as opposed to poleward migration (Poloczanska et al. 2016). Species such as Cod have already experienced changes in their distribution due to rising sea surface temperatures (US EPA 2024).

Ocean acidification is a critical issue for shellfish growers and fishers. Ocean acidification does impact groundfish but poses a significant threat to some calcifying organisms such as iconic shellfish species along the Cape (Ries et al. 2009). Some species, including oysters and sea scallops, are at an increased risk of ocean acidification compared to other species such as lobster (Rise et al. 2009).

Coastal Climate Resilience and Adaptive Capacity

Coastal climate resilience refers to the ability of coastal settlements and communities to withstand and quickly recover from climate change related risks and disasters (NOAA n.d.). Coastal resiliency and adaptation take many forms and vary between municipalities and geographies (Lehmann et al. 2021).

Coastal climate resilience and adaptations typically include some form of physical adaptation to a risk or vulnerability. NOAA adaptation strategies to coastal climate risks

generally focus on infrastructure changes (NOAA n.d.). In the United States, physical coastal resilience takes two broad forms, natural (green, nature based) infrastructure and built infrastructure (Sutton-Grier et al. 2015). Examples of natural infrastructure include salt marshes and other natural ecosystems such as dunes. Built infrastructure refers to adaptation measures such as sea walls and levees (Sutton-Grier et al. 2015). However, social dimensions of adaptation and resilience are central to how communities prepare for a changing climate (Cinner et al. 2018; Cinner and Barnes 2019). A community's ability to build resilience is influenced by its adaptive capacity (Cinner et al. 2018). Adaptive capacity to climate change can be determined by five domains, including assets, flexibility, organization, learning, and agency (Cinner et al. 2018). Barriers to coastal adaptation for small towns tend to include lack of local and state leadership, conflicting values and beliefs, lack of resources such as staff, money, and time, and lack of information (Hamin et al. 2014).

Existing Challenges with Kelp Aquaculture

While the kelp industry has grown in popularity over the past decade, there are still significant challenges facing the industry including levels of engagement in the industry between states, processors, and growers, the ability to scale up from a smaller industry to a larger industry, the facilitation of information transfer between farmers, researchers, and industry regulators, including federal and local governments (Kotowicz et al. 2024).

Out of the identified challenges, issues associated with industry scaling pose significant risk to the longevity of the nascent industry (Heidkamp et al. 2022). In

Massachusetts, some growers are facing difficulty with kelp production, including issues with the acquisition of seeded string and transporting product to processors (Kotowicz et al. 2024). After kelp is landed and in the hands of processors, there are more difficulties within the value chain of kelp including ways to utilize the product (Kotowicz et al. 2024).

Research Questions

This thesis explores the following research questions:

- What factors contribute to the long-term establishment of the kelp aquaculture industry?
- How can the kelp industry continue to develop in Massachusetts?
- How can the kelp industry contribute to coastal climate resilience in the Commonwealth?

To answer the above research questions, this thesis will utilize two main methods, a literature review and a GIS analysis. Chapter 2 will provide an overview of the methods and methodology used to answer the research questions. Chapter 3 will provide a literature review of relevant knowledge and research surrounding kelp aquaculture under three broad themes: economic, environmental, and social and governance. Lastly, Chapters 4, 5, and 6 will present the results of the literature review and GIS analysis, as well as a discussion and set of recommendations for the future of the industry in Massachusetts.

The findings of this research indicate varied suitability for kelp aquaculture across the state, and present conflicting challenges and priorities of Massachusetts ocean resources explored further in this thesis.

Chapter 2 - Methodology and Methods

Introduction

This thesis takes a social-ecological systems approach to the exploration of the kelp industry (Ostrom 2009). This approach considers social, economic, political, and ecological elements of the kelp industry to be interconnected, and thus essential features of each of these spheres, their relationships to one another and how they interact, will be explored in this thesis (Ostrom 2009). This approach provides a more holistic understanding of the system as a whole, and a clearer sense of possible interventions that may improve overall system performance without major disruption (Ostrom 2009).

The thesis will respond to the research questions outlined in Chapter 1 using a critical constructivist methodology focused on understanding the wide variety of considerations, factors, and priorities, that can contribute to the establishment and growth of a kelp industry in Massachusetts. While this thesis aims to determine a suitable and equitable approach to siting kelp aquaculture within Massachusetts, meaning that the outcome for the industry is accessible to fishing and coastal communities and adheres to the local marine and social context. The findings do not reveal a singular truth, but rather one that is biased by my own lived experience and research interests. This thesis utilizes a constructivist approach with the understanding that there is not a singular truth to how the kelp industry is perceived and where individual stakeholders may believe it is best located and utilized. This thesis takes a critical approach to research with the understanding that what does not happen in a decision-making process is as important as what is implemented (Forester 2007).

Literature Review

The literature review serves as a foundation to understand what data is necessary to include in the analysis. From the literature review, economic, social, and environmental data points will be determined and used as part of the geospatial analysis.

The literature is comprised of grey and scholarly articles sources from Google and Google Scholar using a range of search terms related to kelp aquaculture. Importantly, to ensure that literature was not missed due to different nomenclature, multiple searches were completed using a variety of words to describe kelp aquaculture including, but not limited to, 'kelp aquaculture', 'seaweed aquaculture', 'kelp farming', and 'seaweed farming'. Sources were included based on relevance to kelp aquaculture. An article was deemed irrelevant if the focus of the article was on kelp aquaculture as opposed to naturally occurring kelp forests, with some minor exceptions in the "environmental aspect of kelp aquaculture" section of the literature review. Additionally, articles were screened for relevance related to the topic of this thesis. For example, articles focused on the chemistry or biology of kelp were typically not included in the literature review. Articles related to food security were also generally excluded from the review, as kelp farming is typically not considered a source of food security in the United States. Most articles used in the review fall between 2015 and 2025, given the rapidly changing perspectives on kelp aquaculture in the last decade. However, some articles from earlier time periods (prior to 2015) were included.

Geospatial Analysis

While a suitability analysis may appear to be the ideal approach for mapping potential spots for kelp farming in Massachusetts, this thesis will use more of an asset-mapping approach, where each data set is weighed with the same consideration and unaltered from its original form. This way, the analysis does not determine what could be considered the ideal location based on a value judgement (even if those values are grounded in a substantial literature review). Rather, this method will enable broader, more constructivist approach, that explores all possible locations with few restrictions. The resulting map shows areas with higher user conflicts, regulatory barriers, and existing conditions, that could be used to better understand where kelp would thrive in state waters. This approach supports the reader to make their own value judgements about ideal locations for kelp production in Massachusetts, based on their own internal ranking systems and other considerations.

While the thesis does not include a detailed geospatial analysis, the results are intended to visualize the competing interests, priorities, and environmental conditions present within Massachusetts waters, and to represent the various, and often conflicting, spatial, political, economic, and social priorities of Massachusetts ocean resources. The results are highly dependent on the cartographic principles and symbology choices made to express environmental conditions and competing interests while maintaining a level of order and legibility for the viewer. However, the final map product attempts to avoid placing value judgements through visual representations of space by avoiding visualization choices that would present some sort of value of “good or bad” or a hierarchy of interests. This will better answer the research questions than a specific suitability analysis that would identify

only a few areas that present the least amount of overlap because it shows the full array of factors that would contribute to the success or challenges of the developing industry. Additionally, it helps to visualize existing ocean resources and interests before the introduction of kelp to the space.

The kelp asset map was created using data points that emerged as relevant from the literature review. The data was categorized into dimensions like those of the literature review to ensure that each section of the literature review was represented within the map. From there, an asset map was created to show the spatial dimensions of different factors that could affect the growth of the kelp industry within Massachusetts. The resulting map also contains four generalized results indicating overlap between different dimensions identified within the literature review. In addition, a second “winter season” map was created to demonstrate how seasonality decreases the overlap between uses, priorities, and potential conflict within Massachusetts waters.

The process outlined in this section is similar to that of Marine Spatial Planning, a process in which human activities within marine ecosystems are sited and managed to decrease user conflicts and implement ecosystem-based management (Collie et al. 2013). Since the 1980s, marine planning has grown in popularity and been adopted around the world to varying degrees of success (Ehler 2021; Collie et al. 2013). Similar to other marine spatial plans, this thesis and mapping exercise does not attempt to provide a singular vision for successful planning but instead presents the relevant conflicts and uses to provide future avenues of marine planning (Collie et al. 2013). The mapping methods used in this thesis are similar to those of the 2021 Massachusetts Ocean Management Plan in

which competing interests are mapped and overlayed to show priorities within marine spaces.

Chapter 3 - Literature Review

Introduction

This literature review provides a foundational understanding regarding the economic, ecological, social, and regulatory aspects of kelp aquaculture in Massachusetts. This information is needed to guide the geospatial analysis undertaken in Chapter 4.

Economics of Kelp Aquaculture

Introduction

The global seaweed market was valued at \$17 billion in 2021 (United Nations 2024). However, there have been mixed economic results for US based farms, and less certainty in kelp outputs once landed. In states like Maine and Alaska, kelp markets are more developed since the industry has been around for decades. This means that those states have more producers, as well as more options for processing and distributing kelp once it's landed at ports. In Maine, there is a high number of kelp landings as well as more processing capacity and distribution that allows production to grow (Robidoux & Good 2023) Meanwhile, Massachusetts based kelp markets are less developed meaning there are less processing and distribution options making it more challenging for growth on the production side of the industry. This review process uncovered few details regarding market options of Massachusetts growers. This section explores the economics of kelp aquaculture with a focus on the role of economic diversification for climate adaptation and resiliency.

Blue Economy

Kelp aquaculture is part of an emerging 'blue economy'. There is some disagreement regarding the definition of the blue economy, however, it has been broadly defined as the “sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems” (United Nations n.d., 1). Other organizations, such as the European Commission, see the blue economy as all economic activities related to the oceans, seas, and coasts (United Nations n.d., 1). The United Nations uses a definition geared more towards sustainability of the ocean economic sector: “An economy that comprises a range of economic sectors and related policies that together determine whether the use of ocean resources is sustainable” (United Nations n.d., 1). Recent iterations of the blue economy have also emphasized socially equity, sustainability, and economic viability (Cisneros-Montemayor et al. 2022). This thesis will broadly use the World Bank’s definition of the Blue Economy with the additional considerations of social equity and economic viability determined by Cisneros-Montemayor et al. (2022).

Massachusetts has long supported some form of blue economy, with its economic vitality linked to the sea at least since colonization. However, investments in kelp production could be seen as a new iteration of the blue economy with a focus on sustainability, rather than solely on the economics of ocean sectors.

Kelp takes on multiple roles within the blue economy. Since the 1970s, kelp has been an ocean-based industry in the United States (California Sea Grant n.d.). Commercial

and research-based kelp operations began in the 20th century, but in recent years it has been promoted as a sustainable industry (California Sea Grant n.d.).

In theory, kelp aquaculture is a prime example of the success of the blue economy. The industry has a low barrier to entry and can be pursued by a wide variety of people. Within the Global South, many of the farmers are women, especially in Tanzania (Sultana et al. 2023) where the industry has provided opportunities for economic development despite traditional gender barriers. In the United States, it can cost as little as \$20,000 to get into kelp farming, making it a more equitable startup industry due to this low cost of entry (GreenWave n.d.). For environmental stewardship and sustainability, kelp requires no inputs (meaning it does not require fertilizer or feed), it simply requires clean and cold ocean water to grow.

Much of the commercial success of the blue economy is dictated by policy decisions (Cisneros-Montemayor et al. 2022). In Massachusetts, the kelp industry is not heavily regulated and only requires a permit from the state department of Marine Fisheries to get started. With that in mind, it would appear that kelp production could be a valuable opportunity to expand the blue economy in Massachusetts. In Maine, there have been examples of kelp operations that are able to turn a profit such as Atlantic Sea Farms. But in Massachusetts, where modern kelp production has been underway only recently, there is still no well-known, commercially successful operation that is at all comparable to the industry in Maine.

Economic Diversification for Climate Resiliency

Economic diversification refers to shifting incomes, or even an entire economy, away from a single source and towards multiple, diverse markets (UNFCCC n.d.).

Economic diversification has long been a tool for fishers looking to increase their annual income or to become less reliant on a single stock. In the face of climate change, economic diversification has taken on a new role that could prove to be a successful adaptation strategy for fishers.

Climate change creates significant uncertainty for fishers around the world. In the Gulf of Maine, and Massachusetts waters specifically, ocean acidification and changes to surface water temperatures are expected to change species distribution and the productiveness of shellfish stocks (Waldbusser et al. 2011, Okon et al. 2023). To address this challenge, fishers operating in the area are increasingly looking to diversify the stock that they harvest or otherwise diversify their business opportunities. When fishers rely on a single species or stock, they are more vulnerable to changes both in the market and within the ecosystem. Aquaculture and shellfish growers already work to diversify their portfolio to account for seasonal shifts in products that can go to market.

For many shellfish farmers in Massachusetts, economic diversification is already factored into their operation. Many aquaculturalists grow multiple species such as scallops and oysters, and some use shellfish aquaculture as a secondary income. Of the roughly 250 growers on Cape Cod, 50% utilize shellfish aquaculture as secondary income (Augusto and Homles 2015). The half of shellfish growers on the Cape that have not diversified their portfolios are more vulnerable to decreased income as shellfish experience the effects of a changing climate.

In many instances, kelp aquaculture has been proposed as a climate friendly way to diversify incomes. Some aquaculturists have added kelp production to their farm portfolio to try and lessen reliance on a single product. In Massachusetts, many of the aquaculture farms grow shellfish, with around 400 shellfish operations permitted across the Commonwealth (Massachusetts Department of Agricultural Resources n.d.). Although there is a growing interest among shellfish growers in producing seaweed, specifically sugar kelp, as a secondary product, production continues to be limited, as growers face several challenges.

Kelp Production in Massachusetts: Challenges and Opportunities - Inputs

One of the most popular aspects of kelp production is that it requires virtually no inputs to start growing (Ballantyne 2025). If it is planted in clean and cold sea water, kelp can grow without fertilizer or other inputs required for terrestrial crops. The only necessary inputs for the farm are a permit, a small boat, two mooring balls, and a line to connect them. After the farm has been set up, growers need to acquire kelp seed. Other than the seed and the materials for the farm itself, there are few inputs needed to start a kelp farm, making barriers to entry relatively low, especially for individuals who already are engaged in the fishing industry and have some of the necessary equipment at their disposal.

Permit pricing varies by state. For Massachusetts, it costs around \$1,300 for a permit from the Department of Marine Fisheries and takes approximately 2-6 months to go through the permitting process. The estimated cost of a permit (\$1,300) includes the cost

of acquiring permits at the local level, a step not necessary for kelp aquaculture. So, it's possible the total cost of permitting may be lower for kelp farmers than other fishers.

It is important to note there is not one specific type of boat used for kelp farming; a variety of larger fishing boats, work skiffs, and even custom designed kelp harvesting boats are used (Ocean Rainforest 2021). While the size of the ship may dictate safe distances to go offshore to access a farm, some fishers or growers will feel comfortable further offshore in smaller boats than others, making it difficult to determine what an "appropriate" distance from shore would be for a kelp farmer.

Kelp Production in Massachusetts: Challenges and Opportunities - Outputs

A significant contribution to the success of the kelp industry in Massachusetts is the economic viability of the product once it's landed. Kelp can be sold right off the boat, but much of the discourse around kelp aquaculture has to do with the products it can go into, including biofuels, livestock feed, plastics, and other products (Nayar and Bott 2014). The goal of market development is to move away from kelp as a garnish at a high-end restaurant, and instead to use it in a variety of products (Heidkamp et al. 2022). Expanding the market for kelp into a wide range of products also allows for the expansion of the number of kelp farms. In other words, for the number of kelp farms to increase (supply) there must be a market demand for kelp-based products. Many of the products that have been developed tend to encourage the narrative of kelp as a climate solution; some aim to alleviate pressure on terrestrial systems, reduce GHG emissions, or provide a more

sustainable alternative to environmentally harmful products including plastics. The following subsections briefly review some of the more common uses for kelp.

Kelp as food: One of the most predictable outputs of landed kelp are kelp-based food products. Kelp can be sold fresh in bulk or dried depending on when it was landed. Once kelp is landed, it has a shelf life of around 7-9 days maximum with refrigeration (Wirenfeldt et al. 2022). However, if stored properly, dried kelp has a longer shelf life of up to a few years (Eddy 2019). One of the largest producers of kelp, Atlantic Sea Farms, processes landed kelp into other food products. Some products include veggie burgers, salad mix, and pre-made smoothie cubes (Atlantic Sea Farms n.d.). Other than processed kelp products, the company sells dry kelp in bulk and frozen fresh kelp. Processing kelp, as opposed to drying it or selling it fresh is mostly on the part of the processor (Heidkamp et al. 2022). Below are some prominent examples of kelp products after landed.

Kelp as fuel: Kelp can be used as an input for biofuels. Biofuels refer to fuel that is derived from organic matter. For kelp, there are multiple conversion pathways from seaweed to biofuel including sugar, volatile fatty acids, and methane to produce ethanol (Fasahti et al. 2022). Studies suggest that the most profitable pathway is sugar, which can be sold for an average maximum price of around \$12.6/metric ton. While this is the more profitable option for converting kelp into biofuel, it still does not compete with the market price of other aquaculture products such as oysters or scallops (Fasahti et al. 2022; Bricker 2022).

Kelp as livestock feed and fertilizer: A 2021 study found that feeding cattle seaweed-based feed had dramatic GHG emission reduction of around 80% (Roque et al. 2021). This finding led to a renewed interest in producing kelp for livestock feed, however there is still little known about the economic viability of kelp livestock feed for seaweed farmers. The market price of a 50lb bag of seaweed-based feed is around 100 USD; it is not clear what the profit margin would be for the farmer as there is a gap in the literature regarding exact profit margins for farmers. Kelp is also sold as fertilizer, typically used for house plants or small gardens. However, studies suggest that kelp can increase crop yield by up to 15% and can be beneficial for early seed germination (Pei et al. 2024; T and Jayasri 2023).

Kelp for cosmetics and plastics: Seaweed based cosmetics can be found in stores across the country and has continued to grow as a market (Couteau and Coiffard 2016). Many of the small-scale kelp farmers in the Global South produce kelp for inputs into cosmetics. This market is not as well defined in the United States but could prove to be a significant economic driver of the industry. In recent years, seaweed has been used as an input for biodegradable alternatives to some plastics (Wan Yahaya et al. 2023). Much of the focus around seaweed-based plastics have been for single use plastics and packaging such as food wrappers, take out containers, and retail bags (Ayyakkalai et al. 2024).

Limitations of kelp and markets

A significant difference between the kelp industry and other aquaculture or fisheries operations has to do with the division of labor within the value chain. Unlike most fisheries,

kelp farmers mostly process their own product due to a lack of landing facilities and shoreside processors (Stevant and Rebours 2021). Additionally, it's necessary for most producers to stabilize their own product before it can be sold (Stevant and Rebours 2021). For many, this requires drying or fermenting kelp before it can be sold to market (Stevant and Rebours 2021). This puts the burden of increasing the market value of kelp within the production and value chains on the producer (Stevant and Rebours 2021).

It appears there is no lack of effort to grow kelp in the United States. Market demand for kelp has grown in the US over the past several years, however the US continues to import more kelp than it produces (Kim et al. 2019; Heidkamp et al. 2022). While the barriers to entry for kelp production are considerably lower than other aquaculture schemes, the overall profitability of the venture is less than other aquaculture-based endeavors (Bricker 2022). There is, however, continued interest in increased profitability for kelp through labeling, shoreside production, and changes to the value chain (Heidkamp et al. 2022, Stevant and Rebours 2021).

Other market limitations include the scalability of farms. Since seaweed is not as profitable as traditional aquaculture products, the farms must operate at scale to be profitable (Kim et al. 2019). It is unclear what acreage of farm counts as industry or commercial scale, however some farms in Maine considered to be commercial scale brought in 1.3 million pounds of kelp in 2024 while some cities and towns in the state classify large farms as anything over 5-50 acres (Schreiber 2024; Protect Maines Fishing Heritage Foundation n.d.). However, Massachusetts waters are filled with user conflicts. Not only do farms have to compete for space with other farms and fishers, but they must

also contend with commercial ship traffic, recreational boaters, kayakers, swimmers, and individuals who utilize the Massachusetts shoreline for recreation. Additionally, there are environmental user conflicts including concerns over critically endangered North Atlantic right whale entanglement, and water resource conservation areas. All these factors combined can make it difficult for farmers to find the space necessary to scale and create an economically viable farm. In Maine, the industry has faced difficulty to scale up due to the states' developed coast and the competition for marine resources, specifically in relation to the lobster industry (Heidkamp et al. 2022). User conflicts will be discussed in greater detail in both the ecological considerations for kelp and social dimensions of kelp chapters. In addition to user conflicts, ecosystem-based limitations may hinder the economic vitality of the nascent industry. This topic will be discussed further in the following chapter.

Future opportunities

While markets for kelp are growing, however limited in scope due to shoreside processing, there is no shortage of ideas for how to use kelp and expand the scope of the product into different sectors. As the industry evolves, it is possible that new opportunities will arise, however for right now there are not a lot of viable markets for farmers to sell their product at a price that warrants growing kelp. The World Bank has identified emerging seaweed applications that could contribute to the longevity of the industry including animal feed, fertilizer, nutritional supplements, bioplastics, pharmaceuticals, and even construction materials (World Bank 2023). If these markets were to develop, it could assist in alleviating pressure from terrestrial systems. If the future of kelp is taking terrestrial

pressures and moving them to the sea, there may be more opportunities than currently available to farmers.

Conclusion

While kelp farming may be an excellent example of an emerging, climate-friendly blue economy, the Massachusetts industry appears to be deficient in market links and opportunities for farmers once they land their harvest. There are plenty of applications for kelp in the market, but the processing burden of the grower may hinder production output. Further research is needed to better understand where Massachusetts grown kelp specifically goes after landing.

Ecology of Kelp

Introduction

While there are many socioeconomic factors that determine the productivity of the kelp industry in Massachusetts, it is important to understand the environmental and ecological factors that contribute to kelp's success or failure in the Commonwealth. Given that sugar kelp (*Saccharina latissimi*) is the main seaweed product produced throughout New England (Robidoux & Good 2023), this section will only focus on the environmental conditions and preferences necessary to produce sugar kelp. This section will consider current and future environmental conditions as well as other key considerations associated with sugar kelp survival in Massachusetts waters.

Preferred Environmental Conditions for Sugar Kelp

Sugar kelp requires cold, clean, and nutrient rich waters to grow efficiently (Handa et al. 2013). Kelp is most productive in cold waters ranging between 10-15c (50-59F) (Redmond et al. 2014). Temperatures at or exceeding 24c (75.2F) can lead to significant loss of biomass with a kelp mortality rate greater than 90% (Nepper-Davidsen et al. 2019). Kelp's preference for cool waters has led to productive kelp growth in northern New England waters and much of coastal Alaska (Robidoux & Good 2023). In cooler waters, sugar kelp has the potential to grow longer, as much as 20ft in Long Island Sound during winter months (Long Island Sound Study 2021). In warmer waters, kelp does not grow as productively (Redmond et al. 2014; Nepper-Davidsen et al. 2019). If temperatures surpass the preferred temperature range, it can present increasing challenges for kelp growth, making kelp a crop that cannot be grown year-round in many areas.

In kelp forests, sugar kelp will grow from the seabed towards the surface to collect more nutrients as well as absorb more sunlight than at the bottom where light attenuation is more significant. In an aquaculture context, where kelp is grown from the surface down, light attenuation is not as significant of a problem as the kelp is near the surface of the water. In a natural kelp forest, sugar kelp grows best in areas with a rocky seabed with sufficient sunlight and enough movement within the water to provide nutrient circulation (White and Marshall 2007; Kregting et al. 2023). Water motion such as tides and currents are important factors for increasing sugar kelp yields and facilitating growth (Kregting et al. 2023). Since photosynthesis facilitates the growth of sugar kelp, naturally occurring kelp forests rarely occur past around 130ft in depth due to light attenuation

(NOAA 2024). Since kelp farms are grown from the surface down and not reliant on growth from the seabed, shallower waters may not necessarily lead to improved growth results. However, light attenuation dynamics and farmed kelp growth are outside the scope of this thesis and appear to not yield search results from Google Scholar.

Biofouling, or fouling, refers to the “settlement, metamorphosis, and growth of plants and animals” (Nys and Ison 2008, 527). For kelp, biofoul can include invertebrates and other marine flora (Rolin et al. 2017). Biofouling can lead to significant problems for kelp farmers, as fouled kelp blades decrease the overall amount of product that goes to market and decreases profitability overall (Alaska National Science Foundation EPSCoR 2024). Blades with fouling are not appealing for consumers, but biofouling also limits the total nutrient uptake of kelp necessary for productive growth (Visch et al. 2020).

Fouling is most common in warmer waters and is not as common during the majority of the kelp season (Visch et al. 2020). Aquaculture sites with greater water motion, such as currents and tides, experience less biofouling (Visch et al. 2020). Even during cold winter months, kelp are still susceptible to biofouling, but not at the same rate as in warmer seasons (Visch et al. 2020). Given this biofouling pattern, fouling follows a similar seasonality as kelp production and fouling risk increases towards the end of the growing season (Visch et al. 2020).

Current Massachusetts Conditions

Massachusetts surface water temperatures vary geographically with a high of around 65F near Boston to a high of around 75F near Nantucket. Low temperatures range

from around 39F near Boston to 37F near Nantucket (NOAA 2025). Temperatures fluctuate around Cape Cod with an average maximum temperature between 65F to 75F (NOAA 2025). pH levels within the Gulf of Maine fluctuate with the seasons. In the fall, pH levels are lower while they peak in the spring (Massachusetts Ocean Acidification Working Group 2021). While pH does not pose a risk to kelp like the highly lucrative shellfish grown in Massachusetts waters, it still plays a role in understanding what can and cannot be grown at certain seasons within Massachusetts waters. Additionally, kelp aquaculture has been discussed as a potential way of mitigating the impacts of decreased pH on shellfish by integrating kelp production in shellfish plots (Young et al. 2019).

Biofouling poses a significant risk to kelp, as discussed in the previous section. Fouling is worse in the warmer months with less biofouling in cooler parts of the year (Handa et al. 2013). Many aquaculturalists and research institutes, including MIT Sea Grant, are working on methods to slow biofouling or prevent it within shellfish populations. However, the same work has yet to be applied to the kelp industry.

Predicted conditions with climate change

The Gulf of Maine is one of the fastest warming regions in the world (Gulf of Maine Research Institute 2024). In recent years, there has been an increase in the strength of the Gulf Stream that brings warmer waters north. Additionally, the geography of the gulf makes it difficult for cool water to enter the Gulf given its almost bathtub like shape, with a deep entrance for water to flow between the Georges Bank and Browns Bank (Gulf of Maine

Research Institute 2024). The Gulf has warmed by around .5 F in the last decade and is projected to increase by another 1.1 C to 2.4 C (Gulf of Maine Research Institute 2024).

Ocean acidification is potentially a significant threat to fishers and aquaculturalists in the region. Ocean acidification refers to the decrease of ocean pH levels due to the absorption of carbon dioxide (NOAA 2024). Earth's oceans absorb roughly 30% of all anthropogenic carbon dioxide emissions (Gruber et al. 2017). The Gulf of Maine is more likely to see increased levels of ocean acidification than other bodies of water (Kiest 2013). This is due to the cold temperatures and the inflow of fresh water into the gulf, allowing it to absorb more carbon dioxide (Siedlecki 2021). In the Gulf, pH levels naturally fluctuate seasonally with lower pH values in the spring and higher pH values in the fall (Massachusetts Ocean Acidification Working Group 2021). Currently, the pH level of Earth's oceans averages out to around 8.1 with predictions that the Gulf will decrease by 0.3 to 0.5 by 2100 (Massachusetts Ocean Acidification Working Group 2021; Boulais et al. 2017). The decreased ocean pH leaves certain types of calcifying organisms, such as oysters and scallops, at higher risks of disease and damaged shells, potentially hindering the organism's ability to grow or reproduce, thus having a negative impact when the product goes to market (Waldbusser et al. 2011; Okon et al 2023). The changes in shellfish productivity could lead to a need for more economic diversification that may be satisfied by kelp, or lead to integrated kelp and shellfish plots to minimize pH changes (Durate et al. 2017).

In addition to increased sea surface temperatures and ocean acidification, sea level rise and increased precipitation and storm severity are expected in Massachusetts (EPA

2016). While these events may not directly impact the ability of sugar kelp to grow in the state, increased runoff from storms and inundation events could lead to worsening water quality and increase the frequency of harmful algal blooms throughout the state, both in marine and inland waters (EPA 2025; Mass dept of health n.d.). Depending on the type of pollution, kelp grown in these areas may not be safe for human consumption (Shaughnessy et al. 2023). This topic will be further discussed in the “Climate Adaptation Benefits” section of this chapter.

Climate Mitigation Benefits

Kelp aquaculture plays a role in both physical resiliency through wave attenuation, and increased social climate resilience through economic diversification, making fishers less reliant on a single asset and providing flexibility to fishers impacted by climate change. Naturally occurring kelp forests sequester large amounts of carbon – estimates suggest roughly five megatons of carbon annually (Eger et al. 2023). To date, there has not been much research done to determine the total amount of carbon sequestered through kelp aquaculture, and the industry has not been included in global carbon accounting of kelp sequestering contributions (Eger et al. 2023).

There is evidence that kelp aquaculture could contribute to climate mitigation, through rapid uptake of carbon dioxide and its ability to increase localized pH levels (Bednarsek et al. 2024; Eger et al. 2023). However, under current systems, it is likely that any carbon sequestration would be outweighed by the total emissions associated with production (Pessarrodona et al. 2024). While kelp itself is not responsible for emitting

carbon dioxide, the supply chain around kelp is heavily dependent on fossil fuels for production and transportation (Pessarrodona et al. 2024). Additionally, much of the carbon sequestered by kelp is stored in short-term reservoirs and much of the product does not make it into long-term reservoirs (Pessarrodona et al. 2024). Short-term vs long-term reservoirs refer to the amount of time the sequestered carbon is stored before being released back into the carbon cycle (Boyce et al. 2022). Kelp sequesters carbon through photosynthesis, which is considered a short-term reservoir as compared to sequestration through sedimentary sequestration (Boyce et al. 2022) or carbon sequestration through wetlands that can store carbon for centuries (Schuster et al. 2024). Changes in the final product of kelp and the supply chain of kelp production could improve the net sequestration benefits of kelp, however further research is needed to assess its effectiveness (Pessarrodona et al. 2024).

While there is still uncertainty about the sequestration potential for farmed kelp, some companies and startups have argued that farming large quantities of kelp and dumping it into the deep sea could bring carbon dioxide levels back to pre-industrial levels (Temple 2021). The science behind this notion is still not clear, and it is possible that dumped kelp would not stay in the deep sea (Temple 2021). Some scientists argue that dumping kelp in the deep sea is unethical, not economical sound, and could have implications for ocean ecosystems (Chopin et al. 2024).

Climate Adaptation Benefits

This section focuses specifically on climate adaptation benefits related to the environment and physical climate adaptation as opposed to social and economic climate adaptation discussed in the Economic of Kelp section. To better understand the potential benefits of kelp aquaculture, it is helpful to first understand why naturally occurring kelp forests are an important ecosystem and the services they provide. Kelp forests provide critical habitat, wave attenuation, and are a cornerstone of some coastal marine ecosystems (NOAA 2024). However, there are two significant differences between a naturally occurring kelp forest and a kelp farm; 1) kelp farms are temporary in nature and typically only occur in the water during the winter season, and 2) kelp farms are typically vertical farms suspended from lines attached to buoys, not planted into the sea floor.

Kelp forests are associated with a wide variety of ecosystem services that can be considered beneficial for humans under a changing climate, including that they support an abundance of biodiversity. Kelp forests provide habitat for fish, seabirds, microorganisms, crustaceans, and of course charismatic megafauna such as sea otters and sea lions (NOAA 2024). It has been suggested that dense seaweed farms could also provide coastal habitat for species and increase overall biodiversity (Durante et al. 2017), although more studies are needed to clarify this claim. In tropical environments, studies suggest that kelp farms have higher amounts of biodiversity than controlled plots and could provide a method to enhance fisheries (Radulovich et al. 2015).

In addition to biodiversity benefits, kelp farming provides some potential for wave attenuation, if the farm is installed perpendicular to the direction of the waves (Zhu et al. 2021; Zhu et al. 2022). For example, if the prevailing wave direction results in waves typically flowing east to west, farms installed with mooring balls ranging north to south are more effective for wave attenuation. However, it is not clear if this method would work as well under differing conditions such as confused seas that are typical during storms. Naturally occurring kelp forests have been found to reduce wave heights by around 60% in parts of Norway (Durate et al. 2017). It is important to note that like naturally occurring kelp forests, kelp farms are susceptible to damage during storms (Durate et al. 2017).

Evidence suggests that kelp aquaculture may increase localized pH levels around the farm with some species of kelp providing an increase of up to 0.10pH in the plot (Xiao et al. 2017). It is possible that the localized changes to pH levels could provide benefits for aquaculturalists growing shellfish susceptible to ocean acidification by mixing dense kelp vegetation into their farms (Durate et al. 2017).

In addition to improving pH levels, kelp aquaculture has the potential to improve localized water quality and mitigate eutrophication (Jiang et al. 2020). Eutrophication refers to excessive plant and algal growth that takes place because of an increase in either sunlight, carbon dioxide, or nutrients (Chislock et al. 2013). In other words, eutrophication occurs when one of the limiting factors of photosynthesis is increased (Chislock et al. 2013). In many instances, eutrophication occurs due to increased amounts of nitrogen or phosphorus, two elements typically found in fertilizers and runoff that enter waterways (Jiang et al. 2020). Eutrophication is a common problem in Massachusetts, especially

around Cape Cod, an area that experiences excess nitrogen and phosphorus runoff (Cape Cod Waters 2024).

Kelp aquaculture has been found to mitigate eutrophication through kelp absorbing nutrients in the water such as nitrogen and phosphorus (Xu et al. 2023). At larger scales, kelp has the potential to remediate waterways (Xu et al. 2023). A study found that large scale kelp-aquaculture in a small bay off the coast of China was able to absorb 1309 tons of carbon, 104 tons of nitrogen and 12 tons of phosphorus (Xu et al. 2023). However, it is important to note that the bay used in this study is almost completely full of kelp aquaculture, a scale that is not found in the United States.

While kelp can mitigate eutrophication and improve water quality, it can provide some concern for human health if consumed. Since kelp has an efficient nutrient uptake, it has the potential to absorb high concentrations of heavy metals including arsenic, lead, and mercury in wild and farmed kelp in the New England region (Shaughnessy et al. 2023). However, if kelp is not grown for human use, it does have the ability to grow in polluted areas, improve water quality, increase localized pH levels, and increase oxygen levels in hypoxic zones (Bednarsek et al. 2024).

Other Environmental Considerations and Potential Harms

Beyond climactic and water conditions, there are a range of other environmental considerations important in siting kelp farming (Grebe et al. 2019). Overall, there is the potential for changes to local fisheries and fishing communities due to increased kelp production (Grebe et al 2019).

While kelp aquaculture can have positive impacts on the environment, it is important to note that it can also be detrimental to the ecosystem and its biodiversity. Kelp aquaculture could have negative impacts on local seagrasses. Seagrasses provide critical habitat and food for local biodiversity and support the overall coastal marine ecosystem. Eelgrass, a type of seagrass critical for local marine habitats and estuaries, has been on the decline for decades due to disease, habitat destruction, pollution, light availability, eutrophication, and climate change in Massachusetts (Massachusetts Division of Marine Fisheries 2016). Considerable resources have been allocated towards the protection and conservation of eelgrass. Kelp aquaculture poses a risk to the health and abundance of eelgrass, with studies suggesting that kelp farming over existing seagrass beds can decrease seagrass production by around 15% due to diminished sunlight and competition for nutrients (Durate Moreno et al. 2021). Shading also poses risks to other benthic species that require sunlight to thrive (Campbell et al. 2019). Alterations to the seafloor from moorings and gear are another risk posed by kelp farming (Grebe et al. 2019).

Another significant biodiversity consideration in Massachusetts waters is whale entanglement. Whales, specifically critically endangered North Atlantic right whales, are frequently identified entangled in fishing gear in Massachusetts waters. The issue has garnered much public attention, including from organizations such as the New England Aquarium, New York Times, and other news organizations. In 2020, an award-winning documentary, *Entangled*, garnered further public interest in the problem. Concerns about whale entanglement from kelp aquaculture have led to research and investment in alternatives to fiber ropes for kelp production (Kross et al. 2021), but there are no verified

cases of actual whale entanglements with kelp lines. However, whales have become entangled in naturally occurring kelp in Alaskan waters (Bolling et al. 2023).

A final concern to point out regarding kelp farming, is that when kelp reaches full maturity on a kelp farm, it has the potential to release gametes into the local waters which could compete with local seaweed populations, causing a decline in local populations or decreased disease resistance as overall genetic diversity of the population decreases (Grebe et al. 2019).

Social and Policy Dimensions of Kelp

Social Aspects of Kelp Farmers

One of the selling points of kelp in the late 2010's was that it is almost universally accessible since it requires few inputs and can cost as little as \$20,000 to begin farming (GreenWave n.d.). Seaweeds and macroalgae have been harvested by indigenous populations long before colonization of the area. In much of the world, kelp is farmed and harvested by smallholder aquaculturalist in the Global South and is particularly viable for women who predominantly lead seaweed aquaculture in Africa (Msuya et al. 2022).

Kelp farming is undertaken by both men and women living in coastal communities around the world (Delaney and Frangoudes 2016). Depending on location and harvesting technique, farmers have varying degrees of benefits, including economic and social safety nets. For example, in Spain, if a kelp farmer harvests kelp from a boat, they are recognized as a fisher and are entitled to the same benefits as other fishers (Delaney and Frangoudes 2016). However, if a kelp farmer in Spain harvests their kelp by hand, they do not have the

same protections as other fishers, and do not get the same benefits as their boating peers (Delaney and Frangoudes 2016).

The social status of kelp farmers in the United States is somewhat unclear, largely due to the emergent nature of the industry. This research did not uncover any broad demographic studies on kelp farmers and a lack of robust data on current fisher demographics other than an infrequent survey conducted by NOAA regarding age, income, education, health insurance, race, and primary species fished throughout the East Coast (Culter et al. 2022). The study suggests there is a wide age range in fishers from 18 to 55 or older as well as varied income with around 50% of fishers surveyed making \$90,000 or less annually (ibid). Most fishers surveyed have a high school degree, GED, or less and 89% of respondents were white (ibid). There was no discussion on gender identity of fishers.

In the United States kelp industry, women and indigenous groups are involved in the industry. However, like the fishing industry more broadly, it is unclear at what rates women, indigenous peoples, and other minorities are active in the industry. One the largest kelp producers in the country, Atlantic Sea Farms, is a women founded and led company that lands some of the largest quantities of kelp in the United States (Atlantic Sea Farms n.d.). Other similar companies include Cold Current Kelp (Kittery, Maine) and Shinnecock Kelp Farmers (Long Island, New York) (Cold Current Kelp n.d.; Shinnecock Kelp Farmers n.d.). Shinnecock Kelp Farmers is also a multi-generational group of indigenous women who continue their peoples 10,000-year traditional sea-based livelihoods (Shinnecock Kelp Farmers n.d.). The organization uses kelp farming to improve local water quality in their region (Orlinsky 2025). In Massachusetts, there is no publicly available data to identify who

is growing kelp in the Commonwealth, and therefore it is unknown how many, if any, kelp farmers in Massachusetts are minorities.

Some efforts have been made to create worker cooperatives for prisoners based on kelp production and kelp forest restoration in California (Diago 2025). However, these have not emerged as a stable endeavor, and none currently exist.

Key Players and Plans

The kelp industry is made up of an assortment of actors and stakeholders within the private and public sector. The most significant stakeholder for this study is the kelp farmer, the individual responsible for cultivating the crop. Additional relevant stakeholders include processors, federal, state, and local regulators, commercial fishers and shellfish growers, local advocacy groups, such as fisher organizations, environmental organizations, and other local groups, and harbor masters and other individuals responsible for port infrastructure necessary to grow and land kelp (Grebe et al. 2019). More peripheral actors could include recreational boaters, conservationists, residents, and coastal property owners (Grebe et al. 2019).

In Massachusetts, the Executive Office of Energy and Environmental Affairs is responsible for the development of the Massachusetts Ocean Plan, a framework that could impact the development pattern of large-scale aquaculture production in the state (EEA 2021). Unlike other aquaculture operations, kelp farming does not require a permit from the local municipality in Massachusetts. Instead, the grower acquires a permit from the Massachusetts Division of Marine Resources, making the state a more consequential

player than the municipality. In addition to the Division of Marine Resources, the US Army Corps of Engineers must approve the plot as well (NOAA 2021).

Massachusetts does not require a public meeting or notice for new kelp farms (NOAA 2021). The lack of a public engagement process can make it difficult for community members to voice their support, or opposition, to the project in the same way they may be able to do with shellfish aquaculture in the state. In other states such as Maine, where kelp goes through the same permitting process as all other aquaculture sites, nonregulatory actors can make official public comments on aquaculture projects, voicing support or opposition and potentially impacting the permitting process. While there has not been public pushback to kelp farming in the state, it is possible that the lack of public engagement process could lead to use conflicts in the future, as the power dynamics largely rest outside the jurisdiction of local communities.

While the state leverages the formal power within kelp aquaculture siting, it is important to acknowledge the role of outside actors on the industry. Kelp has soared in popularity in recent years, mostly due to its promise of a climate solution (Robey 2022; Yong et al. 2022; Nature Conservancy 2022; Vernick 2024). A simple Google search for “kelp as a climate solution” produces a wide variety of sources indicating that kelp can play an important role in mitigating climate change ranging from the World Resource Institute, WWF, ABC, and Monterey Bay Aquarium. A wide variety of actors unassociated with the actual production of kelp have advocated on behalf of the crop. In Massachusetts, organizations such as Woods Hole Oceanographic Institute has administrated multiple pilot projects to increase seaweed cultivation (Woods Hole Oceanographic Institution n.d.)

More broadly, organizations such as GreenWave have created wide reaching initiatives to bring in new kelp farmers. Beyond research and nonprofits, venture capital has invested in the industry and provided funding for a variety of projects including Running Tide, a well-known kelp starts up that promised to sequester large amounts of carbon and had to close its doors in 2024 (Simson and Rabinowtiz 2024). Outside actors such as venture capitalists and international NGOs are regularly left out of stakeholder mapping of kelp farming, but they have played a key role in the development of the industry in the US, as well as in the recent increase in public interest in the industry.

Use Conflicts

It is common for conflict to arise from resource management and allocation (Brown et al. 2017). Kelp aquaculture is no exception. In Maine, kelp has already become part of a growing discourse around community opposition to large scale aquaculture projects. Groups such as Protect Maine's Fishing Heritage Foundation have worked to ban industrial aquaculture in Maine through state and local regulation (Protect Maine's Fishing Heritage n.d.). The organizations' goal is to limit, or eliminate, the permitting of aquaculture operations over five acres, which would include kelp aquaculture under current proposals. While kelp aquaculture can still experience user conflicts that are difficult to minimize along the shore, within some aquaculture communities there is some user agreement on seaweed farming at smaller scales and focused on local markets (Fong et al. 2024).

Use conflicts generally refer to two types of conflict; social values conflicts, and interpersonal conflicts (Brown et al. 2017). Social values conflicts are those that occur due

to differing values or norms between parties, while interpersonal conflicts refer to conflicts caused by the physical presence or behavior of different parties (Brown et al. 2017). Within kelp aquaculture, it is possible that both types of conflict could arise. For example, social values conflicts could arise between individuals who may believe kelp farming is not worth the geographic space used, while someone else may think it is a worthy endeavor. An example of interpersonal conflict within kelp aquaculture could be as simple as someone developing a kelp farm in a spot a member of the community likes to use for recreational fishing.

The increase in demand for marine resources, coupled with the effects of climate change, have led to more frequent conflicts over marine resources (Saunders et al. 2024). Marine use conflicts can be caused by many factors including “contending values, identities, ways of knowing, access and control, ownership, sovereignty, rights, terms of use, human-nature relationships, and alienation of coastal and indigenous communities” (Saunders et al. 2024 3).

Aquaculture production has long been affiliated with use conflicts. In California, even individuals working in the aquaculture sector have differing views on the role, scale, and production of aquaculture in the states future (Fong et al. 2024). In Rhode Island, user conflicts between industry and the community are typically caused by the type of gear used and the scale of production (Costal Resource Management Council 2019).

Aquaculture siting within fishing grounds can create conflicts amongst fishers and shellfish growers, while any pollution from the operation may cause conflict with local communities, the tourism industry, and environmental actors (Stiens 1998)

Use conflicts can be mitigated through partnerships and cooperation, and through restructuring power relations (Saunders et al. 2024). Examples of standard methods to mitigate use conflicts between aquaculture and other priorities can be found throughout laws in New England. Rhode Island General Law states that “it is the public policy of [Rhode Island] to preserve the waters of [Rhode Island] as free and common fishery. The health, welfare, environment, and general well-being of the people of [Rhode Island] require that the state restrict the uses of its waters and the land thereunder for aquaculture, and in the exercise of the police power, the waters of the state and land thereunder...” (RI Gen L 20-10-1). In Massachusetts, some use conflicts can be mitigated by state law requiring public notice and hearing of a potential shellfish permit from local municipalities prior to issuance of the permit (General Laws: Part I, Title XIX, Chapter 130, Section 57).

Other methods to mitigate use conflicts within new England have used more transformative or cooperative methods including Vineyard Wind and its fisheries compensation program designed to provide financial compensation for fishers who’s historic fishing areas have been impacted by the development of offshore wind (Vineyard Wind 2024). The fund opened millions of dollars of compensation for qualifying fishers. However, offshore wind developers are encouraged to first attempt to avoid and minimize disturbance to the fishing industry before attempting mitigation (Lennon 2024).

Regulatory Considerations for Permitting

As of 2021, kelp aquaculture does not require a permit from the local municipality like shellfish production (NOAA 2021) but does require a permit from the Massachusetts Department of Marine Fisheries (NOAA 2021). However, in some cases further permissions for the farm may be required by local by-laws, such as in Duxbury, MA where a local farm required approval from the town's conservation commission (Nadler 2021).

There is no seaweed-specific permitting structure in Massachusetts, but kelp aquaculture does require a general aquaculture special project permit (NOAA 2021). Farms must receive permission from the US Army Corps of Engineers and complete the pre-construction notification process (NOAA 2021). It is possible that farms may need permission from the Department of Environmental Protection if the project is within Chapter 91 waterways or coasts (NOAA 2021). Chapter 91 refers to the Massachusetts General Law Chapter 91 which protects and promotes public use of the state's tidelands and inland waterways (Massachusetts Office Coastal Zone Management n.d.). The goal of Chapter 91 is to ensure the preservation and proper use of state waterways and is generally administered by the state Department of Environmental Protection (Massachusetts Office Coastal Zone Management n.d.). Lands subject to Chapter 91 include flowed tidelands, filled tidelands, great ponds, and non-tidal rivers and streams (Massachusetts Office Coastal Zone Management n.d.). Great ponds refer to ponds or lakes greater than 10 acres in their natural state (Massachusetts Office Coastal Zone Management n.d.). For kelp farming, the waters that would be most likely to fall under Chapter 91 purview would be in flowed tidelands where jurisdiction extends from the seaward side of the present mean

high-water shoreline to three miles seaward (Massachusetts Office Coastal Zone Management n.d.).

In Massachusetts, the state led an initiative known as the Massachusetts Aquaculture Permitting Plan (MAPP) (Massachusetts Executive Office of Energy and Environmental Affairs (EEA) 2021). This initiative was able to streamline the permitting process for shellfish growers and increase understanding of the steps within the permitting process (EEA 2021). However, this process seems to have missed kelp aquaculture and instead focused primarily on shellfish and finfish production. Unlike Massachusetts, other states require kelp aquaculture to secure an aquaculture permit from the local municipality. In Maine, kelp aquaculture operations must follow the same aquaculture permitting and leasing process as any other form of aquaculture; the permit is the same cost, and applicants must go through the same approval process with the town. Given that this requirement does not exist in Massachusetts, it could be argued that it is less burdensome for an aquaculturalist to gather the necessary documentation to farm kelp than it is in other states that produce larger quantities. This means there could be an overall lower barrier to entry for potential Massachusetts-based kelp farmers.

Massachusetts Ocean Management Plan (2021)

Massachusetts has taken on Marine Spatial Planning at the state level, similar to other states including Oregon and Rhode Island (Ehler 2021). In 2008, the Commonwealth of Massachusetts passed the Oceans Act, which was established to better manage ocean resources and protect critical marine habitat (Massachusetts Office Coastal Zone Management n.d.). In 2009, the state also created an Ocean Management Plan, which was updated in 2015 and most recently, in 2021. The Plan details how the state will use its



Figure 1. Massachusetts Ocean Management Plan Area. 2021. Massachusetts Executive Office of Energy and Environmental Affairs.

oceans and protect marine habitat through established management standards (EEA 2021).

The area of planning concern within Massachusetts is along the coast, from the North Shore to the Islands with a buffer of around 3 nautical miles offshore. This area encapsulates the entirety of Cape Cod Bay as well as the waters near Martha's Vinyard and Nantucket. However, parts of Nantucket Sound are not included within the management area (ADD MAP). The majority of the planning area is designated as multi-use, with the exception of the Cape Cod Ocean Sanctuary, in compliance with the Ocean Sanctuaries Act, a state law establishing five ocean sanctuaries within Massachusetts waters. It is important to note that this sanctuary is unrelated to the Stellwagen Bank National Marine Sanctuary located between Cape Ann and Provincetown.

The plan identifies areas of special, sensitive, or unique resources (SSU resources) as well as concentrations of water-dependent uses. Examples of SSU resources include whale habitat, eelgrass beds, tern and other sea bird's habitat, important fish resources, and intertidal flats (EEA 2021). Concentrations of water-dependent uses include concentrated recreational fishing, commerce traffic, recreational boating, and fixed fishing facilities (EEA 2021). The plan does discuss offshore wind development, however, designated areas for offshore wind are outside the boundaries of the Massachusetts Ocean Plan Management Area. Offshore wind is designated to two specific Wind Energy Areas south of Marthas Vinyard and Nantucket and are thus outside the scope of this study.

The actual administration of the Ocean Management Plan falls mostly on EEA. The Oceans Act specifically gives the Secretary of EEA the responsibility of oversight, coordination and planning authority of Massachusetts ocean waters (EEA 2021). In addition to EEA, other governmental agencies including the Office of Coastal Zone Management, Department of Environmental Protection, Department of Fish and Game, and the Division of Marine Fisheries all play a role in the coordination and implementation of the plan (EEA 2021).

Much of the existing aquaculture production in the state is happening landward of the management area and does not fall under the purview of the Ocean Management Plan (EEA 2021). Within multiuse areas, a wide variety of uses are allowed including the harvesting and propagation of fish and shellfish in all forms (EEA 2021). While there is not a specific use example for kelp aquaculture, the allowable use within multiuse areas is not exhaustive and would allow for kelp farming. However, there are parts of Massachusetts waters where shellfish aquaculture is prohibited by the state, unrelated to the Ocean Management Plan. This area includes some select estuaries along Cape Cod, some smaller south shore ports, and the entirety of the coast and some deeper ocean from Cohasset to Gloucester including the entirety of Boston Harbor and the surrounding area.

Chapter 4 – Results

Introduction

The literature review in Chapter 3 provided an overview of the key economic, ecological, social and regulatory aspects of kelp aquaculture in Massachusetts that need to be considered in a spatial analysis. This chapter will utilize review findings to set the parameters for a further, integrated assessment of the spatial considerations of kelp siting in Massachusetts. Summaries of key literature findings are included below.

Economic considerations: Based on the findings regarding the economic aspects of kelp aquaculture, it is ideal for kelp farms to be sited near existing ports and facilities that can process landed kelp and provide smooth geographic connections to markets for kelp products. It is important to consider the town or regional reliance on the fishing and aquaculture industry when determining what areas may be more suitable for kelp farming.

Ecological and environmental considerations: Sea surface temperatures during growing season (winter to early spring) must be considered for kelp to grow productively, and farm siting should take into consideration the projected changes within the region's sea surface temperature. Given the ability of kelp to locally increase pH levels, siting could also be considered near existing aquaculture plots or areas that experience higher pH levels than other parts of the state. This approach could potentially integrate the benefits of growing kelp into the wider network of aquaculture occurring in the area. Considerations should be made for existing sea grass, critical whale habitat, and preferred nesting areas

for seabirds. Additionally, consideration should be given to current and future runoff that could jeopardize kelp's ability to be sold for human consumption.

Social and regulatory considerations: Kelp aquaculture siting in Massachusetts is not held to the same permitting standard as other aquaculture uses and has a less apparent permitting process. There should be consideration given to Chapter 91 waterways and the complications associated with siting kelp farming in or near these waterways. Additionally, siting should be consistent with outlined state priorities and agendas in the 2021 Ocean Management Plan. Lastly, there should be significant consideration given to reducing user conflicts between future kelp production and commercial and recreational activities including other forms of aquaculture or marine capture fishing, areas highly trafficked by recreational boaters, existing commercial navigation routes, and near shore land uses that may not be compatible with aquaculture, such as areas zoned for residential or near community assets that would cause conflict or irritation.

Geospatial Analysis Results

Table 1. Variables identified from the literature review relevant to kelp aquaculture.

Based on the findings of the literature review, an asset map was created using layers that represented the important geospatial aspects of the literature review section. From this, data sets were divided into four dimensions (Table 1): economic, ecological, governance, and recreation. The economic dimensions represent key geographic information necessary for kelp siting including shipping lanes, major ports, and areas of particular importance for the fishing industry. The ecological dimension mostly covers

climatic and biodiversity considerations including sea surface temperature, pH, whale habitat, bathymetry, and seagrass restoration locations. Governance includes data points such as prohibited growing areas, Chapter 91 waters, and potentially conflicting land uses such as residential and recreation (park space). The last dimension, recreational, represents potential user conflicts from recreational boating and fishing that are prominent in Massachusetts waters, especially during the summer. For the purposes of determining overlap, governance and recreation were combined into 1 category, “Governance/Social” due to the low number of inputs for recreational activities that would lead to less productive findings as its own category (Figure 1 and Figure 2). Overall, the three considerations that were most prevalent in the findings were whale habitat, commercial traffic, and recreational traffic.

Dimension	Variable	Source
Economic	Major ports	NOAA
	Shipping lanes	Massachusetts CZM
	Areas of high priority for fishing industry	Massachusetts CZM
Ecological	Seagrass beds	Massachusetts CZM
	Core whale habitat	Massachusetts CZM
	Localized pollution (prohibited areas)	Massachusetts CZM
	Sea surface temperature	NOAA
	Bathymetry	Massachusetts CZM
Governance	Prohibited areas	Massachusetts CZM
	Chapter 91 waters	Massachusetts GIS
	Multiuse waters	Massachusetts CZM
	Nearshore land use	Massachusetts GIS
Recreation	Recreational fishing	Massachusetts CZM
	Recreational boating	Massachusetts CZM

Table 1. Variables identified from the literature review relevant to kelp aquaculture.

The analysis shows that there is significant overlap in priorities, especially for ecological considerations that included large swaths of Massachusetts waters that are part of the core whale habitat in New England. The analysis shows significant overlap in uses, especially near Boston, the South Shore, and parts of the Northshore south of Gloucester. However, there are significantly less user conflicts along the coast from Rockport to Newburyport. Areas along the South Shore and Cape Cod experience higher levels of commercial and recreational traffic that contribute to more overlap.

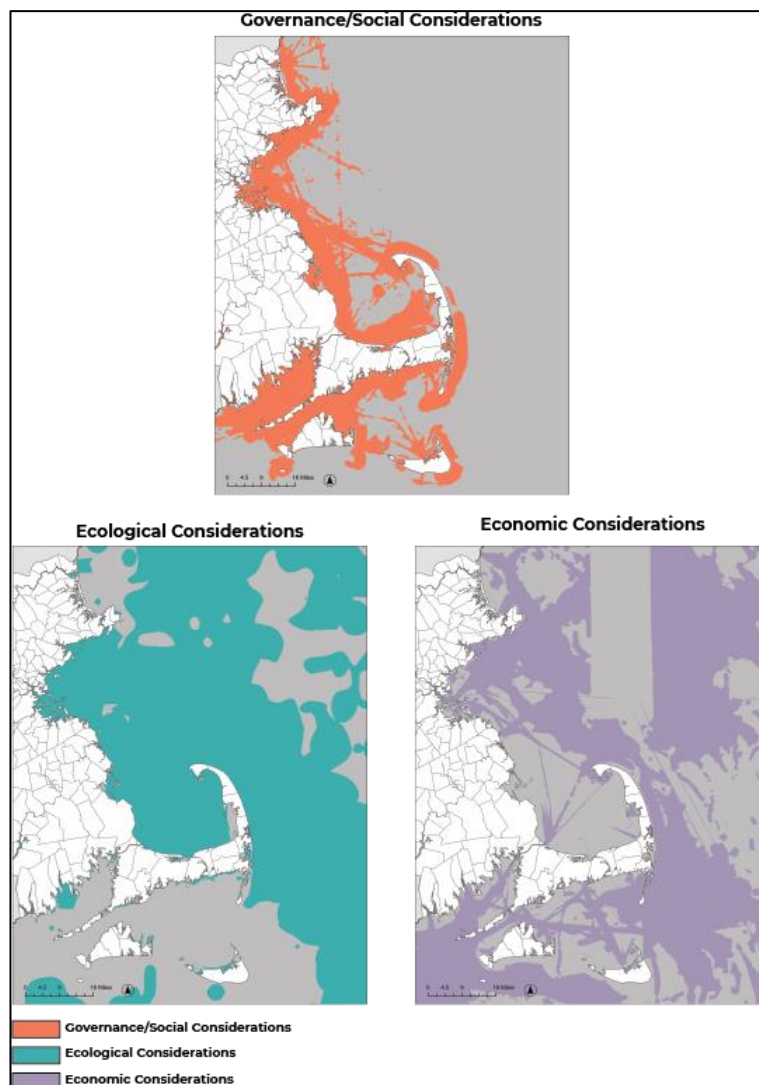


Figure 1. governance/social, ecological, and economic considerations within Massachusetts waters.

There is less overlap and potential use conflicts due to ecological considerations south of Cape Cod and North of Cape Ann.

The analysis presented several shoreside and nearshore user conflicts including chapter 91 jurisdictional areas and incompatible land uses such as residential and recreational lands that may be suboptimal for nearshore farms. The literature review identified potential user conflicts between community members and the development of aquaculture nearshore, making residential uses less optimal. The analysis indicates there

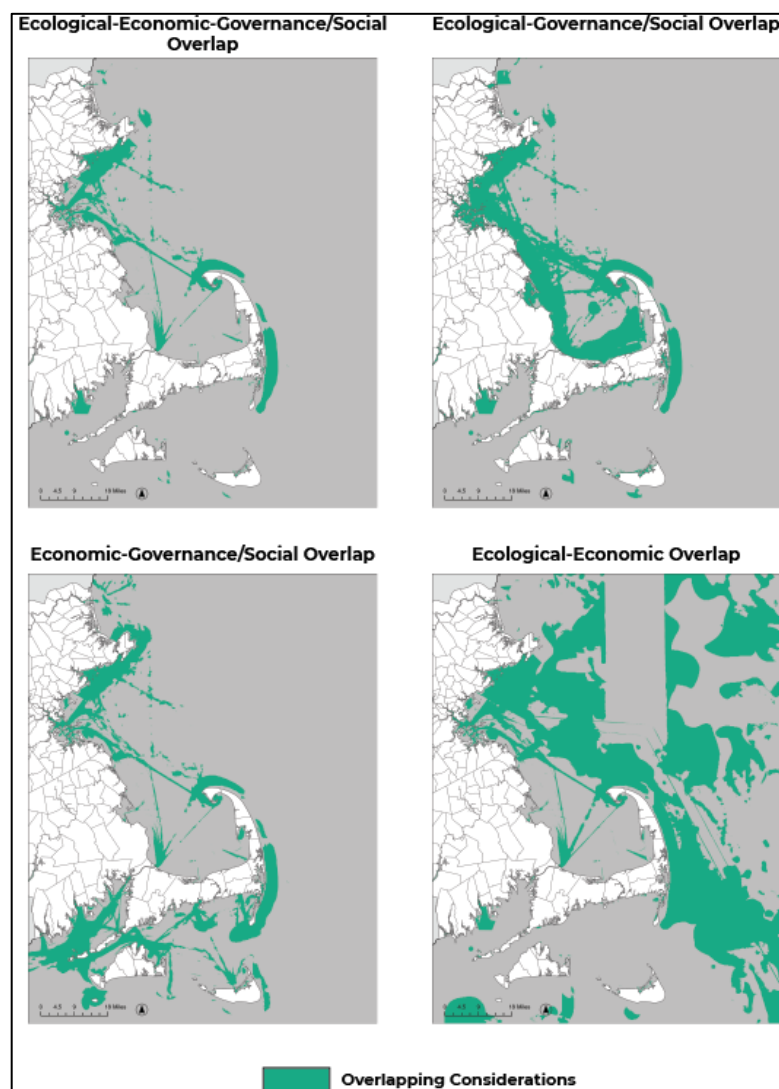


Figure 2. Overlap of governance/Social, ecological, and economic considerations within Massachusetts waters.

are several environmental justice communities surrounding Massachusetts coasts with the greatest density around the greater Boston area. However, not all Environmental Justice census tracts near the coast are engaged in the fishing industry. The results also indicate a large number of use conflicts and overlapping priorities around major ports, especially near New Bedford, Boston, and Gloucester. The majority of prohibited shellfish growing areas that have poor water quality for human consumption are concentrated around major ports, leading to a potential disconnect between areas safe for growing kelp for human consumption and ports with significant marine industries.

When comparing the overall use conflicts map with the seasonal map (figure 4 and figure 5), there are less use conflicts, especially around the South Shore and Cape Cod with less recreational traffic and whale populations migrating south for winter. This suggests that there could be more opportunities for kelp production near the Cape during winter months without interfering with other priorities and uses.

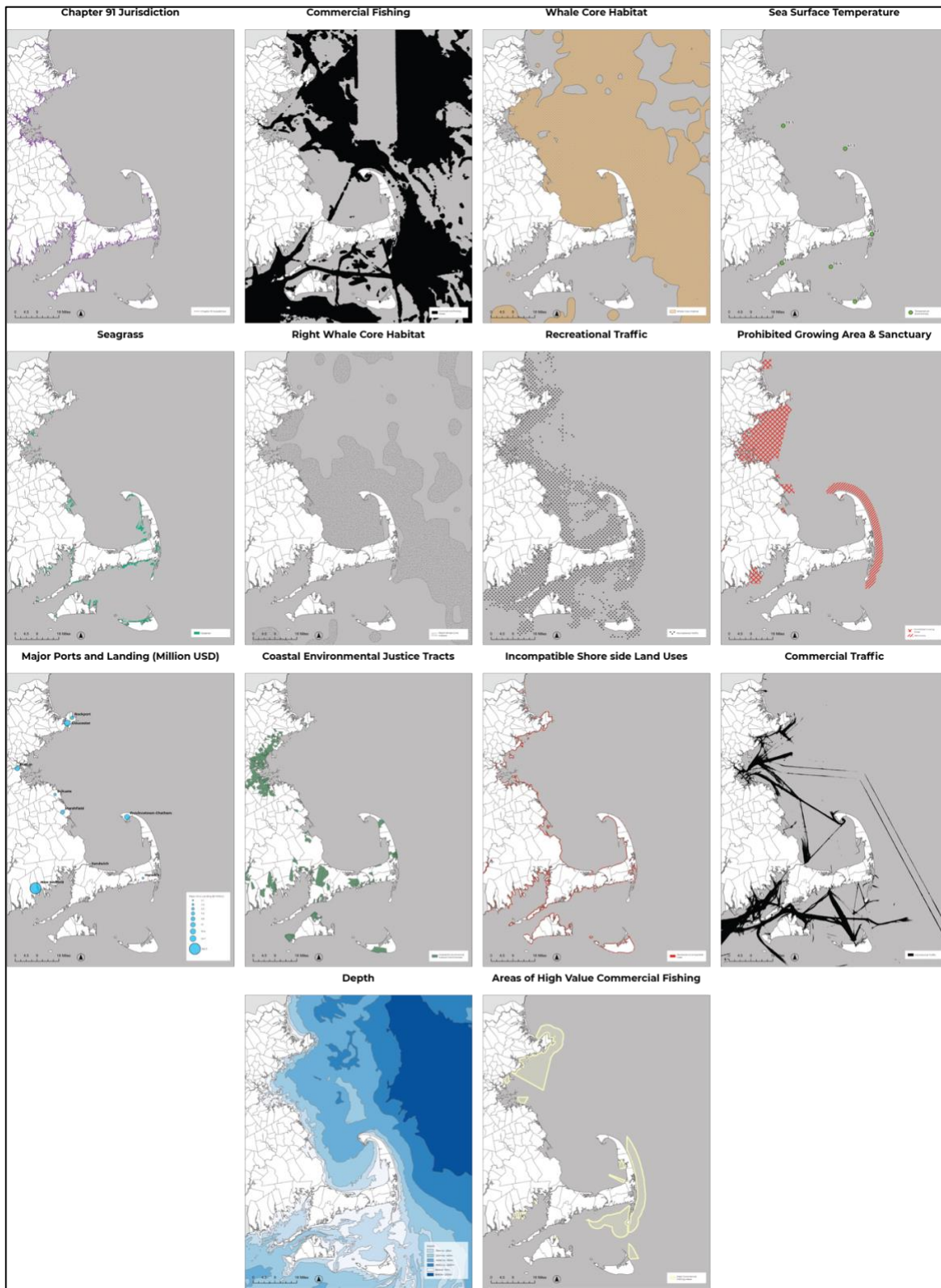


Figure 3. Inputs of final existing conditions map.

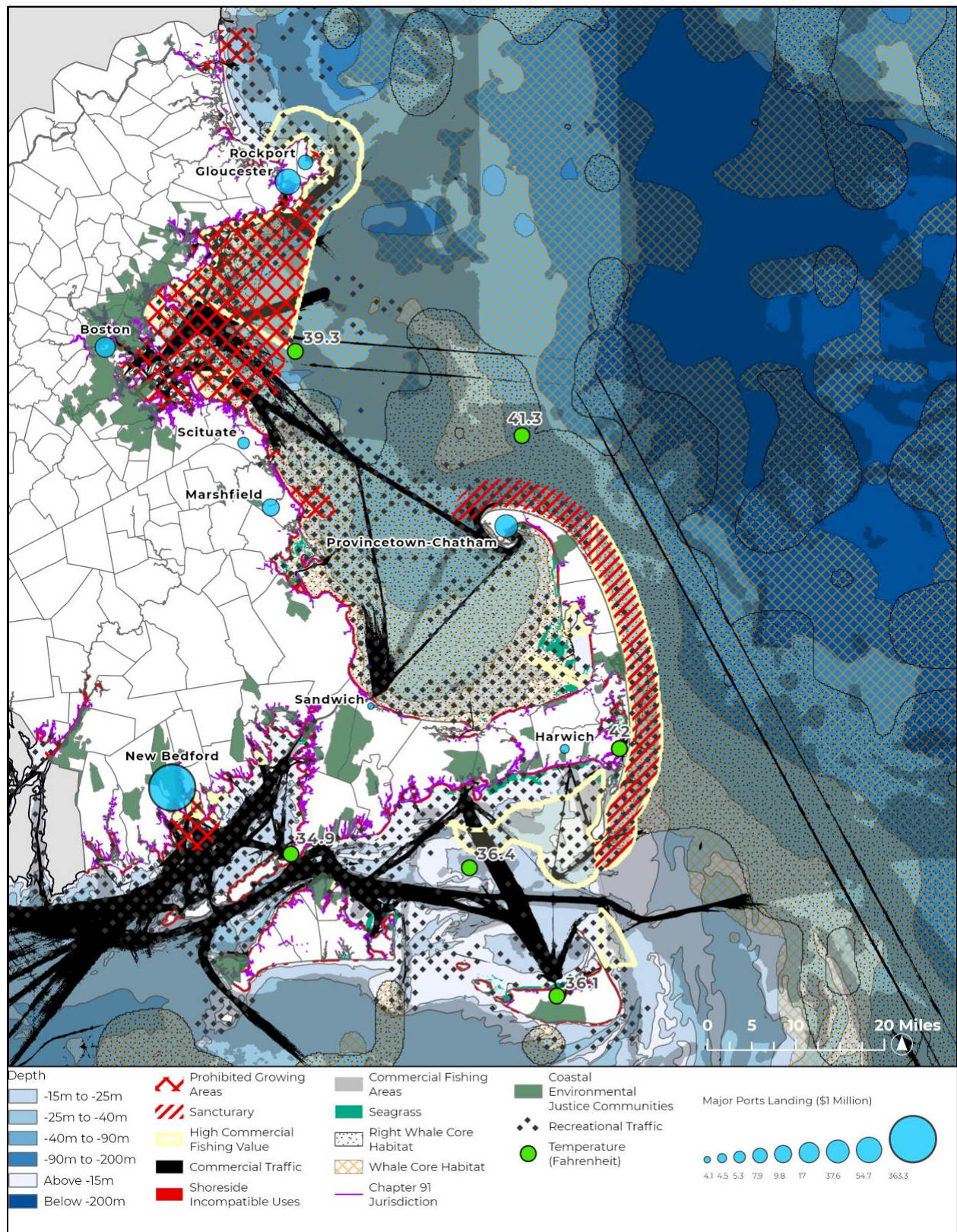


Figure 4. Existing Conditions map showing competing interests and priorities within Massachusetts waters and relevant shoreside considerations.

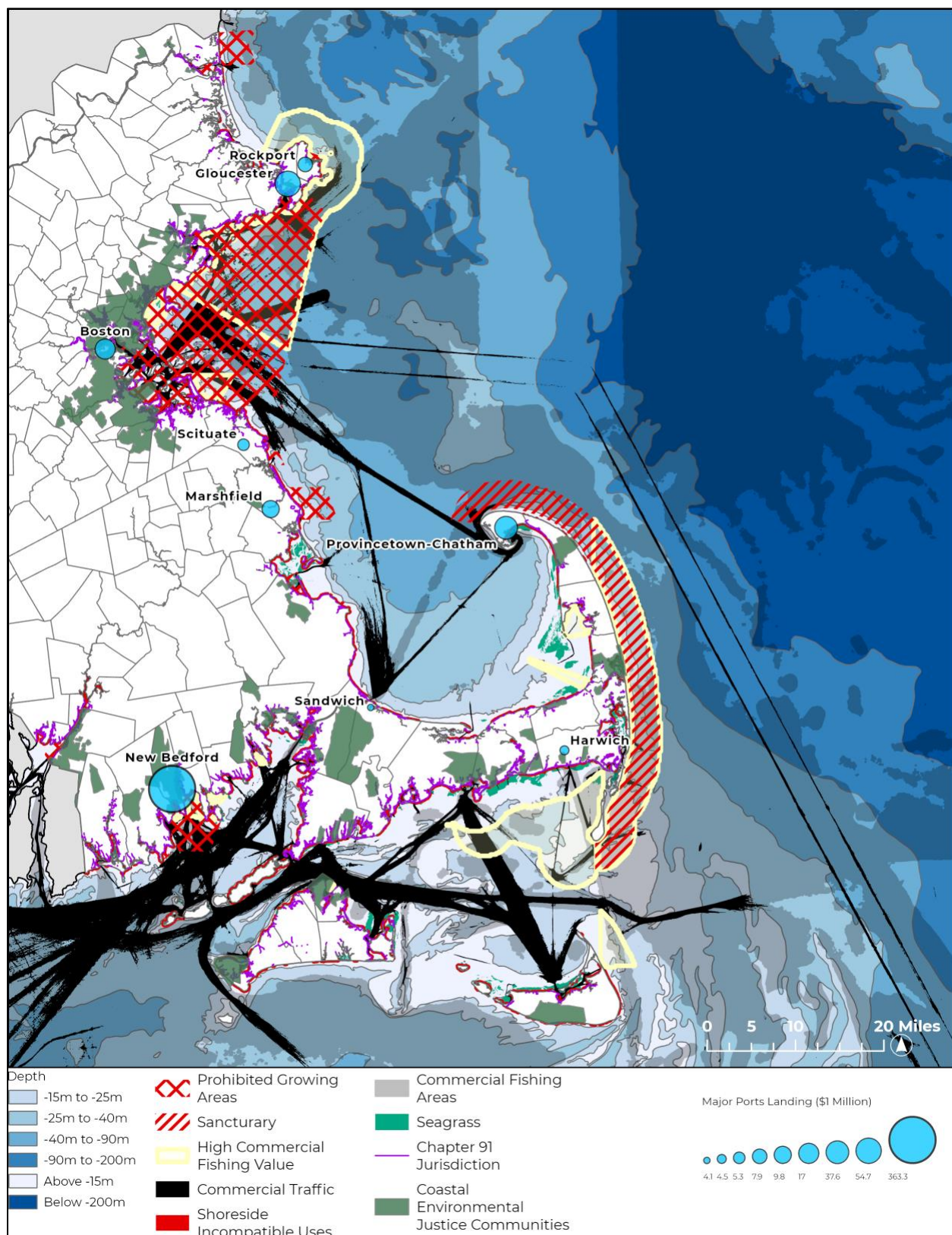


Figure 5. Existing Conditions map showing competing interests and priorities within Massachusetts waters and relevant shoreland considerations in winter.

Chapter 5- Discussion

Introduction

This chapter brings together the findings from the literature review and geospatial analysis to explore the competing interests, geographic suitability, opportunities for policy reform, and market viability of the kelp industry in Massachusetts.

Competing Interests and Seasonality

The integrated assessment of spatial considerations for kelp siting in Massachusetts shown in Chapter 4, presents significant overlap in uses and priorities (Fig X). However, while this geospatial representation presents a complicated reality, it is also inherently inaccurate. For example, while some areas may experience significant recreational activity in the summer months, during the kelp growing season in the winter, there is less traffic and therefore fewer conflicts between users.

There is also seasonality to whale activity in the region. During the winter months, North Atlantic right whales migrate south off the shore of South Carolina, Georgia, and Florida to calve while their summer months are spent feeding in Massachusetts waters (NOAA 2025). While most of the waters around Massachusetts are within the core habitat for the right whale, there are not always whales nearby, and it is possible that a kelp farm could be sited within the core habitat and yet there are never any whales in that area. With only 370 whales remaining in the population, it is possible that the whales may never encounter kelp farms when they migrate north (NOAA 2025). However, it is important that

kelp aquaculture, an industry typically marked as a “green initiative”, mitigates risk to the population whenever possible.

In the winter, sea surface temperatures are significantly cooler than in the summer, which could provide favorable conditions for kelp growth and mitigate biofoul (Handa et al. 2013). Massachusetts waters may pose a viable ground for kelp aquaculture in cold winter months when user conflicts are minimized, and environmental conditions are favorable.

Even in winter months there is the potential for overlapping priorities between the kelp industry and the existing fishing industry. There is also a disconnect between port locations and areas that are permissible for existing aquaculture for shellfish production. For example, the results show that New Bedford is the highest grossing port in Massachusetts, and the country, but shellfish aquaculture is not permitted near the port. However, this could be a result of the large capture fishery industry as opposed to a large aquaculture. While it is possible for kelp to be grown where shellfish is currently prohibited, if the goal of kelp production is to increase economic output, then kelp should be safe for human grade consumption. It logically follows that, without additional research to indicate otherwise, kelp should have similar sanitary regulations and conditions necessary for shellfish aquaculture due its ability to absorb heavy metals and toxins (Shaughnessy et al. 2023).

Due to the rapidly increasing sea surface temperatures in Massachusetts, and the cool growing conditions required for kelp, it is unclear if kelp could grow in the waters of the Commonwealth after March or May at the latest (Handa et al. 2012; Nepper-Davidsen et al.

2019). A benefit is that occupying colder water ensures that there is less biofoul that could interfere with kelp growth and value at market (Visch et al. 2020; Handa et al. 2013). The changes in sea surface temperature could shorten the growing season leading to decreased viability at market (Visch et al. 2020).

Geographic Suitability

From a marine spatial planning perspective, much of the areas that would be exposed to urban, agricultural, or sewage runoff are already not permissible for shellfish production; if set to the same standard, kelp would also be excluded from these areas. However, with the changing climate and increasing sea surface temperatures, it is possible that eutrophication will worsen (O’Neil et al. 2012). Therefore, when planning for kelp aquaculture, it is important to think about the longevity of a site. If it is already experiencing warming temperatures or eutrophication, it may not be the best site under a changing climate.

The rapid increases seen and projected for sea surface temperatures in Massachusetts waters means that shallower and warmer waters around Cape Cod and Nantucket Sound may not be as viable in the future for kelp production as the deeper, cooler areas along the North Shore. Additionally, one must think about the ability of local infrastructure to support an investment in kelp. Currently the most significant landings in the state come from New Bedford, Provincetown, Boston, and Gloucester (NOAA 2023). These top producing ports may not be the most suitable for kelp aquaculture given their high volume of commercial traffic, competing user interests, and decreased water quality.

However, it is possible these sites could serve as a launching point for future kelp development. Areas around the North Shore, including Gloucester and Rockport have been designated as major ports nationally indicating shoreside infrastructure necessary for marine industries and have less use conflicts and overlapping interests compared to the southern portion of the state (NOAA 2023).

From an equity perspective, it is important to note there are around 50 Environmental Justice Census Tracts as shown on the results map of this analysis. Therefore, it is important to address environmental and climate justice for communities within the development of a kelp aquaculture industry. Fishing communities are already more vulnerable to changes from climate due to the condition of their work, their proximity to the sea, and the low wages often associated with the industry (Colburn et al. 2016). Therefore, a kelp industry developed around the idea that it is accessible for people with a range of racial and socioeconomic backgrounds, should consider environmental justice principles and factors as a core aspect of its siting within the broader Massachusetts context. What this means might be interpreted differently in different communities and geographies; a key feature of this consideration would therefore need to incorporate feedback from the affected EJ communities themselves (Bullard and Johnson 2002). Tensions that may need to be considered include the presence or absence of shore side production facilities necessary to make the kelp industry commercially viable, as well as the climate resilience and adaptation needs of the community. While the kelp industry develops, it's unclear if or how the industry could be beneficial for climate and environmental justice and would require further research outside the scope of this study.

Opportunities for Policy Reform

Unlike much of the fishing industry, regulation and permitting for kelp aquaculture is heavily centralized within the Massachusetts state government, specifically with the state Division of Marine Fisheries (NOAA 2021). However, other aquaculture schemes in Massachusetts require local approval (Massachusetts Division of Marine Fisheries n.d.). The localized approach to permitting allows for greater community input and control over the aquaculture industry. If the permitting structure of kelp aquaculture were to be revised to follow similar processes as other aquaculture operations in the state, further community engagement could aim to engage communities and generally decrease potential user conflicts, similar to efforts in Rhode Island (Costal Resource Management Council 2019). Having a public hearing could provide an opportunity to decrease potential user conflicts and potential community animosity towards kelp production. However, if kelp aquaculture is further from shore to allow greater growing depths, the site may no longer fall within the jurisdictional boundaries of the city or town.

If permitting power continues to lie with the state, a kelp specific aquaculture permit could provide greater clarity for future growers and potentially create a cheaper permitting pathway for farmers who inherently make less from kelp landings than other aquacultural products.

Market Viability

While Massachusetts may work well for kelp production from an environmental perspective during the winter months, there is still significant concern regarding the

viability of kelp markets in the state. Outside of Maine and Alaska, markets are still developing, and extensive processing is needed for kelp to become an input into different products other than wet or dried kelp (Heidkamp 2022). Without an extensive market, the cost of processing may fall back on the farmer, leading to decreased profitability of an already less profitable product compared to shellfish and marine capture fisheries (Bricker 2022; Stevant and Rebours 2021).

Kelp aquaculture appears to currently lack the markets necessary for scaled production that would lead to increased climate resiliency. For kelp to be profitable as an economic diversification method, it requires some sort of increase in scale to compete commercially (Kim et al. 2019). Additionally, the benefits of nutrient uptake, sequestration, wave attenuation could provide further resiliency and mitigation with an increase in economic scale (Kim et al. 2019; Zhu et al. 2022; Pessarrodona et al. 2024; Xu et al. 2023). However, markets have been expanding globally in the past decade and conditions could change in the future (United Nations 2024; Kim et al. 2019). While kelp aquaculture on its own is more economically viable with increased production rates, there are some benefits to its production at a small scale (Bednarsek et al. 2024). For example, shellfish aquaculture could benefit from integrating kelp into its production system to mitigate the changing pH levels from ocean acidification at the very local level (Durate et al. 2017; Young et al. 2022). While the kelp may not be profitable on its own, by mitigating the impacts of acidic waters, it may assist in the profitability of shellfish (Bednarsek et al. 2024). However, it is important to note that much of shellfish aquaculture in the state of Massachusetts occurs near shore where depths may not be suitable for healthy kelp

production. Kelp requires a certain level of depth to grow to profitable lengths. There may be a spatial disconnect between shellfish and kelp production if the goal is to sell kelp for a profit at market (Young et al. 2022). Additionally, to grow kelp at depths most suitable for its growth, further resources would be required to travel further offshore.

Much of the domestic demand for kelp is met by supply from Alaska and Maine as well as imports (Robidoux & Good 2023; Kim et al. 2019). While there is some interest in expanding the supply of kelp from New England to provide some sort of climate resilient future for fishers, markets continue to be smaller and less developed outside of Maine (Robidoux & Good 2023; Heidkamp et al. 2022). However, it is possible that within the next 10 to 15 years, with further research, technology developments, competing priorities for terrestrial resources, and the emergence of a more supported blue economy focused on climate resilience, kelp could become more profitable, especially if more processing plants are created shoreside (Kim et al. 2019). Right now, much of the processing responsibility lies with the producer (Heidkamp et al. 2022). For example, the largest kelp producer in Maine, Atlantic Sea Farms, is responsible for its own processing of kelp from dry or wet product to its other outputs, including smoothies and kelp-based burgers.

Another opportunity for growth of the kelp industry is in the development of a market for aquaculture feed or livestock feed, but this would require both the establishment of processing facilities and market links between the grower and the processor. These challenges to the profitability of the kelp industry indicate a missing component; a key middle actor in the marketplace (Kim et al. 2019). In the fishing industry, much of the landings are not sold directly from the producer to the consumer but are sold to a

distributor (Stevant and Rebours 2021). Right now, the kelp industry is somewhat reliant on the producer to also conduct side processing scheme. If there were more investment in shoreside processing, that could lift the burden off the farmer, and may produce a higher economic output, therefore creating opportunities for the industry to scale up (Young et al. 2019).

Chapter 6- Recommendations and Conclusions

Introduction

This thesis has shown that there is a need for climate resiliency within coastal communities and kelp may be one possible tool for fishers. To support the development of the kelp aquaculture industry as an economic diversification and climate resilience strategy, the following recommendations should be considered for a range of stakeholders including potential farmers, shoreside processors, policymakers, and those interested in developing a kelp industry in the commonwealth.

Economic Recommendations:

- Invest in shoreside processing to decrease the value chain burden on the kelp producer.
- Site kelp aquaculture farms near existing marine infrastructure to decrease processing costs.
- Consider kelp aquaculture as a diversification tool, rather than a main source of income.

Environmental Recommendations:

- Consider existing and future environmental conditions when siting kelp production, including sea surface temperature, currents, and depth.
- When possible, measures should be taken to decrease potential degradation of existing biodiversity, including whale and seagrass populations.

- When possible, integrate kelp aquaculture into existing shellfish production to diversify fisher's portfolio and provide some pH acidity relief.

Policy Recommendations:

- The state should develop a separate permitting pathway for kelp aquaculture that decreases costs and streamlines the process for future producers.
- Kelp aquaculture permitting should follow a similar local pathway as shellfish permitting processes, to allow for local community input and decrease user conflicts.
- Existing regulations on prohibited shellfish growing areas should apply to kelp aquaculture to promote public health and safety.

Limitations and Future Research

The limiting factor for this thesis was the nascency of the industry both in Massachusetts and nationally. Without a centralized database on kelp farming in the state, there is little to no public information on the number of farms in operation in the commonwealth and their total landings.

Further data creation and collection of aspects of the kelp ecosystem and industry within the state could prove helpful in future kelp marine planning endeavors including locations of farms (past, present, and future), more detailed sea surface temperature conditions, and detailed pH mapping. To better understand the role of kelp in the future, it would be helpful to create spatial data on expected marine conditions in Massachusetts.

This thesis has uncovered several future avenues for further research on both kelp aquaculture in Massachusetts, and the United States more broadly.

- Further research is necessary to understand the demographics of kelp farmers in Massachusetts and beyond to better understand the state of the industry. This could apply to the fishing industry more broadly as there does not appear to be a central source of information on fisher demographics in the United States.
- Further research is needed to understand how, or if, kelp can play a role in Environmental Justice and if the kelp as an economic diversification tool could contribute to Massachusetts environmental justice priorities.
- More information is needed to understand how kelp should be sited within the Commonwealth to ensure sanitary conditions for human consumption. This thesis utilized existing sanitary standards for shellfish, but further research may provide further clarification on best practices.
- Building on the 2023 “State of the States: Status of U.S. Seaweed Aquaculture (Robidoux and Good 2023), a comparative analysis of kelp permitting by state could provide further insight into future best practices for state issued aquaculture permits and regulations for kelp.
- Future qualitative research on fishers and kelp farmers perceptions of the industry could provide insight into its ability to serve as a climate resilient method and help determine the interest in scaling the industry from fishing communities.

- A case study analysis of the Maine and Alaska kelp industry could provide further insight into their success and lessons learned that could be applied to other states and regions.

Conclusions

The future of New England's fishing industry and coastal communities is somewhat uncertain in a changing climate. Adaptation and mitigation strategies must be utilized to help address future challenges. Kelp aquaculture has been described as a potential silver bullet for fishing communities facing uncertainty with climate change. However, kelp farming is likely to provide more nuanced benefits for these communities. Instead, it should be viewed as one possible diversification strategy for fishers in parallel with others. Further development in shoreside processing, streamlining of permitting, and general diversification of fisher's livelihoods could improve the economic outlook of the industry for future fishers.

While kelp can sequester large amounts of carbon dioxide, as well as absorb runoff nitrogen and phosphorus, it is still not clear if the industry could provide the mitigation benefits that so many hope for. It is possible that kelp aquaculture could relieve some stress on terrestrial agricultural systems, specifically for livestock and groundfish aquaculture feed. A streamlined approach to regulations and permitting for the industry could provide greater relief to potential farmers that may help increase interest in the industry within the Commonwealth of Massachusetts.

When planning for kelp aquaculture, it is important to consider the interconnectedness and often competing and overlapping priorities within marine planning and industries that dictate the use of our oceans and the health of marine ecosystems. The future of the kelp industry is highly dependent not only on decision-making in Massachusetts waters, but also the policy and economic development of shoreside communities and industries. Any number of decisions ranging from gear restrictions for whale conservation to zoning changes allowing processing in industrial districts along the coast could elevate or hinder the future of the industry.

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