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ECONOMIC FEASIBILITY OF COMMERCIAL

NUTRIENT BIOEXTRACTION IN LONG ISLAND SOUND

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ECONOMIC FEASIBILITY OF COMMERCIAL NUTRIENT BIOEXTRACTION IN LONG ISLAND SOUND

Executive Summary

Excess nitrogen and other pollutants have negatively impacted Long Island Sound and surrounding waters. This research evaluates the economic feasibility for commercial cultivation of alternative species of macroalgae and mollusks in Long Island Sound (LIS). The analysis is conducted along three lines of research, (1) identification of feasible species of seaweed and shellfish for nitrogen extraction not previously commercially cultivated in LIS, (2) evaluation of the commercial market for these species, and (3) an analysis of the cost and operating structure for these alternative species.

The initial Task (1) consisted of creating a searchable database of literature related to bioextraction along with relevant biological variables including nitrogen and other pollutant removal rates, organism growth rates, and other additional ecological variables. In addition, the research team built a quantitative spatial model of habitat availability for each species using ArcGIS. A species rank model was developed to identify suitable species for potential commercial cultivation leading to the identification of the five macroalgae species (*Cladophora sericea, Ulva intestinalis, Ulva lactuca, Ulva prolifera, Porphyra umbilicalis*) and three bivalve species (*Argopectin irradians*, *Geukensia demissa, and Mya arenaria*) for use in bioextraction. In the table below, a photograph of each species is provided except for those in the genera *Ulva*, *Cladophora*, and *Porphyra* because species therein cannot easily be identified from photographs alone and often require detailed anatomical and/or molecular confirmation. These eight species were then utilized in the subsequent marketing and economic analysis.

The marketing team developed an overview of the potential uses and markets for the various macroalgae and shellfish species. As part of this analysis, a separate review of legal and regulatory issues for Connecticut and New York state waters was conducted and is reported. Results for the regulatory analysis found that aquaculture firms seeking to enter this market will have to navigate a challenging and possibly complex regulatory environment for seaweed production. The marketing analysis identified a

number of possible outlets for seaweed and mollusk output including biostimulants, pet food, and cosmetics. They also found the market landscape for traditional uses of seaweed as either food or converted into food additives to be very competitive.

The final task involved developing a full cost structure for the various identified species and evaluating their economic feasibility. Breakeven levels of output were forecast and dependent upon productivity/output, the variable cost of macroalgae production per wet pound ranged between $0.23 to $0.68, and a total cost per wet pound of between $0.69 to $2.03. Estimates of elasticity for the various species found that consumers were very responsive to changes in the price of seaweed, moderately sensitive to changes in prices for soft-shell clams, and not very sensitive to changes in prices for mussels. The economic feasibility analysis found that it is possible for firms engaged in the production of the various macroalgae and shellfish species analysis to operate at or above breakeven, or in other words, they could achieve profitability.

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Table of Referenced Macroalgae and Bivalve Species by Chapter					
Scientific Name	**Common Name(s)**	**Category**	**Chapter 2**	**Chapter 3**	**Chapter 4**
*Alaria esculenta**	Winged Kelp, Atlantic Wakame, Dabberlocks, Badderlocks	Brown Algae		x	x
Ascophyllum nodosum	Bladder Wrack Sea Whistle, Knotted Wrack, Rockweed	Brown Algae	x	x	
Chaetomorpha linum	Green Thread, Green Brillo	Green Algae		x	
Chondrus crispus	Irish Moss	Red Algae	x	x	x
Cladophora albida	N/A	Green Algae	x		
Cladophora sericea	Green Tuft, Green Hair	Green Algae	x		x
Codium fragile	Dead Man's Fingers, Oyster Thief, Green Fleece, Stag Seaweed	Green Algae	x		
Eucheuma spp.*	Sea Moss	Red Algae		x	
Fucus distichus	Rockweed	Brown Algae	x		
Fucus spiralis	Rockweed	Brown Algae	x	x	
Fucus vesiculosus	Rockweed, Poppers	Brown Algae	x	x	
Gracilaria tikvahiae	Graceful Red Weed, Red Spaghetti	Red Algae	x	x	x
Gracilaria vermiculophylla	Worm Wart Weed	Red Algae	x		
Gracilaria spp.	N/A	Red Algae	x	x	x
Grateloupia turuturu	Devil's Tongue Weed, Red Sea Lettuce	Red Algae	x		
Hypnea musciformis	Hook Weed, Crozier Weed	Red Algae	x		x
Laminaria digitata	Horsetail Kelp, Finger Kelp, Kelp, Oarweed, Tangle	Brown Algae		x	
Mastocarpus stellatus	False Irish Moss	Red Algae	x		
Palmaria palmata	Dulse	Red Algae	x	x	
*Porphyra leucosticta***	Laver, Nori	Red Algae	x		
Porphyra umbilicalis	Laver, Nori	Red Algae	x	x	x
Porphyra purpurea	Laver, Nori	Red Algae	x		
Porphyra spp.	Laver, Nori	Red Algae	x	x	
Pyropia spp.***	N/A	Red Algae		x	
Ralfsia spp.	N/A	Brown Algae		x	
Saccharina latissima	Sugar Kelp, Kelp	Brown Algae	x	x	x
Saccharina spp.	Sugar Kelp, Kelp	Brown Algae	x	x	
Sargassum filipendula	Sargasso Weed, Gulf Weed	Brown Algae	x		
Sargassum muticum	Japanese Wireweed	Brown Algae	x		
Sargassum spp.	N/A	Brown Algae	x	x	
Ulva compressa	N/A	Green Algae		x	
Ulva intestinalis	Gut Weed, Green String Lettuce	Green Algae	x		
Ulva lactuca	Sea Lettuce	Green Algae	x	x	x

Ulva linza	Mini Sea Lettuce	Green Algae		x	
Ulva prolifera	Branched String Lettuce, Grass Kelp	Green Algae	x	x	x
Ulva rigida	Sea Lettuce	Green Algae	x		x
Undaria spp.*	N/A	Brown Algae		x	
Argopectin irradians	Bay Scallop	Bivalve	x		x
Ensis directus	Atlantic Jackknife Clam	Bivalve	x		
Geukensia demissa	Ribbed Mussel	Bivalve	x	x	x
Spisula solidissima	Atlantic Surf Clam	Bivalve	x		
Mya arenaria	Softshell Clam	Bivalve	x		x

* Not present in Long Island Sound

** This species was recently reclassified into the genus *Pyropia*; however, some research studies and other publicly available resources continue to refer to this species by the previous name. Therefore, for this report, this species was presented by its previous name, *Porphyra leucosticta*

*** Historically, many species of *Pyropia* have been misplaced in *Porphyra*

Table with Photos of Top Species identified for use in Bioextraction		
Scientific Name	**Common Name**	**Photograph**
Cladophora sericea	Green Tuft, Green Hair	Not available
Porphyra umbilicalis	Laver, Nori	Not available
Ulva intestinalis	Gut Weed, Green String Lettuce	Not available
Ulva lactuca	Sea Lettuce	Not available
Ulva prolifera	Branched String Lettuce, Grass Kelp	Not available
Saccharina latissima	Sugar Kelp, Kelp	
Argopectin irradians	Bay Scallop	
Geukensia demissa	Ribbed Mussel	
Mya arenaria	Soft-Shell Clam	

Photographs: *Saccharina latissima* courtesy of Rebecca Grella; *Argopectin irradians, Geukensia demissa,* and *Mya arenaria* courtesy of New York Department of Environmental Conservation.

CHAPTER 1: FEASIBILITY OF COMMERCIAL NUTRIENT BIOEXTRACTION IN LIS: AN INTRODUCTION

Throughout the nineteenth and early twentieth centuries, Long Island Sound was known for the bountiful harvests of eastern oysters, hard-shell clams, bay scallops, and other bivalves that found their way to restaurants and dinner tables across the Northeast and other parts of the country. The region's economy has evolved from its agrarian roots to industrial manufacturing and is now rooted in post-industrial higher order service sector activities. Over the past two decades, excess nitrogen and other pollutants arising from sources such as runoff from household and commercial lawn care, current and previous agricultural production, sewage related issues (leakage from septic systems), and contaminants/pollutants from long shuttered manufacturing operations have negatively impacted Long Island Sound and surrounding waters.

Commercialization and cultivation of previously unexploited seaweed and shellfish species may be a viable option to address the water quality in the area and help to revitalize the region's commercial aquaculture industry. The objective of this research is to evaluate the economic feasibility for local commercial cultivation of alternative species of macroalgae and mollusks in the waters of Long Island Sound and for local cultivators of these alternate species to participate in these growing markets. The analysis is conducted along three lines of research, (1) identifying the feasibility for use of several species of seaweed and shellfish for nitrogen extraction that have not previously been cultivated in the area commercially, (2) evaluating the commercial market for these species, and (3) conducting an economic analysis of the cost and operating structure to evaluate whether any of these alternative species of macroalgae and shellfish can be cultivated profitably in Long Island Sound. These three objectives, methodologies used to complete the analysis, and the general conclusions of the analysis are described below.

Chapter 2 focuses upon the initial objective of this study, to identify macroalgae and bivalve species already present in Long Island Sound that may be potentially suitable for cultivation and use for bioextraction. Included as part of this objective was the task of updating and expanding the current collection of '*Selected Summaries of Nutrient Bioextraction Peer-Reviewed Journal Articles'* to create a tabular, searchable database of relevant biological and environmental factors for the taxa of interest to this project (*Cladophora* spp., *Geukensia demissa, Gracilaria tikvahiae*, *Sargassum filipendula*, *Saccharina latissima, Sargassum muticum*, and *Ulva* spp.) as well as other additional macroalgae species present in Long Island Sound. Relevant biological variables in this database included: nitrogen removal rate, heavy metal removal rate, and organism growth rate. Additional ecological variables such as tolerances to nitrogen and phosphorus, salinity, and temperature are included. The constructed database was built from previously published literature on each species listed using publicly available resources such as Google Scholar.

The second objective of this task was to quantify the areas within Long Island Sound suitable for each listed species' year-round growth and survival. The research team built a quantitative spatial model of habitat availability for each species using ArcGIS software (Hotaling-Hagan et al., 2017) using LIS-wide environmental monitoring data available from public sources such as the NOAA Multi-scale Ultra-high Resolution (MUR) Satellite program and The Long Island Sound Integrated Coastal Observing System (UConn Long Island Sound Observatory 2024).

A species with high nitrogen removal rates but a low area of suitable habitat for mariculture creates significant constraints for expanding its utility for bioextraction. Therefore, the third objective of this task was to rank each species for suitability of bioextraction using the combination of biological and habitat availability information obtained from the analysis described above. Several traits for each species were given a rank value and then integrated into a simple species rank model (Malena at el., 2021). This analysis resulted in identifying *Ulva prolifera*, *Ulva lactuca*, *Cladophora sericea*, *Porphyra umbilicalis*, *Ulva* *intestinalis*, *Mya arenaria*, *Argopectin irradians*, and *Geukensia demissa* as the top choices of macroalgae and shellfish for use in bioextraction. The identified species were then utilized in the subsequent analysis conducted by the marketing and economics research teams.

The second focus of this research presented in Chapter 3 was to identify and analyze potential market opportunities for various macroalgae and shellfish species recommended by the biology team for use in bioremediation. Using data and literature collected from a combination of sources such as the U.S. Economic Census and various business and economic databases (ABI/Inform Global, Business Source Complete, Nexis Uni, etc.), the marketing developed an overview of the landscape for the use of the various macroalgae and shellfish species. As part of this process, the marketing team conducted interviews of managers and principals of firms that use or market products derived from macroalgae and shellfish to collect primary data on technology, supply chain, market potential, and regulatory issues in eight identified market sectors, i.e. fresh food, dried food, fertilizer for both food and non-food, animal feed, cosmetics, pharmaceuticals, and biofuels. Additional data was collected from market surveys (239 surveys were completed) to ascertain consumer knowledge, understanding, and consumption of seaweed and shellfish related products, or products that incorporated seaweed or shellfish into them.

Alongside the marketing analysis, the team developed a separate review and analysis of the legal and regulatory issues associated with the cultivation and sales of macroalgae and shellfish. Interviews of extension officers (aquaculture related) and regulatory officials in both Connecticut and New York State were conducted as part of this process. Additional interviews were conducted with aquaculture (macroalgae) operators and other industry related stakeholders. The team also reviewed and analyzed existing statutes and regulations for both New York State and Connecticut to further provide an overview of the regulatory environment that new entrants seeking to cultivate any of the identified seaweeds or shellfish may encounter.

The results of the secondary research, interviews, and market surveys were then used to develop a value chain analysis for the identified market sectors. Some of the sectors they investigated were animal feed, biostimulants, pet food, cosmetics, fabrics, nutraceuticals, bioplastics, construction materials, and pharmaceuticals. The marketing team also found that aquaculture firms currently cultivating or seeking to cultivate seaweed must navigate a challenging and potentially complex regulatory environment to grow, process, and market seaweed in the region. They also found the market landscape for traditional uses of seaweed as either food or converted into food additives to be very competitive which could make it difficult for new entrants in Long Island Sound to produce and sell their products profitably.

Chapter 4 provides an overall analysis of the economic feasibility of cultivating the various macroalgae and shellfish species identified in the original NEIWPCC RFP (e.g., *Gracilaria tikvahiae*, *Saccharina latissima*, and *Geukensia demissa*) as well as additional species found by the biology team (e.g., *Ulva prolifera*, *Ulva lactuca*, *Cladophora sericea*, *Porphyra umbilicalis*, *Ulva intestinalis*, *Mya arenaria*, and *Argopectin irradians)* as good candidates for use in bioremediation in Long Island Sound. As part of that process, the economics team collected publicly available data on production costs, prices, and potential revenue from sales for these species to construct cost and revenue functions for the representative aquaculture operation. In addition, the economics team conducted interviews of industry related stakeholders in the Northeastern United States and Long Island Sound region to collect primary data that was both directly used in constructing cost and revenue functions as well as to validate secondary data used in the analysis. Using these functions, we were able to forecast breakeven points, the level of output and sales at which a firm goes from incurring losses to earning a profit, from producing individual macroalgae and shellfish species.[1]

Argopectin irradians (bay scallops) has a history of exploitation in the region. While it was ranked very highly for nitrogen bioremediation by the biology team, it was not formally modeled. The Peconic Bay fishery collapsed almost forty years ago and has continued to encounter large-scale mortalities due to environmental factors (temperature, low DO), disease, predation, and other factors that primarily impacted adult scallops. There are multiple studies and projects underway exploring this issue beyond our research.

As part of estimating the breakeven levels of output, the economics team conducted two levels of sensitivity analysis. By varying the cost of an input (such as wage rates) or the productivity of an input (e.g. growth rate/output per lineal foot of seeded line for macroalgae), it was possible to simulate and forecast how the breakeven level of output would change. In macroalgae production, reported output levels per lineal foot of seeding line from both primary and secondary data sources varied between 2.5 to 7.7 pounds. These different yield levels resulted in the variable cost of production ranging from a cost per wet pound of as high as $0.68 to a low of $0.23, and a total cost per wet pound of over $2.03 to as low as $0.69. Similarly, changing other input productivity levels or costs would significantly affect potential profitability.

Consumer sensitivity, or in other words, how consumption may change because of changes in product price or because of changing income, was evaluated through the estimation of demand and income elasticities for three categories of products: macroalgae, soft-shell clams (*Mya arenaria*), and mussels (using blue mussels as a proxy for Atlantic ribbed mussels). This analysis relied on time series data for prices and output levels for landed output for cultivated seaweed, soft-shell clams, and blue mussels produced in Maine. From this analysis, it appeared that consumers were very responsive to changes in the price of seaweed, moderately sensitive to changes in prices for soft-shell clams, and not very sensitive to changes in prices for mussels. It should be noted that this analysis is based upon total market sales of landed product and does not differentiate between different possible uses for these products from direct consumption as food to other uses as suggested by the marketing team for products, such as pet food, fertilizer, or as inputs for cosmetics and pharmaceuticals.

The economic feasibility analysis found that it is possible for firms engaged in the production of the various macroalgae and shellfish species analysis to operate at or above breakeven, or in other words, they could achieve profitability. This is not a blanket statement that all firms would be profitable, but that under the right market circumstance some individual firms could be profitable. Most of the macroalgae species and the shellfish that were evaluated are commodity products, and as such, will face a very competitive landscape in regional, national, and international markets. Thus, it may be necessary for individual firms to find ways to differentiate their output through various levels of post-harvest processing that could result in them yielding higher revenues than the commodity prices found and used in the analysis.

Chapter 5, the final chapter of this study presents the conclusions and recommendations from the separate research threads. The overall research finding from all three teams is that macroalgae and shellfish cultivation of previously unexploited species may have a role to play in nitrogen bioremediation of Long Island Sound. All the identified macroalgae are native to the region and can be grown using known aquaculture techniques (see Flavin et al. 2019, Radulovich et al. 2015, and Wu et al. 2023 for discussion on production methods for growing macroalgae). The same thing is true for both ribbed mussels (*Geukensia demissa*) and soft-shell clams (*Mya arenaria*) (see Galimany et al. 2017, Gren and Wondmagegn 2021 for a discussion on production methods for mussels; see Hagan and Wilkerson 2018 for a full discussion of growing methods for soft-shell clams). The biologists identified some challenges for some of the seaweed species including increasing water temperatures. Both marketing and economic analysis found that almost all these species can be feasibly cultivated and sold, but there are some market challenges that growers may face.

ENDNOTES

1. *Argopectin irradians* (bay scallops) has a history of exploitation in and around Long Island Sound. While it was ranked very highly for nitrogen bioremediation by the biology team, it was not formally modeled. The Long Island fishery collapsed over forty years ago and has continued to encounter problems as a result of pathogens that have impacted scallops growing to maturity. There are multiple studies and projects underway exploring this issue beyond our research (McKenzie 2008).

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CHAPTER 2: IDENTIFICATION OF SPECIES FOR BIOEXTRACTION

The objective of this task is to update and expand upon the current collection of macroalgae and bivalve species with high bioextraction interest in the "Selected Summaries of Nutrient Bioextraction Peer-Reviewed Journal Articles" (NYSDEC, n.d.). A tabular, searchable database of relevant biological and environmental factors for Long Island Sound species was constructed. The types of publications included for the literature review database were peer-reviewed experimental studies, peer-reviewed theoretical studies, and white papers. Publication date was not restricted because macroalgae not documented recently may be understudied and still occur in these waters. Only papers in English were included. Native and non-native species confirmed to occur in Long Island Sound were included. A preliminary macroalgae species inventory for Long Island Sound was established using Weiss (1995), Villalard-Bohnsack (1995), and Stewart Van Patten and Yarish (2009). Weiss (1995) was used to create a preliminary inventory of Long Island Sound bivalve species. Two strategies, snowball method (Aceves-Bueno et al. 2017) and key terms search method, were then used to identify publications to add to the database.

The present work is intended to identify alternative species that can be explicitly employed as novel sources for bioextraction in the Long Island Sound. Thus, species from locally well-established commercial aquaculture and wild harvest industries, such as Eastern Oyster (*Crassostrea virginica*), Blue Mussel (*Mytilus edulis*), and Hard Clam (*Mercenaria mercenaria*), were excluded in this analysis; while they do carry out bioextraction, their fisheries have been doing so since they were initially established. Bioextraction data contributed by these established species should be interpreted as baseline knowledge of current Long Island Sound bioextraction levels and thus were outside the scope of this work. Furthermore, although the Bay Scallop (*Argopectin irradians*) was once a notable commercial industry in local marine waters, such as the Peconic and Gardiners Bays, its fishery declined sharply after 1985 (MacKenzie 2008), but efforts to restore this fishery have persisted. Therefore, *Argopectin irradians* is considered in this analysis because in the event that this fishery recovers, it has the potential to substantively contribute to existing bioextraction levels. Regarding macroalgae species, no species were excluded. The species *Porphyra leucosticta* was recently reclassified into the genus *Pyropia.* However, much of the published literature found for inclusion in the updated database uses the previous genus designation. Additionally, some recent research studies and other publicly available resources for aquaculturists continue to refer to this species by its previous genus name. Therefore, in this report, this species was presented as the previous name *Porphyra leucosticta*.

In the snowball method, coined by Aceves-Bueno et al. (2017), an initial pool of relevant papers is identified from a targeted review, and then a reference search is conducted for all papers that were cited in the studies of this initial pool. Next, all citations in the new group that meet specific criteria are included for the next round of literature review. This process is repeated iteratively until no new relevant studies are encountered. Beginning with the compilation in "Selected Summaries of Nutrient Bioextraction Peer-Reviewed Journal Articles" (NYSDEC, n.d.), we identified all references that were cited within these studies and reviewed them for relevant data (see inclusion/exclusion criteria below). Next, we identified every reference that was cited within these studies and reviewed them for relevant data. This procedure was repeated iteratively until no new relevant citations were found. Up to six iterations were required for some papers. Table 2.1 provides the total number of citations reviewed using the snowball method, and although it includes duplicates, the data conveys both effort and likelihood of success for finding relevant papers.

Table 2.1. Total number of citations reviewed (T) and the total number of citations 'Flagged for further review' (F) from the snowball method of literature review. Citations in the first column are publications in the "Selected Summaries of Nutrient Bioextraction Peer-Reviewed Journal Articles." Numbers are not dereplicated.

NYSDEC 'Selected Summaries' Papers	Round 1		Round 2		Round 3		Round 4		Round 5		Round 6	
	T	F	T	F	T	F	T	F	T	F	T	F
Bricker et al. 2015	199	1	3	2	42	0	0	0	0	0	0	0
Gorman et al. 2017	47	15	868	17	757	9	329	1	55	0	0	0
Johnson et al. 2014	64	14	477	23	817	13	399	5	168	0	0	0
Kim et al. 2017	122	18	844	29	1074	5	221	4	178	0	0	0
Kim et al. 2019	48	5	214	9	363	3	88	0	0	0	0	0

Rose et al. 2015	50	0	0	0	0	0	0	0	0	0	0	0
Bricker et al. 2018	73	0	0	0	0	0	0	0	0	0	0	0
Kellogg et al. 2018	32	0	0	0	0	0	0	0	0	0	0	0
Rose et al. 2014	67	2	358	7	47	3	62	0	0	0	0	0
Grizzle et al. 2017	42	3	191	10	343	23	910	14	352	0	0	0
Hudson et al. 2016	37	7	325	20	694	44	1202	50	1457	12	381	0
Sebastiano et al. 2015	65	0	0	0	0	0	0	0	0	0	0	0
Total	846	65	3330	117	4137	100	3211	74	2210	12	381	0

In the snowball method, 14,115 papers were reviewed, a sum that included duplicate papers. This total list of papers was later dereplicated (i.e., duplicate papers were removed), yielding 8,236 unique papers reviewed for inclusion in the database. The basis for inclusion of papers was mention of any macroalgae or bivalve species found in Long Island Sound and if the peer-reviewed publication included data that could be used in the next subtask – specifically, nitrogen (in any form), phosphorus, heavy metal, growth, temperature, salinity, pH, and/or dissolved oxygen. Citations that were not full journal articles (i.e. citations that were conference abstracts only) or papers that were inaccessible without payment were excluded from the literature database. Of the 8,236 unique papers, 367 (4.5%) were flagged for further review with the potential to be added to the database. Of the remaining papers, 6402 (77.7%) did not mention any target species; 795 (9.7%) mentioned target species but did not include relevant data regarding nitrogen extraction or environmental parameters for ArcGIS modelling; 243 (3.0%) were not in English; 48 (0.6%) were non-peer-reviewed conference abstracts; and 381 (4.6%) were not publicly accessible. After review and further quality control, all 367 papers were approved for final inclusion. Of the 367 papers 295 papers were on macroalgae and 72 papers covered bivalves. From this effort, a final list of 24 macroalgae species and 5 bivalve species was identified using the snowball approach.

In the key term search method, we filled gaps of more recent papers by utilizing key terms via Google Scholar. In this approach, the scientific name of each of the 24 macroalgae species or 5 of the bivalve species previously identified in the snowball approach was coupled with a specified key term. For example, a species name was coupled with “nitrogen,” and the papers that appeared in the first five pages of search results were reviewed based on content in their abstract. After three pages of search results, new papers were usually not discovered. The same method was used for the following additional search terms: “nitrogen uptake,” “bioextraction,” “heavy metal,” “temperature,” “Long Island Sound,” and “extractive aquaculture.” Table 2.2 provides a rank of the most successful key terms that returned approved papers (data are not de-replicated). As with the snowball method, the basis for inclusion of papers in the key terms method was mention of any macroalgae or bivalve species found in Long Island Sound and if the peer-reviewed publication included data that could be used in the next subtask – specifically, nitrogen (in any form), phosphorus, heavy metal, growth, temperature, pH, and/or dissolved oxygen. Papers that were inaccessible without payment were excluded from the literature database. Additional key terms were not used on the basis of results from a preliminary analysis of additional search terms often synonymous with "bioextraction" or ”nitrogen uptake.“ In this preliminary analysis, other relevant key terms (e.g., “nutrient removal,” “nitrogen removal,” “bioremediation”) were explored for a subset of species, but success rates of finding new approved papers to add to the database were minimal, (consistently less than 1% for any additional terms), and none of these new papers contributed novel information for ArcGIS modelling.

Table 2.2. Rank of key terms that returned approved papers not present in snowball database. Numbers of papers shown are after dereplication.

Key Term	No. Papers	Category
[Species Name] + nitrogen	74	Macroalgae
[Species Name] + extractive aquaculture	66	Macroalgae
[Species Name] + temperature	45	Macroalgae
[Species Name] + heavy metal	33	Macroalgae
[Species Name] + nitrogen uptake	18	Macroalgae
[Species Name] + bioextraction	6	Macroalgae
[Species Name] + Long Island Sound	3	Macroalgae
TOTAL NUMBER OF APPROVED PAPERS	**245**	
[Species Name] + nitrogen	11	Bivalve
[Species Name] + heavy metal	10	Bivalve
[Species Name] + nitrogen uptake	7	Bivalve

[Species Name] + Long Island Sound	6	Bivalve
[Species Name] + extractive aquaculture	5	Bivalve
[Species Name] + bioextraction	0	Bivalve
[Species Name] + temperature	0	Bivalve
TOTAL NUMBER OF APPROVED PAPERS	**39**	

Key-term search for macroalgae resulted in approximately 8,400 papers (24 target species x 10 hits per page x 5 pages x 7 key terms) reviewed. A final list of dereplicated papers was compiled, which had 731 papers. Of the 731 papers, 486 papers were excluded generally because they were inaccessible without payment (n = 127), did not contain relevant data (n = 233), or were already in the snowball database (n = 126). In summary, the total of added macroalgae papers from the key terms search was 245. Key-term search results for bivalves resulted in approximately 1,750 papers (5 species x 10 hits x 5 pages x 7 key terms) that were reviewed and then de-replicated down to 89 papers. Of these 89 papers, 50 papers were excluded generally because they were inaccessible (n=16), did not contain relevant data (n=18), or were already in the snowball database (n=16). In summary, the final total of bivalve papers added from the key terms search was 39.

A final merged database was constructed, consisting of 651 papers derived from combining results from the snowball method and key terms search.

Features of the Task 1 Literature Database

The final merged literature database, hereafter referred to as the Task 1 Literature Review Database (Appendix A), is a tabular, searchable database of relevant biological and environmental factors for the taxa of interest lists peer-reviewed publications and their data for following categories, when present: names of Long Island Sound target species mentioned, location of study, nitrogen bioextraction data (i.e., total tissue nitrogen in % dry weight, nitrogen uptake rate from water in µM per grams dry weight per time, or other units or rates), nitrogen load amount in water, phosphorus bioextraction data, heavy metal concentration in tissue, growth/yield values, filtration rate, and water quality parameters (e.g., temperature range, salinity, dissolved oxygen, pH).

The final form of this database is a Microsoft Excel spreadsheet with two worksheets. The first worksheet includes information on all approved publications. Publications that included multiple target species were split into multiple rows such that each row only included information for one target species. For the topics covered category, any subset of the following terms was used to describe the publication: nitrogen uptake, nitrogen load, phosphorus uptake, filtration rate, growth, temperature, salinity, dissolved oxygen, pH, and heavy metal. The second worksheet provides descriptive information, such as descriptions of the categories (Table 2.3), and a final list of macroalgae and mollusk species (Table 2.4). Within cells of the Task 1 Literature Review Database, units of measurement are presented as they appeared in the original publication.

Table 2.3. Categories in Task 1 Literature Review Database.

CATEGORY	DESCRIPTION
Authors	Authors of publication
Article Title	Title of publication
Target Species Mentioned	Target species of macroalgae or shellfish mentioned
Topics Covered	Topics covered in publication
Article Category	Categorization of publication as experiment, review, or modeling
Location of Study	Geographic location of publication
Nitrogen Bioextraction (total tissue N in % dry weight)	Nitrogen bioextraction data: Total tissue nitrogen expressed as a percent of dry weight
Nitrogen Bioextraction (uptake from water in µM per gdw per time)	Nitrogen bioextraction data: Nitrogen uptake values from water (in µM per gdw per time)
Nitrogen Bioextraction (other units static or rate)	Nitrogen bioextraction data: Other mention of nitrogen bioextraction parameters
Phosphorus Bioextraction	Phosphorus bioextraction parameters mentioned
Growth	Growth rate per time, expressed in various units
Yield	Yield (biomass) per area per time, expressed in various units
Temp Range (°C)	Temperature or temperature range (in Celsius) mentioned
Salinity (ppt)	Salinity (in ppt) mentioned
Dissolved Oxygen	Dissolved oxygen mentioned
pH	pH mentioned
Filtration Rate	Filtration rate mentioned
Heavy Metals	Types and amounts of heavy metals mentioned

Access	Status of article's accessibility - Full paper available or Abstract only
APA Citation	Article formatted in APA style
URL	Link to PDF of publication
Database	Type of database - Snowball or Key Terms
Key Term(s) Used	For Key Terms database only: Key Terms used to find article

Table 2.4. Final list of commercially important or potentially commercially important Long Island Sound macroalgae and mollusk species identified in the Task 1 Literature Review Database.

MACROALGAE		
Ascophyllum nodosum	*Gracilaria tikvahiae*	*Porphyra purpurea*
Chondrus crispus	*Gracilaria vermiculophylla*	*Saccharina latissima*
Cladophora albida	*Grateloupia turuturu*	*Sargassum filipendula*
Cladophora sericea	*Hypnea musciformis*	*Sargassum muticum*
Codium fragile	*Mastocarpus stellatus*	*Ulva lactuca*
Fucus distichus	*Palmaria palmata*	*Ulva intestinalis*
Fucus spiralis	*Porphyra leucosticta**	*Ulva prolifera*
Fucus vesiculosus	*Porphyra umbilicalis*	*Ulva rigida*

BIVALVES		
Argopectin irradians	*Geukensia demissa*	*Mya arenaria*
Ensis directus	*Spisula solidissima*	

* This species was recently reclassified into the genus *Pyropia*; however, some research studies and other publicly available resources continue to refer to this species by its previous name. Therefore, in this report, this species was presented as the previous name *Porphyra leucosticta*

Task 1b – To identify sites along Long Island Sound most suitable and least suitable for growth or harvest of each listed species

Several biological and environmental variables limit geographic range and growth rate of marine algae and invertebrates, with significant implications on the viability of those species for bioextraction. While compiling the literature database for Task 1a, data for several biological and environmental parameters were recorded including temperature, salinity, pH, and dissolved oxygen. These data were to be used as constraining factors for subsequent habitat mapping. Of the 653 papers in the Task 1 Literature Review Database, 399 (61%) contained temperature data, representing all 24 species of macroalgae and all 5 species of bivalve included in this study. Similarly, 241 (37%) out of 653 papers in the literature database contained salinity data, representing 22 macroalgae species and 4 out of 5 bivalve species included in this study. On the other hand, only 92 (14%) and 43 (6.5%) out of 653 papers in the literature database had data values for pH and dissolved oxygen, respectively. Therefore, habitat mapping moving forward used only temperature and salinity data.

Sea surface temperature (SST) data from the Multi-scale Ultra-high Resolution (MUR) Satellite, which has daily ocean SST data across the globe at a 1km scale, was downloaded from the NOAA ERDDAP data download webserver (ERDDAP - Multi-scale Ultra-High Resolution (MUR) SST Analysis Data Access Form, 2024). The SST data included daily temperature values across 10 years starting from July 2013 through July 2024. The data downloaded was within the boundary of 41.50N, 40.52S, -74.46W, -71.34E; this is roughly all of Long Island Sound and the New York Bight region. SST data downloaded as a NetCDF (or .nc) file and then imported into ArcGIS Pro as a multidimensional raster layer. This raster layer was then reduced (via the 'Extract by Mask' setting) to only include pixels within a defined boundary of LIS and associated embayments (Figure 2.1). Daily SST values fluctuate greatly, and many species can tolerate such short-term temperature elevations above a thermal threshold (or short-term declines below a lower thermal threshold). Therefore, the daily SST values for each month of each year were averaged to a monthly SST value for each year. A new raster layer was created that contained the maximum monthly SST value (across all months of 2013 through 2023) within each pixel of the map layer (Figure 2.2). All cells in this raster layer contained an SST value from the month of August. Similarly, a new raster layer was created that contained the minimum monthly SST value (across all months of 2013 through 2023) within each pixel of the map layer (Figure 2.3). All cells in this raster layer contained an SST value from the months of January or February.

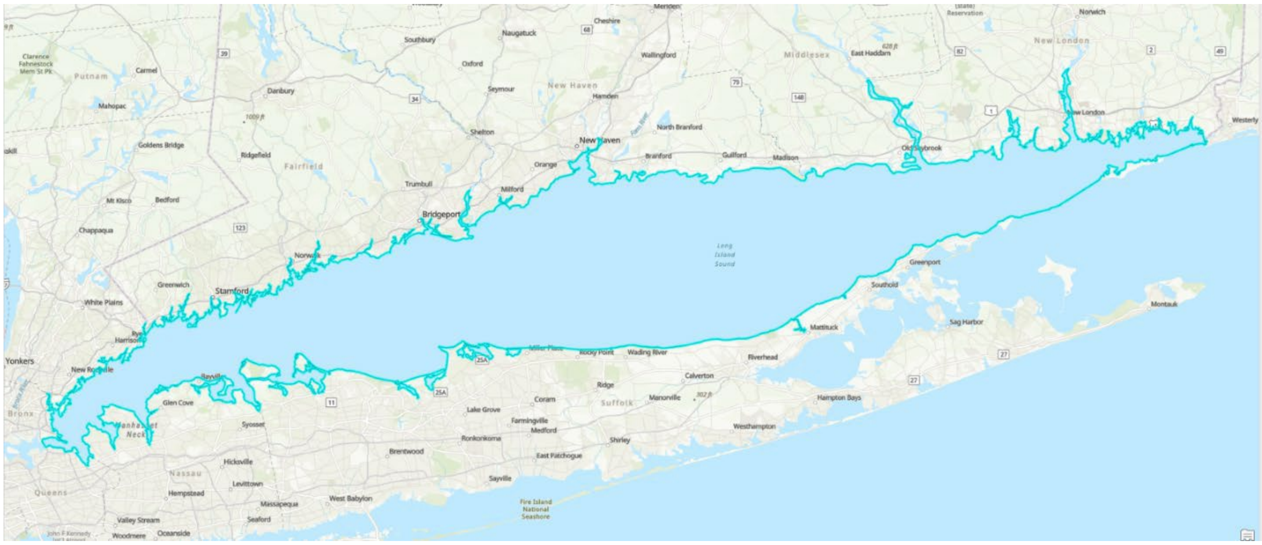

Figure 2.1. Defined Boundary of LIS and embayments used for habitat mapping analysis.

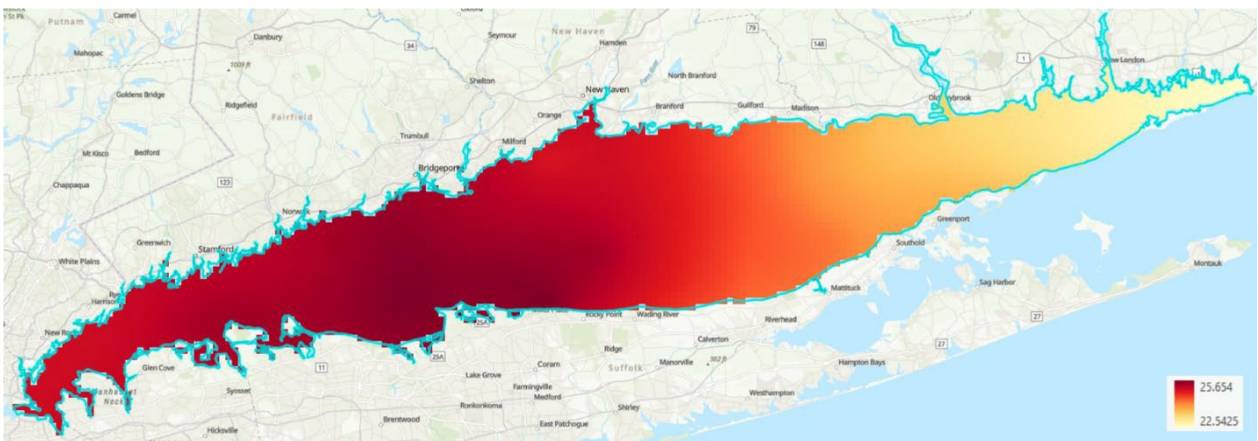

Figure 2.2. Map of Maximum monthly SST values across LIS

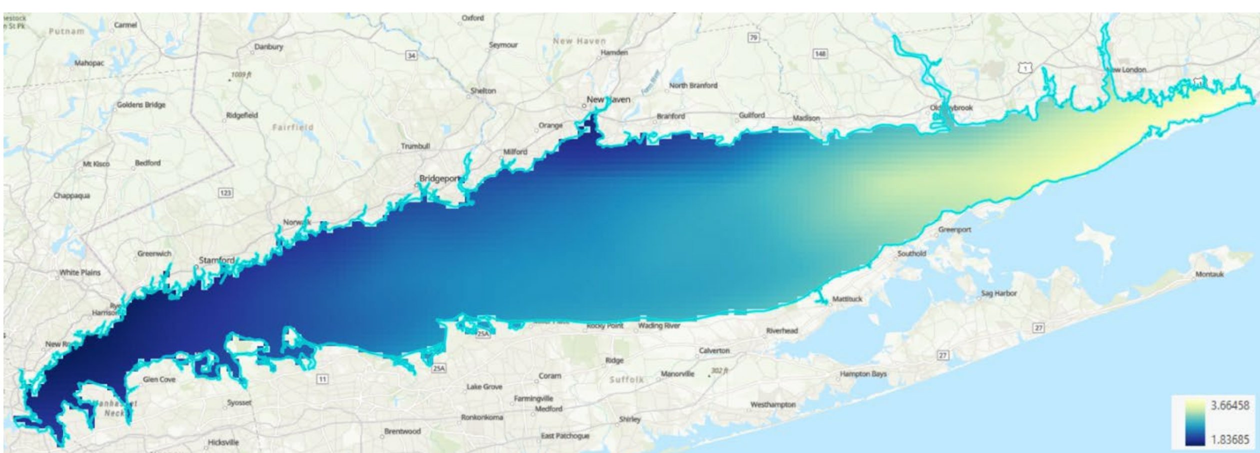

Figure 2.3. Map of Minimum monthly SST values across LIS

There are no corresponding satellite-based salinity data measurements available at the same spatial resolution as the SST data used above. The lowest spatial resolution found was at 25 km per pixel (data from NASA JPL). In lieu of satellite data, discrete measurements of surface (< 1 m depth) salinity were obtained from various sources that included data from 2013 through 2023 across 250 specific locations across LIS and associated embayments (Figure 2.4). Salinity data included buoy, cruise, and shore-based sampling from the Long Island Sound Integrated Coastal Observatory System (UConn's Long Island Sound Observatory 2024), the United Water Study (UWS) program (Save the Sound 2024), and the Interstate Environmental Commission (Interstate Environmental Commission 2024). For each site, daily, weekly, and/or biweekly data were averaged into a monthly value. Then, a table of maximum monthly salinity values was created and imported into ArcGIS Pro as a feature class. Similarly, a table of minimum monthly salinity values was also imported into ArcGIS Pro as a feature class. A model was used to interpolate the given data to project salinity values across the entire defined boundary of LIS. An interpolated model was created for the maximum monthly salinity values (Figure 2.5) and for the minimum monthly salinity values (Figure 2.6). The salinity-based maps used the same dimensions and used the same pixels as the temperature raster layers, and thus the salinity map has the same spatial resolution of 1 km per pixel.

Figure 2.4. Sites where discrete salinity measurements used for habitat mapping were taken

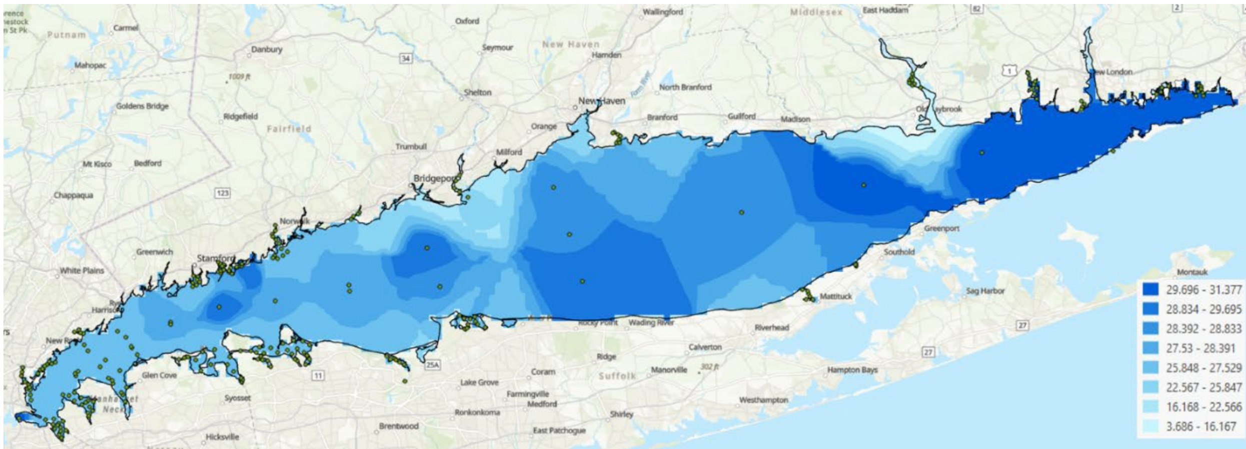

Figure 2.5. Map of Maximum monthly salinity values across LIS from interpolated model

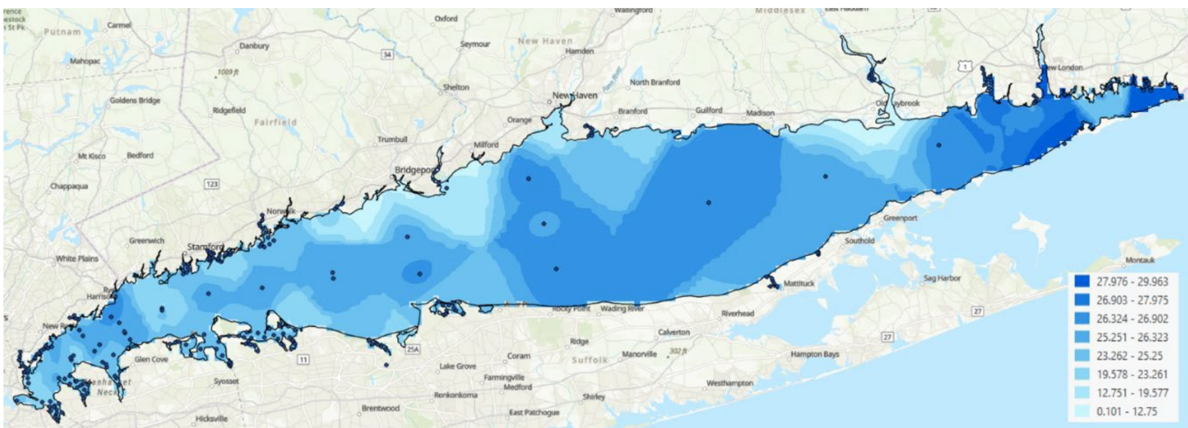

Figure 2.6. Map of Minimum monthly salinity values across LIS from interpolated model

In summary, both temperature-based maps are a true representation of maximum and minimum monthly sea surface temperatures measured in LIS from satellite data at a spatial resolution of 1 km per pixel. In contrast, the salinity-based maps are projections (interpolated models at a spatial resolution of 1 km per pixel) based on a collection of discrete salinity measurements.

Task 1c – Ranking each species for suitability for bioextraction using the combination of biological and habitat suitability

Nitrogen Uptake-based Ranking

Nitrogen uptake data was reported from 216 papers representing all 24 macroalgae species and 3 out of 5 bivalve species included in this project. Nitrogen extraction or uptake was reported using 23 different units (Table 2.5). These units included static measures of nitrogen uptake (i.e. % nitrogen in tissue or grams nitrogen per gram tissue) as well as dynamic measures of nitrogen uptake (nitrogen uptake per gram tissue per unit time). The five most common units were: (a) % N per gram dry weight (gdw) of tissue, (b) g N per gdw of tissue, (c) g N per gdw of tissue per day, (d) µM NH4 per gdw of tissue per hour, and (e) µM NO3 per gdw of tissue per hour (Table 2.6). Because all other units either had less than 10 data points or were present in less than 10 species, they were excluded from consideration for nitrogen-based ranking. For the top three most abundant units of measure, the maximum value reported per paper was used for ranking. Each maximum value was plotted against both reported temperature and reported nitrogen load, where available, to determine whether either of these values were strongly correlated with maximum nitrogen uptake measurements.

Table 2.5. Number of papers and number of species represented by different nitrogen uptake units included in Literature Review Database

Unit	Type of Unit	# Papers	# Macroalgae Species	# Bivalve Species
% N per gdw tissue	static	166	21	3
g N per gdw tissue	static	47	16	0
g N per gfw tissue	static	1	1	0
µM N per gdw tissue	static	1	1	0
µM NH_4 per gdw tissue	static	1	1	0
µM NO_3 per gdw tissue	static	2	1	0
µM NH_4 per gfw tissue	static	1	1	0
µM NO_3 per gfw tissue	static	1	1	0
kg N per ha	static	4	1	0
g N per gdw tissue per hr	dynamic	25	13	1
g N per m^2 per day	dynamic	16	5	0

µM N per gdw tissue per hr	dynamic	5	3	0
µM NH_4 per gdw tissue per hr	dynamic	39	15	0
µM NO_3 per gdw tissue per hr	dynamic	33	15	0
µM NO_2 per gdw tissue per hr	dynamic	1	1	0
µM N per day	dynamic	1	1	0
µM NO3 per m2 per day	dynamic	1	0	1
µM N per L per hr	dynamic	1	1	0
µM NH4 per L per hr	dynamic	4	4	0
µM NO3 per L per hr	dynamic	2	2	0
kg N per ha per year	dynamic	3	1	1
g N per m longline	dynamic	5	1	0
kg N per raft per month	dynamic	1	0	1
Note: Total number of papers in column is greater than 216 because some papers report more than one nitrogen uptake value.				

A total of 25 measurements for the nitrogen uptake unit “g N per gdw per hr” were collected across the 211 papers, and this nitrogen uptake data represented 13 out of 24 macroalgae species and 1 out of 5 bivalve species included in this study. There were no nitrogen uptake measurements in this unit collected for: *Ascophyllum nodosum*, *Codium fragile*, *Fucus distichus*, *Fucus spiralis*, *Grateloupia turuturu*, *Hypnea musciformis*, *Mastocarpus stellatus*, *Porphyra purpurea*, *Sargassum filipendula*, *Sargassum muticum, and Ulva intestinalis*. Nitrogen uptake for this unit was not correlated with either temperature or level of NH_4 in the surrounding seawater ($p > 0.05$), but because of the low number of data points for this unit and an N of 1 for most (8 out 13) species, this unit was not considered further for ranking analysis.

A total of 33 measurements for nitrogen uptake unit “µM NO_3 per gdw per hr” were collected across the 216 papers, and this NO_3 uptake data represented 15 out of 24 macroalgae species and 0 out of 5 bivalve species included in this study. There were no NO_3 uptake measurements collected for: *Ascophyllum nodosum*, *Cladophora albida*, *Cladophora sericea*, *Fucus spiralis*, *Grateloupia turuturu*, *Hypnea musciformis*, *Porphyra umbilicalis*, *Sargassum filipendula*, and *Sargassum muticum*. Levels of NH_4 in surrounding seawater were significantly correlated with the NO_3 uptake data points collected ($F = 9.613$, $p = 0.0059$) (Figure 2.7). Because of the low number of data points for this unit and the strong correlation to surrounding seawater conditions, this unit was not considered further for ranking analysis.

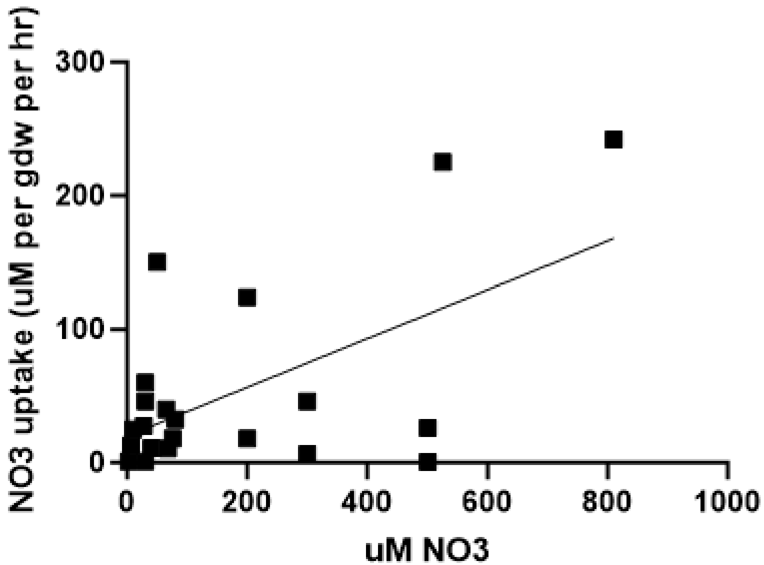

Figure 2.7. Nitrogen Uptake (in µM NO_3 per gdw per hr) plotted against NO_3 levels in surrounding seawater.

A total of 39 measurements for nitrogen uptake unit "µM NH_4 per gdw per hr" were collected across the 211 papers, and this NH_4 uptake data represented 15 out of 24 macroalgae species and 0 out of 5 bivalve species included in this study. There were no NH_4 uptake measurements collected for: *Ascophyllum nodosum*, *Cladophora albida*, *Fucus spiralis*, *Hypnea musciformis*, *Mastocarpus stellatus, Porphyra leucosticta, Porphyra umbilicalis, Sargassum filipendula,* and *Sargassum muticum*. Levels of NH_4 in surrounding seawater were significantly correlated with the NH_4 uptake data points collected ($F = 7.601$, $p = 0.0102$) (Figure 2.8). Because of the low number of data points for this unit and the correlation to surrounding seawater conditions, this unit was not considered further for ranking analysis.

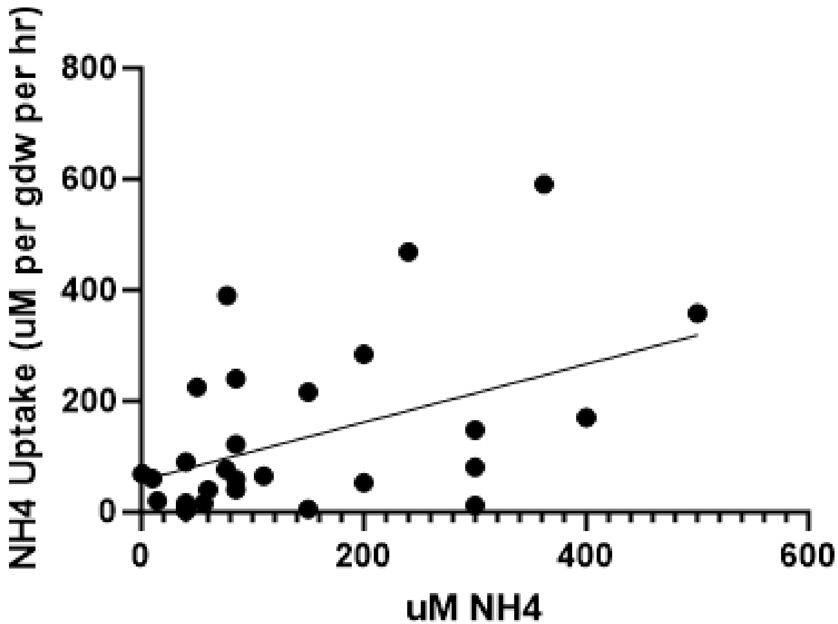

Figure 2.8. Nitrogen Uptake (in µM NH_4 per gdw per hr) plotted against NH_4 levels in surrounding seawater.

A total of 166 measurements for the nitrogen uptake unit "% N per gdw" (or % N) were collected across the 216 papers, and % N data represent 21 out of 24 macroalgae species and 3 out of 5 bivalve species included in this study. Even though % N is a static measure of nitrogen uptake, it had over 3 times the amount of data compared to the dynamic units of measure. Thus, it was considered for ranking. There were no % N measurements collected for *Cladophora albida*, *Grateloupia turuturu*, and *Mastocarpus stellatus*. Temperature was not significantly correlated with the % N data points collected ($F = 0.3409$, $p = 0.5605$) (Figure 2.9a); levels of NH_4 in surrounding seawater were not significantly correlated with the % N data points collected ($F = 0.5593$, $p = 0.4594$) (Figure 2.9b); and levels of NO_3 in surrounding seawater were not significantly correlated with the % N data points collected ($F = 0.1775$, $p = 0.6757$) (Figure 2.9c). Thus, no adjustments to the data to normalize to these potential confounding variables were needed.

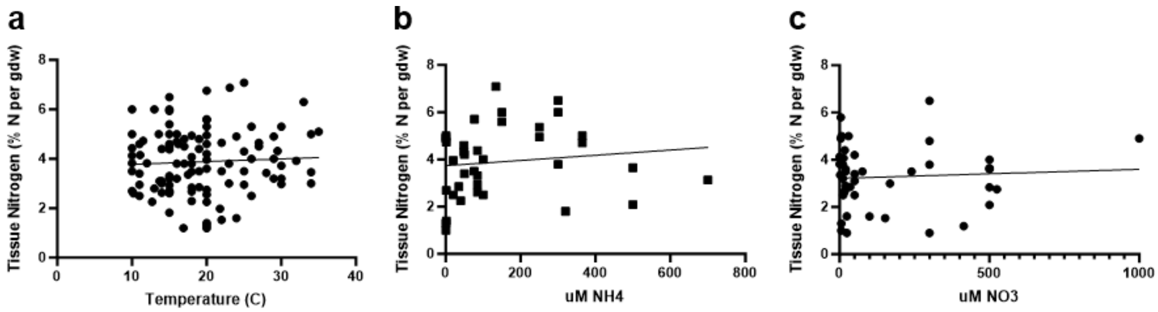

Figure 2.9. Tissue nitrogen (% N per gdw) plotted against a) temperature, b) NH_4 in surrounding seawater, and c) NO_3 in surrounding seawater.

Because % N had a much greater number of data points, represented almost all species included in this project, and was not correlated with temperature or nitrogen levels in surrounding water, this unit of nitrogen bioextraction was used to complete the nitrogen-based ranking over the dynamic units of nitrogen uptake. Three macroalgae species had only one % N value, so these two species were removed from the species level ranking. The maximum value of % N per paper was averaged within a species, and then these average values were used to rank species. For the macroalgae, this same process was conducted at the level of genus and macroalgae group (red algae, brown algae, green algae).

There were significant differences in mean % N in tissues of different macroalgae species (ANOVA: $F = 4.61$, $p < 0.0001$). At the level of species, *Porphyra purpurea* had the highest mean of maximum % N (Table 2.6, Figure 2.10). The top three highest % N values overall belonged to *Ulva lactuca* (7.1%), *Porphyra umbilicalis* (6.7%), and *Porphyra purpurea* (6.5%). At the level of genus, there were also significant differences between macroalgae (ANOVA: $F = 5.666$, $p < 0.0001$). At the level of genus, *Porphyra* had the highest mean of maximum % N (Table 2.7, Figure 2.11). At the level of macroalgae group, the green algae had the highest mean % N (3.99%); however, there was no significant difference between % N in green algae compared to % N in red algae (ANOVA with Tukey's comparisons: $p = 0.9943$) (Figure 2.12). Brown algae had significantly lower mean % N compared to the other groups (ANOVA with Tukey's comparisons; $p < 0.0008$) (Figure 2.12).

There were no % N data values found for *Ensis directus* or *Spisula solidissma*. There were only one or two data values of % N per bivalve species. *Mya arenaria* showed the greatest % N value (10.25%), followed by *Geukensia demissa* (8.1%), and then *Argopectin irradians* (5.26%). However, this ranking should be considered preliminary until more values can be added to this dataset.

Table 2.6. Ranking of Macroalgae species and ranking of Bivalve species included in this study based on nitrogen bioextraction potential (as measured by mean of the max percentage of nitrogen incorporated into tissue)

Ranking	**Macroalgae species**	**Bivalve species**
1	***Porphyra purpurea***	***Mya arenaria***
2	***Ulva prolifera***	***Geukensia demissa***
3	***Chondrus crispus***	***Argopectin irradians***
4	***Porphyra umbilicalis***	
5	***Porphyra leucosticta***	
6	*Cladophora sericea*	
7	*Ulva lactuca*	
8	*Gracilaria vermiculophylla*	
9	*Palmaria palmata*	
10	*Gracilaria tikvahiae*	
11	*Ulva intestinalis*	
12	*Fucus vesiculosus*	
13	*Codium fragile*	
14	*Ulva rigida*	
15	*Saccharina latissima*	
16	*Fucus spiralis*	
17	*Hypnea musciformis*	
18	*Ascophyllum nodosum*	
ND	*Sargassum filipendula*	
ND	*Sargassum muticum*	
ND	*Mastocarpus stellatus*	
ND	*Grateloupia turuturu*	
ND	*Cladophora albida*	
ND	*Fucus distichus*	

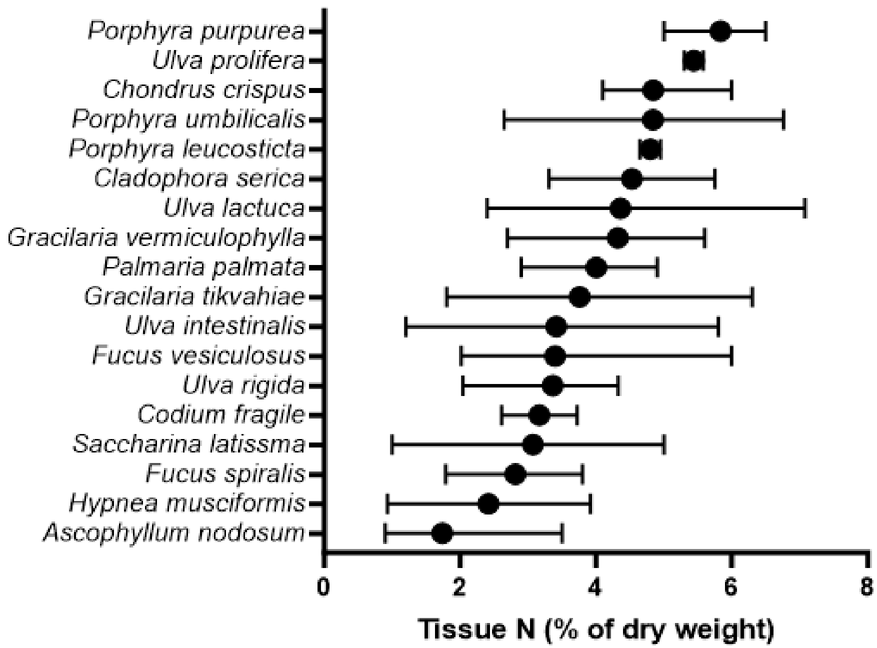

Figure 2.10. Mean and Range of maximum % N values for macroalgae species included in this study.

Table 2.7. Ranking of Macroalgae genera and ranking of Bivalve genera included in this study based on nitrogen bioextraction potential (as measured by mean of the max percentage of nitrogen incorporated into tissue)

Ranking	Macroalgae genus	Bivalve genus
1	***Porphyra***	***Mya***
2	***Chondrus***	***Geukensia***
3	***Cladophora***	***Argopectin***
4	***Ulva***	
5	***Palmaria***	
6	*Gracilaria*	
7	*Fucus*	
8	*Codium*	
9	*Saccharina*	
10	*Sargassum*	
11	*Hypnea*	
12	*Ascophyllum*	

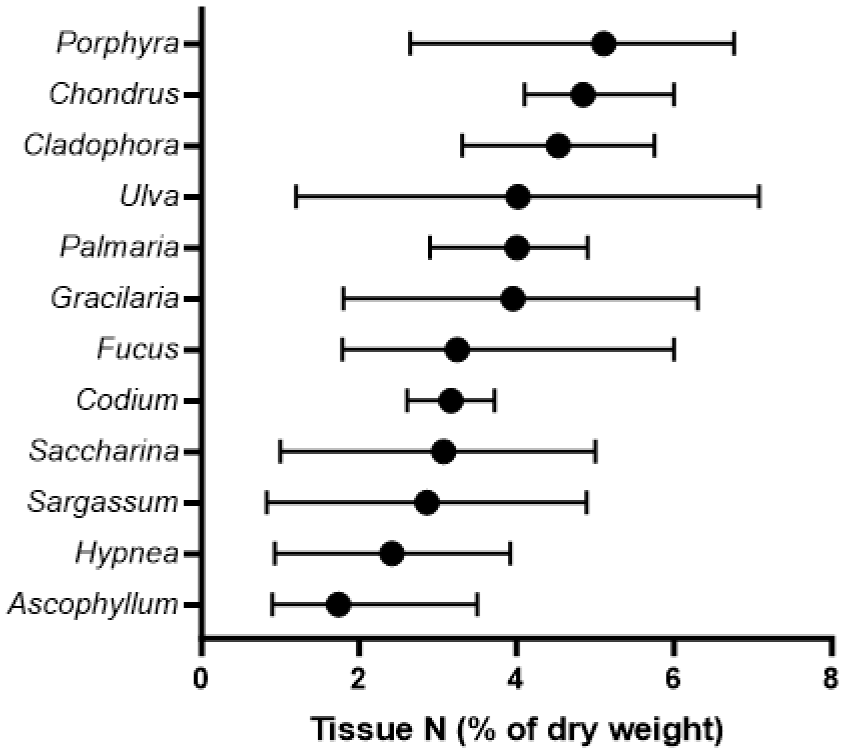

Figure 2.11. Mean and Range of maximum % N values for macroalgae genera included in this study.

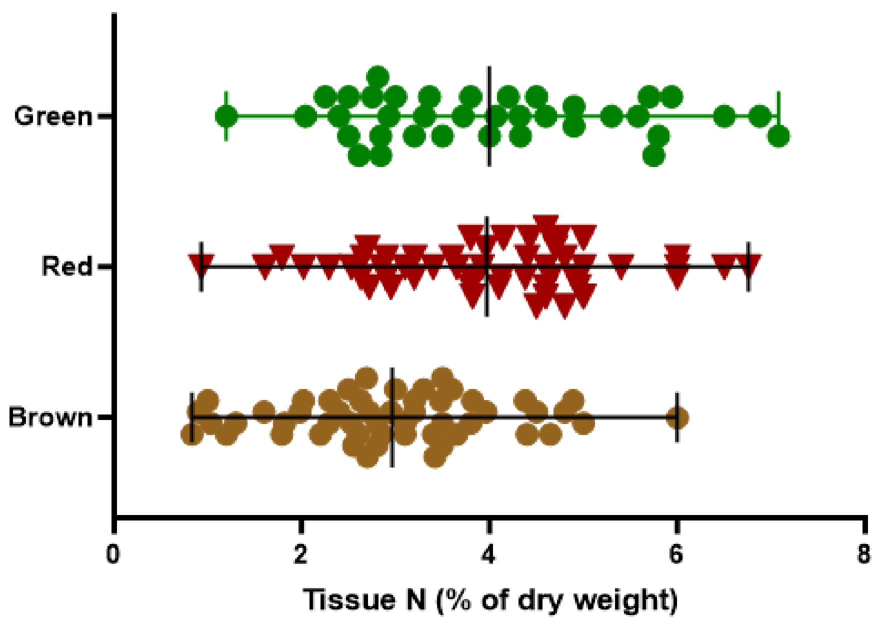

Figure 2.12. Mean and Range of maximum % N values for the three groups of macroalgae.

Growth Rate-based Ranking

Growth rate data was reported from 278 papers representing all 24 macroalgae species and all 5 bivalve species included in this project. Growth rate was reported using 13 different units (Table 2.8). These units included length-related (ex. cm per day), mass-related (ex. percent change in weight per day), and area-related measures of growth. The two most common units were: (a) % change in fresh weight (FW) per day, (b) cm per day, and (c) gram dry weight per m^2 per day. For the macroalgae species, all units except % FW per day either less than 50 data points and/or were present in less than half of the macroalgae species were excluded from consideration for growth rate-based ranking. Thus, only % FW per day was unit as the unit of analysis to compare macroalgae growth rates. The maximum % FW per day value reported per paper was used for ranking of macroalgae species. This ranking was repeated, at the level of macroalgae genus and macroalgae groups. Each maximum value was plotted against reported temperature, where available, to determine whether this potentially confounding variable was strongly correlated with maximum growth rate measurements. For the bivalve species, the unit of "cm per day" represented all three bivalve species included in this study and had the most data values; therefore, this unit was chosen to compare bivalve growth rates.

Table 2.8. Number of papers and number of species represented by different nitrogen uptake units included in Literature Review Database

Unit	Type of Unit	# Papers	# Macroalgae Species	# Bivalve Species
cm per day	length	78	13	5
% length per day	length	30	11	1
grams dry weight (gdw) per day	mass	22	11	1
grams fresh weight (gfw) per day	mass	20	11	0
gdw per m^2 per day	mass	46	11	2
gfw per m^2 per day	mass	6	2	0
kgdw per ha per day	mass	1	1	0
kgfw per m^2 per year	mass	2	2	0
ton per ha per year	mass	5	2	0
ton per year	mass	1	1	0
kgfw per m longline	mass	11	2	0

% Fresh Weight (FW) per day	mass	135	21	1
% Dry Weight (DW) per day	mass	5	4	0
% area per day	area	12	5	0

A total of 135 measurements for the growth rate unit "% FW per day" were collected across the 278 papers, and this growth rate data represented 21 out of 24 macroalgae species and 1 out of 5 bivalve species included in this study. For this unit of growth rate, there were no measurements collected for: *Cladophora albida*, *Codium fragile*, *Fucus distichus*, *Fucus spiralis, Geukensia demissa,* and *Mya arenaria*. Temperature was not significantly correlated with macroalgae growth measurements of % FW per day (p = 0.4302) (Figure 2.13).

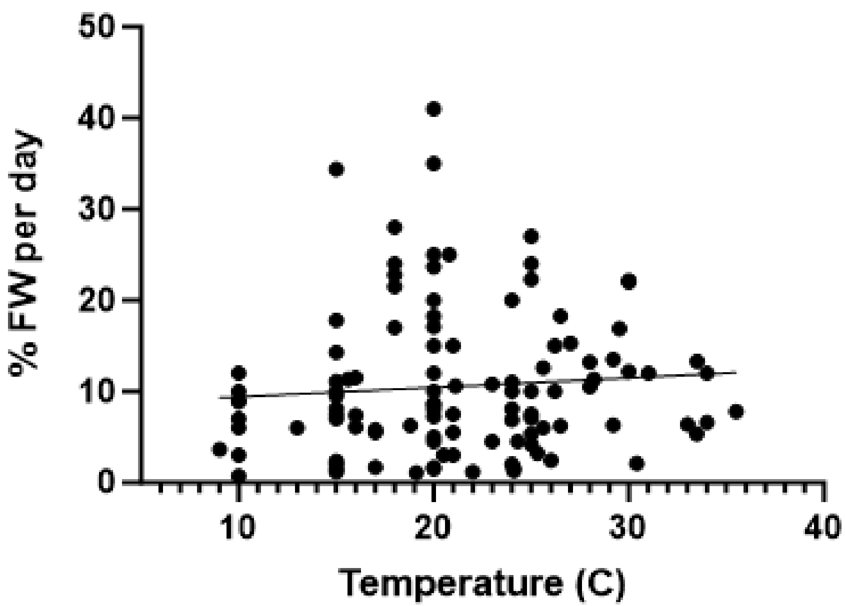

Figure 2.13. Macroalgae maximum growth rate (% FW per day) plotted against temperature

There were significant differences in mean % FW per day between macroalgae species (ANOVA: F = 2.267, p = 0.0032). At the level of species, *Ulva prolifera* had the highest mean of maximum % FW per day (Table 2.9, Figure 2.14). The top three highest % FW per day values overall belonged to *Ulva intestinalis*

(41.0%), *Ulva lactuca* (36.0%)*, and Ulva prolifera* (35.0%). At the level of genus, there were also significant differences between macroalgae (ANOVA: F = 3.475, p = 0.0002). At the level of genus, *Ulva* had the highest mean of maximum % FW per day value (Table 2.10, Figure 2.15). At the level of macroalgae group, the green algae had the highest mean % FW per day value (15.00%); and there was a significant difference between % FW in green algae compared to % FW per day values of both red algae and brown algae (ANOVA with Tukey's comparisons: p < 0.0001) (Figure 2.16). Red algae and brown algae had no significant differences in % FW per day values (ANOVA with Tukey's comparisons; p = 0.1011) (Figure 2.10).

All five bivalve species had at least one data value for growth rates measured in cm per day. *Argopectin irradians* had a higher mean maximum growth rate (0.09 cm per day) as compared to *Mya arenaria, Geukensia demissa, Ensis directus, and Spisula solidissma with* 0.06*,* 0.015, 0.013, and 0.010 cm per day, respectively (Table 2.9). However, these differences in growth rate were not significant (ANOVA with Tukey's comparisons: P = 0.4167).

Table 2.9. Ranking of Macroalgae species and ranking of Bivalve species included in this study based on Growth Rate (as measured by mean of the max percentage of fresh weight gained per day or cm gain per day)

Ranking	Macroalgae Species (% FW per day)	Bivalve Species (cm per day)
1	***Ulva prolifera***	***Argopectin irradians***
2	***Ulva rigida***	***Mya arenaria***
3	***Ulva intestinalis***	***Geukensia demissa***
4	***Ulva lactuca***	***Spisula solidissma***
5	***Porphyra umbilicalis***	***Ensis directus***
6	*Cladophora sericea*	
7	*Porphyra purpurea*	
8	*Hypnea musciformis*	
9	*Porphyra leucosticta*	
10	*Grateloupia turuturu*	
11	*Gracilaria tikvahiae*	
12	*Gracilaria vermiculophylla*	
13	*Mastocarpus stellatus*	
14	*Sargassum muticum*	
15	*Sargassum filipendula*	

16	*Saccharina latissima*	
17	*Palmaria palmata*	
18	*Chondrus crispus*	
19	*Fucus vesiculosus*	
20	*Fucus spiralis*	
21	*Ascophyllum nodosum*	
ND	*Cladophora albida*	
ND	*Codium fragile*	
ND	*Fucus distichus*	

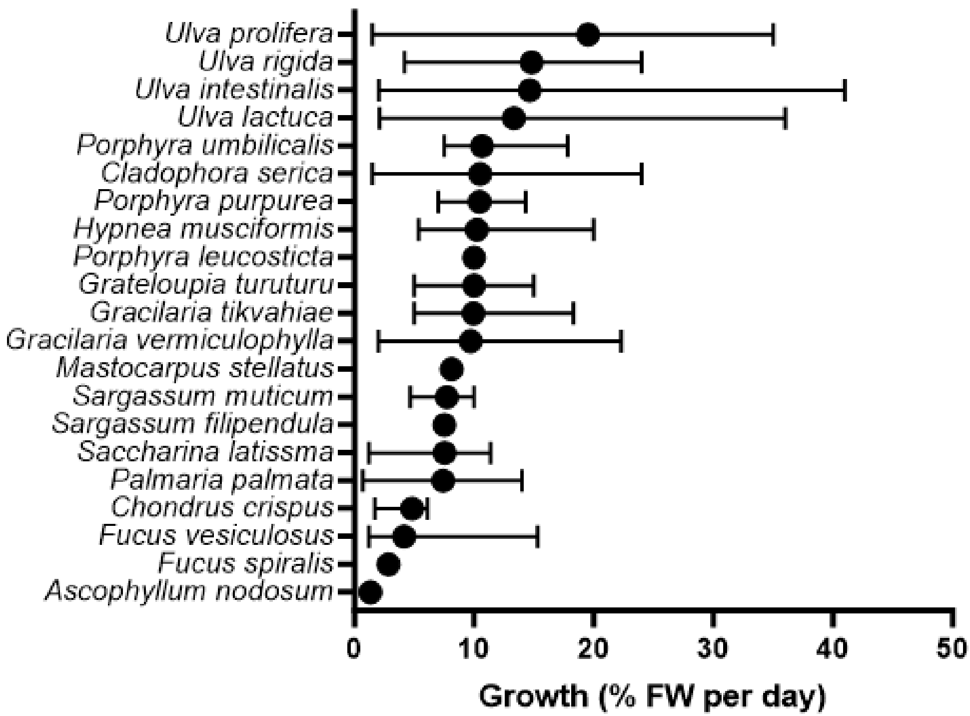

Figure 2.14. Mean and Range of maximum % FW per day values for macroalgae species included in this study.

Table 2.10. Ranking of Macroalgae genera and ranking of Bivalve genera included in this study based on Growth Rate (as measured by mean of the max percentage of fresh weight gained per day and max cm gained per day)		
Ranking	**Macroalgae Genus**	**Bivalve Genus**
1	***Ulva***	***Argopectin***
2	***Porphyra***	***Mya***
3	***Cladophora***	***Geukensia***
4	***Hypnea***	***Spisula***
5	***Grateloupia***	***Ensis***
6	*Gracilaria*	
7	*Mastocarpus*	
8	*Sargassum*	
9	*Saccharina*	
10	*Palmaria*	
11	*Chondrus*	
12	*Fucus*	
13	*Ascophyllum*	

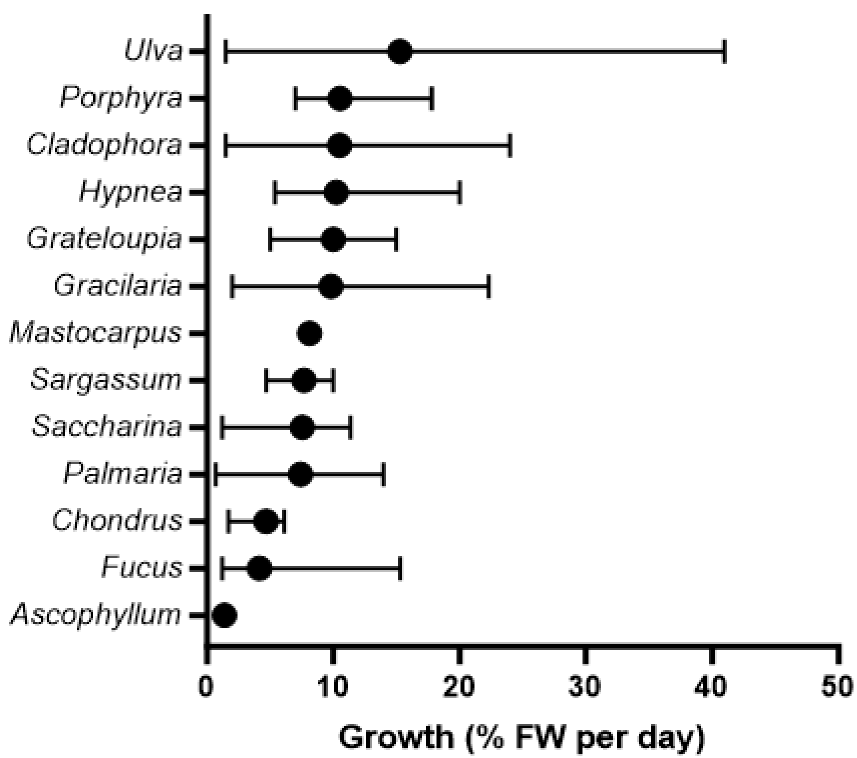

Figure 2.15. Mean and Range of maximum % FW per day values for macroalgae genera included in this study.

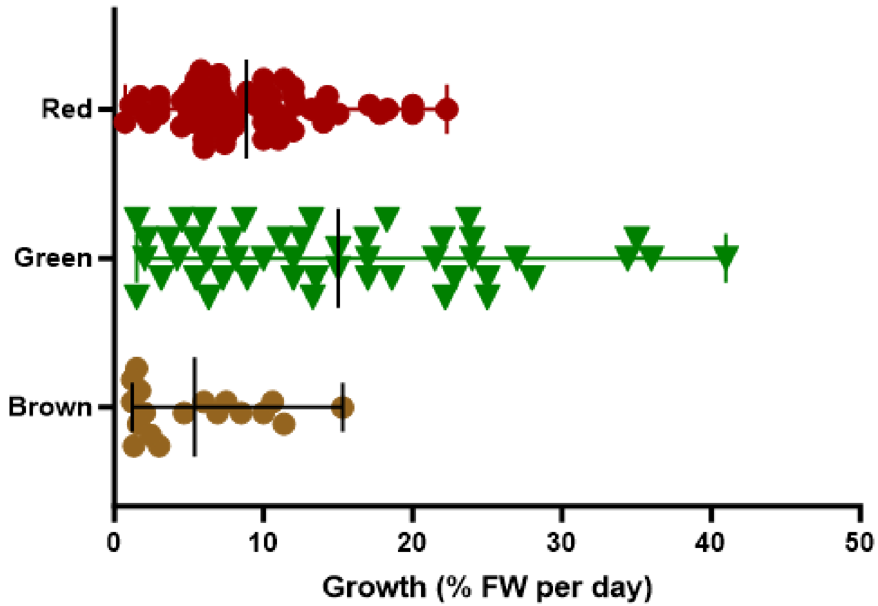

Figure 2.16. Mean and Range of maximum % FW per day values for the three groups of macroalgae.

Habitat Suitability-based Ranking

Minimum and maximum temperature and salinity values (both in field measurements and temperatures held for experiments) were summarized for all species. For 3 species, *Mastocarpus stellatus*, *Porphyra purpurea*, and *Porphyra umbilicalis*, minimum and/or maximum salinity tolerances were not able to be summarized from the data in the literature database. Thus, values from pre-print papers regarding *Mastocarpus* and dissertations and peer-reviewed papers of other species of *Porphyra* were used (Stekoll 1999; Eppley & Cyrus 1960; Coyle et al. 2023; Lin 2000). These values, presented in Table 2.11 below, were used to define lower and upper temperature and salinity tolerances for each species.

Table 2.11. Upper and Lower Temperature and Salinity tolerances used for Habitat Mapping				
	Reported Temperature (°C)		**Reported Salinity (PPT)**	
Species Level Analysis	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Ascophyllum nodosum	0.0	28.0	5	35
Chondrus crispus	0.0	30.0	5	45
Cladophora albida	0.0	40.0	0	60
Cladophora sericea	0.0	30.0	0	34
Codium fragile	0.0	30.0	6	48
Fucus spiralis	0.0	28.0	3	35
Fucus vesiculosus	0.0	28.0	0	35
Fucus distichus	0.0	23.8	0	45
Gracilaria tikvahiae	0.0	36.0	6	42
Gracilaria vermiculophylla	1.0	35.0	5	40
Grateloupia turuturu	3.0	32.3	12	52
Hypnea musciformis	6.0	33.0	13	37
Mastocarpus stellatus	0.0	30.0	5	34
Palmaria palmata	0.0	22.0	15	40
Porphyra leucosticte	0.0	25.0	10	29
Porphyra purpurea	5.0	25.0	10	40
Porphyra umbilicalis	0.0	25.0	10	40
Saccharina latissimi	0.0	25.0	10	35
Sargassum filipendula	0.0	35.0	5	42
Sargassum muticum	2.0	30.0	5	38
Ulva intestinalis	0.0	30.0	8	42
Ulva lactuca	0.0	32.0	5	40
Ulva prolifera	2.0	30.0	0	40
Ulva rigida	0.0	35.5	0	42
Argopectin irradians	0.0	31.7	0	36
Geukensia demissa	0.0	40.0	5	75
Mya arenaria	0.0	30.0	4	34
Spisula solidissma	2.0	29.0	5	32
Ensis directus	3.0	29.0	5	35

Most macroalgae species (14 out of 24) had temperature tolerances greater than both the minimum (1.8°C) and maximum (25.6°C) monthly temperatures for LIS; however, for the remaining 10 macroalgae species, the maximum or minimum monthly temperature fell outside of their tolerance (Table 2.11). All 3 bivalve species had temperature tolerances greater than both the minimum and maximum monthly temperatures for LIS (Table 2.11). All macroalgae species and all bivalve species had an upper salinity tolerance greater than the maximum monthly salinity for LIS (31.4 PPT); however, only 6 macroalgae species (*Cladophora albida*, *Cladophora sericea*, *Fucus distichus*, *Fucus vesiculosus*, *Ulva prolifera*, and *Ulva rigida*) and one bivalve species (*Argopectin irradians*) had a lower salinity tolerance greater than the minimum monthly salinity for LIS (0.1 PPT) (Table 2.11) for the remaining 18 macroalgae species, the maximum or minimum monthly salinity fell outside of their tolerance (Table 2.11). Thus, only maximum temperature tolerance, minimum temperature tolerance, and minimum salinity tolerance were used to create Habitat Maps.

For each species, a new raster layer was created where a value of 1 was assigned if the maximum temperature tolerance, minimum temperature tolerance, and minimum salinity tolerance temperature was greater than the minimum and maximum temperature or salinity measurements for that pixel, and a value of 0 was assigned if the maximum temperature tolerance, minimum temperature tolerance, and minimum salinity tolerance temperature was less than the minimum and maximum temperature or salinity measurements for that pixel. Pixels with a value of 1 should be considered potentially suitable habitat for year-round growth/survival of the species based on temperature and salinity tolerance. See an example potential habitat map created for *Sargassum muticum* provided in Figure 2.17 below. Then the percentage of map pixels (out of 3,331 total map pixels) that had a value of 1 was calculated as a measure of the amount of habitat in LIS that each macroalgae species could inhabit. These percentages were then ranked numerically where the highest percent coverage was given the rank of 1 (Table 2.12). Species with identical percent coverage were given the same rank number. This ranking was repeated for the bivalve species. For genus-level and macroalgae group-level analysis, the most wide-ranging temperature and salinity tolerances were selected for mapping and ranking.

Five macroalgae species (*Cladophora albida*, *Cladophora sericea*, *Fucus distichus*, *Fucus vesiculosus*, and *Ulva rigida*) shared the top ranking and have potentially suitable habitat across all pixels of the LIS map (Table 2.12). In contrast, three macroalgae species (*Hypnea musciformis*, *Palmaria palmata*, and *Porphyra purpurea*) had no pixels that were marked as potentially suitable habitat (Table 2.12). For each of these, temperature tolerances were the limiting factor. For *Palmaria palmata*, the upper temperature tolerance was lower than the minimum summer monthly temperature in the LIS map. Whereas for *Hypnea musciformis* and *Porphyra purpurea*, the lower temperature tolerance was higher than the maximum winter temperature in the LIS map. At the genus level, *Cladophora*, *Fucus*, and *Ulva* shared the top ranking and have potentially suitable habitat across all pixels of the LIS map (Table 2.13). At the level of macroalgae group, the green algae and the brown algae have species that have potentially suitable habitat across all pixels of the LIS map, and the red algae have species that have potentially suitable habitat across most (> 99%) pixels of the LIS map (Table 2.14).

For the bivalve species, *Argopectin irradians* had the top ranking and has potentially suitable habitat across all pixels of the LIS map (Table 2.15). Both *Mya arenaria, Geukensia demissa,* and *Spisula solidissma* have potentially suitable habitat across most (> 95%) pixels of the LIS map. However, because of the higher low salinity threshold of *Ensis directus*, only 17% of LIS habitat was marked as potentially suitable. Because there is only one representative species per bivalve genus in this analysis, the genus level rankings are the same as the species level rankings (Table 2.16).

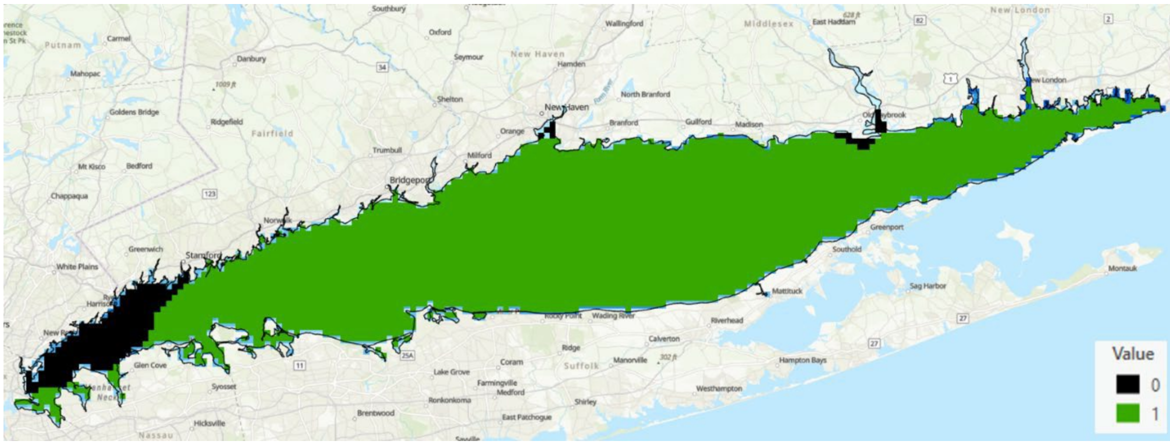

Figure 2.17. Example Habitat Map for *Sargassum muticum*. Pixels marked as ”0” and highlighted black on the map are potentially unsuitable habitat for *S. muticum*. Pixels marked as ”1” and highlighted green on the map are potentially suitable habitat for S. *muticum*.

Table 2.12. Potential Habitat in LIS and Habitat Availability Ranking for Macroalgae species

	Habitat within temperature and salinity tolerance		
Species	**# pixels**	**% pixels**	**Ranking**
Ascophyllum nodosum	3315	99.5	2
Chondrus crispus	3315	99.5	2
Cladophora albida	3331	100.0	1
Cladophora sericea	3331	100.0	1
Codium fragile	3315	99.5	2
Fucus distichus	3331	100.0	1
Fucus spiralis	3315	99.5	2
Fucus vesiculosus	3315	100.0	1
Gracilaria tikvahiae	3315	99.5	2
Gracilaria vermiculophylla	3315	99.5	2
Grateloupia turuturu	590	17.7	7
Hypnea musciformis	0	0.0	8
Mastocarpus stellatus	3315	99.5	2
Palmaria palmata	0	0.0	8
Porphyra leucosticta	1493	44.8	5
Porphyra purpurea	0	0.0	8
Porphyra umbilicalis	1493	44.8	5
Saccharina latissima	1493	44.8	5
Sargassum filipendula	3315	99.5	2
Sargassum muticum	3123	93.8	4
Ulva intestinalis	3315	99.5	2
Ulva lactuca	3315	99.5	2
Ulva prolifera	3139	94.2	3
Ulva rigida	3331	100.0	1

Table 2.13. Potential Habitat in LIS and Habitat Availability Ranking for Macroalgae genera			
	Habitat within temperature and salinity tolerance		
Genus	**# pixels**	**% pixels**	**Ranking**
Ascophyllum	3315	99.5	2
Chondrus	3315	99.5	2
Cladophora	3331	100.0	1
Codium	3315	99.5	2
Fucus	3331	100.0	1
Gracilaria	3315	99.5	2
Grateloupia	590	17.7	4
Hypnea	0	0.0	5
Mastocarpus	3315	99.5	2
Palmaria	0	0.0	5
Porphyra	1493	44.8	3
Saccharina	1493	44.8	3
Sargassum	3315	99.5	2
Ulva	3331	100.0	1

Table 2.14. Potential Habitat in LIS and Habitat Availability Ranking for Macroalgae group			
	Habitat within temperature and salinity tolerance		
Group	**# pixels**	**% pixels**	**Ranking**
Green	3331	100.0	1
Brown	3331	100.0	1
Red	3315	99.5	2

Table 2.15. Potential Habitat in LIS and Habitat Availability Ranking for Bivalve species			
	Habitat within temperature and salinity tolerance		
Species	**# pixels**	**% pixels**	**Ranking**
Argopectin irradians	3331	100.0	1
Geukensia demissa	3315	99.5	2
Mya arenaria	3315	99.5	2
Spisula solidissima	3139	94.2	3
Ensis directus	590	17.7	4

Table 2.16. Potential Habitat in LIS and Habitat Availability Ranking for Bivalve Genera			
Species	**Habitat within temperature and salinity tolerance**		**Ranking**
	# pixels	**% pixels**	
Argopectin	3331	100.0	1
Geukensia	3315	99.5	2
Mya	3315	99.5	2
Spisula	3139	94.2	3
Ensis	590	17.7	4

Combined Ranking

Three parameters were used for a combined ranking: (1) potential nitrogen uptake (rank from mean values of percent nitrogen in tissue), (2) growth rate (rank from mean values of growth rate as measured by daily percent increase in fresh weight), and (3) habitat suitability (rank from percent of pixels of LIS temperature and salinity maps that could support species growth). Each of these parameters was weighted equally for a combined ranking, and ties were broken using the rank value from potential nitrogen extraction ranking. Because *Spisula solidissma* and *Ensis directus* had no nitrogen uptake data, they were excluded from the ranking analysis. A combined ranking was conducted at both the species and genus level. The top 5 species and genera are shown in Table 2.17 below.

Table 2.17. Final Ranking of Macroalgae and Bivalve species based on nitrogen extraction Potential, growth rate, and habitat availability

Top 5 Rank	Macroalgae Species	Macroalgae Genus	Bivalve
1	*Ulva prolifera*	*Porphyra*	*Mya arenaria*
2	*Ulva lactuca*	*Ulva*	*Argopectin irradians*
3	*Cladophora sericea*	*Cladophora*	*Geukensia demissa*
4	*Porphyra umbilicalis*	*Gracilaria*	-
5	*Ulva intestinalis*	*Chondrus*	-

Conclusions

Literature Review

The objective of Task 1 was to update and expand upon the current collection of macroalgae and mollusk species with high bioextraction interest found in "Selected Summaries of Nutrient Bioextraction Peer-Reviewed Journal Articles" (NYSDEC, n.d.). Using a "snowball" approach in conjunction with a "key term" search method, 9,027 unique papers were screened with 238 papers on nitrogen uptake being identified and compiled into a database. Additional papers were included in the database with data on seaweed environmental parameters and tolerances, growth rates, and potential for heavy metal uptake that may be of use to various stakeholders. This database of 653 papers is sorted by several variables and includes citation and weblinks where available for easy access to the source manuscripts.

There were two key takeaways learned through this literature review. The first takeaway is that some macroalgae and bivalve species lack data on several nitrogen uptake or other environmental parameters. In particular, *Hypnea musciformis*, *Grateloupia turuturu*, *Cladophora albida,* and *Mastocarpus stellatus* either had no nitrogen uptake data, salinity data, or growth data that could be used in the ranking analysis. Similarly, all the non-commercially utilized bivalve species identified in this study had far fewer papers relative to macroalgae, and there were even fewer bivalve papers that had relevant information for inclusion in this database. Thus, a clear knowledge gap exists in a subset of macroalgae species and most non-commercial bivalves, within which opportunity exists for future research to make meaningful contributions and impact to the field of bioextraction and to the aquaculture industry.

The second key takeaway is that the papers compiled in this literature database likely represents the majority of the data that has been published. The use of additional key-terms during the key-terms search yielded very few additional papers to be included in the database. Additionally, of the 8,236 unique papers screened from the snowball search, only 381 (4.6%) were inaccessible for further screening. Although it is unlikely that all 381 papers would have contained information relevant to this study, commitment to and funding for open-access publishing will help alleviate this issue for future investigations. An exception to this conclusion may be data for the macroalgae species *Porphyra leucosticta*. The key term used to search for this species included '*Porphyra*', even though this species has recently been reclassified to the genus '*Pyropia*'. Thus, data on this one species is underrepresented in the literature database due to exclusion of recent papers which only used the genus '*Pyropia*' within the text of the publication.

Habitat Mapping

Habitat mapping of potential suitable environments for Long Island Sound macroalgae and bivalve species was conducted using ArcGIS. The term "potentially suitable" here should be interpreted cautiously as a preliminary description of areas based on current available data because the universe of all environmental and social factors that must be considered in the expansion of macroalgae aquaculture in Long Island Sound is presently unknown. Another consideration is that social factors, such as water accessibility and regulatory restrictions were not fully explored in this study. Habitat mapping also did not include wave action due to limited available data on the impact of wave action on growth or survival of individual macroalgae species. Physical environmental variables, such as wave action, storm events, and current speed are notable considerations as many macroalgae bear delicate thalli (e.g., *Ulva* spp., *Porphyra* spp.), making them especially vulnerable to damage from such factors in aquacultural settings. The present habitat mapping also did not take into consideration water depth because it was assumed that all current and future methods of macroalgae cultivation could utilize buoyed lines or nets at or near the sea surface. However, depth would be a practical consideration for any entity exploring the feasibility of a large-scale seaweed cultivation operation in Long Island Sound. For example, overhead costs for infrastructure and maintenance are likely to scale up considerably as utilized depth increases, and so, it is likely that any operator will prioritize being as near shore as possible when establishing an operation to minimize fuel costs and damages associated with physical factors (e.g., wind, waves, storms). Thus, taken together, while the tolerances of the recommended species in this work to the environmental factors explored may suggest 95% or more of LIS is suitable, in reality, there may be a fairly narrow band of nearshore areas along the New York and Connecticut shorelines that are actually practical for operation. In conclusion, future efforts at habitat mapping should take into account various physical variables and depth, which are likely to be key limiting factors in macroalgae crop yields. Data derived from community science-based and citizen science-based projects and ongoing programs were instrumental to the completion of the salinity tolerance habitat mapping in the present work. However, several recreationally active embayments along the north and south coast of LIS did not have any discrete data available that could be incorporated into the interpolation model. Consequently, this model could be significantly improved in the future by incorporating such data from embayments along LIS coasts. Outreach efforts may continue to provide invaluable data, such as temperature, pH, dissolved oxygen, and wave action that can complement future habitat mapping endeavors, especially in understudied embayments where macroalgae and bivalve farms are likely to become established. Thus, funding and outreach for continued and expanded community-based environmental monitoring will significantly improve such models and aid future efforts for more refined habitat suitability modeling.

Finally, the habitat mapping in this study assumes that macroalgae and bivalve species can tolerate the temperature and salinity constraints for year-round survival and growth in LIS. It should be noted that some species, such as *Saccharina latissima*, must be reseeded every year and are only grown within colder seasons. In contrast, most *Ulva* species are likely to grow relatively year-round. Thus, due to this variability across species, the area of potential suitable habitat for some species may be greater than what is displayed via this analysis. With these restraints, however, the analysis did find that most species (18 out of 24) were able to grow within most of the open waters of LIS (> 94% of the pixels of the LIS boundary). Species with less than 50% pixels of LIS marked as suitable habitat were restricted either by summer temperatures (i.e. LIS is too warm during the summer) or minimum salinity (i.e. coastal areas with too much freshwater influence).

Final Ranking and Recommendations

The final ranking of macroalgae species was conducted at the species, genus, and division (or group) level. A species-level ranking was important to identify optimal algal types in regard to nitrogen uptake potential and growth rate. However, we acknowledge that, in practice, some algal species within the same genus (e.g., *Porphyra* spp., *Gracilaria* spp., *Ulva* spp., and possibly some *Fucus* spp.) are nearly impossible to distinguish in the field probably without access to molecular techniques. Thus, the genus-level ranking is recommended for continued work as it may be more useful to the broadest range of stakeholders. Even though *Porphyra* was listed as the #1 ranked genus in the mathematical ranking that considered all three aspects of study (potential nitrogen uptake, growth rate, and habitat availability), habitat availability in LIS is predicted to be quite limited for some *Porphyra* species due to temperature constraints. Thus, we recommend species of *Ulva* and *Cladophora* to be better candidates for potential commercial cultivation and bioextraction within LIS.

Of three species of bivalves, *Mya arenaria* emerged as the top bivalve for potential bioextraction within LIS. However, this ranking is based on much more limited data. It is interesting to note that all three species of bivalves had a potential nitrogen uptake value (6.01, 6.80, and 10.25%) (as measured by percent nitrogen incorporated into tissues) that was much greater than the highest macroalgae potential nitrogen uptake value (4.33%). Based on this one metric, these bivalve species may have a greater impact on nitrogen bioremediation than macroalgae. However, bivalves take a couple of years to grow to harvestable size (compared to most macroalgae which take less than one-year for harvest), which may reduce the overall bioextraction potential of these bivalves as compared to the macroalgae included in this study.

Overall, the green algae (*Ulva* spp. and *Cladophora* spp. primarily) emerged as the top group for potential nitrogen bioextraction within LIS. The green algae had the overall highest potential nitrogen uptake (as measured by percent nitrogen incorporated into tissues) as well as having the highest growth rates (as measured by daily percent increases in fresh weight). The other group of top-ranking macroalgae were members of the red algae (*Porphyra* spp. and *Chondrus* spp. primarily). These two genera also had high potential nitrogen uptake rates, but more slowly as compared to the green algae. Of these top five genera, *Ulva*, *Cladophora*, and *Chondrus* were projected to have the majority occupancy of LIS as potentially suitable habitat. Thus, it is suggested that *Ulva* spp. presents a top candidate for nutrient bioextraction, which is in-line with other sectors of aquaculture, many of which already employ *Ulva* species to remove excess nitrogen within Integrated Multi-Trophic Aquaculture (IMTA) systems for both bivalve and fish production (Ben-Ari et al. 2014, Lawton et al. 2013, Nardelli et al. 2019; Al-Hafedh et al. 2015).

Despite recent regional interest in promoting *Saccharina latissima* (sugar kelp) as a food crop, this species is not projected to be especially impactful for nutrient bioextraction compared to other LIS species. Sugar kelp ranked middle or low in all three categories for ranking (potential nitrogen uptake, growth rate, and habitat suitability). For example, nitrogen uptake for sugar kelp averaged approximately 3% of its tissue as nitrogen, versus *Ulva* spp. which averaged approximately 4% of its tissue as nitrogen. Growth rate for sugar kelp averaged approximately 7.5% daily increase in fresh weight, versus *Ulva* spp. which averaged approximately 15% daily increase in fresh weight. Sugar kelp also had limited habitat availability due to lower temperature tolerances and lower tolerances to low salinity.

Global climate change is likely to have a substantial impact on the presented ranking by altering the amount of available suitable habitat available for growth. Some macroalgae may not be suited to LIS waters in future decades due to increased ocean warming. *Saccharina latissima*, all three *Porphyra* species, and *Palmaria palmata* all had reported temperature tolerances below the monthly maximum SST measured for LIS. Although *Porphyra* was a top-ranking genus, it had one of the lowest temperature-based habitat rank. For *Palmaria palmata*, the listed heat tolerance (22°C) was less than the monthly maximum across all pixels of the LIS map. Thus, LIS may already be too warm to support long-term growth/survival of *Palmaria palmata*, a primarily Artic species. On the other hand, increased ocean warming may open more suitable habitat for some macroalgae species. For example, *Porphyra purpurea* had a listed cold tolerance that was above the minimum monthly temperature across all pixels of the LIS map. Additionally, typically southern genera, such as *Hypnea* spp. and *Sargassum* spp., may become better suited to LIS in future decades. Thus, selection of species to target and invest in greater nutrient bioextraction will need to take ocean warming into close consideration, and where possible, efforts should be made to identify and cultivate more thermally resistant strains of species with high nitrogen uptake potential.

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CHAPTER 3: MARKETING AND REGULATORY ANALYSIS

Introduction

We begin this section with a brief overview of the benefits and challenges for seaweed, followed by an evaluation of the product market sectors and our recommendation as to the market sectors worth pursuing for a more detailed study as it pertains to seaweed production in the Long Island Sound. Our evaluation of the product market sectors includes variables such as potential demand, pricing, competition, consumer perceptions, and business feedback on the seaweed industry. We end this section of the report with a brief value chain analysis, followed by a summary of our recommendations regarding product market sectors worth pursuing in the short term. The product market sectors we recommend worth pursuing in the short term in the Long Island Sound region for potential seaweed-based businesses include bio stimulants, pet food, and cosmetics. We conclude the Task 2 section with suggested directions for future research.

SEAWEED AND SHELLFISH BENEFITS AND CHALLENGES

Seaweed and shellfish have garnered increasing attention for their diverse properties and potential applications across various product sectors. While traditionally recognized for their nutritional value, recent research has shed light on their bioactive compounds and industrial uses.

This general literature review examines the diverse properties of seaweed and shellfish that hold promise for various product sectors, including health-related products, biostimulants in horticulture, bio- plastics, pharmaceuticals, and construction. Seaweed and shellfish contain many bioactive compounds and nutrients with potential uses in disease prevention, nutrition, and industrial processes. Drawing from a brief review of the literature, this review highlights the bioactive components, health-promoting molecules, and industrial potential of seaweed and shellfish, while also addressing challenges and future research directions in harnessing their benefits across multiple sectors.

Seaweed and Shellfish Benefits

Bioactive Components of Seaweed

Seaweed is rich in bioactive compounds such as polysaccharides, unsaturated fatty acids, phenols, peptides, terpenoids, vitamins, minerals, pigments, and proteins, which exhibit various health-promoting effects including antioxidant, anti-inflammatory, anti-cancer, antimicrobial, antiviral, and anti-diabetic benefits. These bioactive components make seaweed an attractive source of natural ingredients for disease prevention and therapeutic interventions, offering potential alternatives to conventional drugs with fewer side effects (Irkin and Yayintas 2018).

Nutritional Value of Seaweed and Shellfish

Seaweeds are packed with essential nutrients including dietary fiber, omega-3 fatty acids, essential amino acids, vitamins (A, B, C, D, and E), minerals (calcium, phosphorous, sodium, potassium), and trace elements, making them a valuable addition to the diet and potentially beneficial for human health (Murphy and Dow 2021) In addition, shellfish are abundant in high-quality proteins, essential amino acids, bioactive peptides, astaxanthin, carotenoids, long-chain polyunsaturated fatty acids, and vitamin B12, all of which contribute to their nutritional value and health benefits.

Industrial Applications of Seaweed and Shellfish

Beyond their nutritional value, seaweed and shellfish exhibit industrial potential in various sectors including food, nutraceuticals, pharmaceuticals, cosmetics, biostimulants in horticulture, bio-plastics, and construction. Seaweed's diverse chemical composition, including pigments, polysaccharides, antioxidants, and polyphenols, makes it suitable for a wide range of industrial applications, while shellfish provide protein-rich raw materials for pharmaceuticals and other industries.

Seaweed and shellfish possess a wealth of properties that make them valuable resources for multiple product sectors, including health-related products and industrial applications. While their nutritional benefits have long been recognized, ongoing research is uncovering new opportunities for their use in pharmaceuticals, cosmetics, biostimulants, bio-plastics, and construction materials. However, challenges such as technology, sustainability, scalability, and regulatory considerations must be addressed to fully realize the potential of seaweed and shellfish across diverse sectors. While the use of seaweed in the food industry has been widespread, the applications in other product sectors such as biostimulants in horticulture, bio plastics, pharmaceuticals, and construction are in the initial stages and further research to develop new products globally is ongoing.

In addition to the properties of seaweed that enable value addition by serving as an ingredient in multiple products, there are other advantages as well. These include environmental and economic advantages.

Environmental Advantages of Seaweed Cultivation

Regenerative Nature: Seaweed exhibits rapid growth rates and can be cultivated in coastal habitats or land-based systems without competing for land, freshwater, or nutrient resources, making it an environmentally appealing alternative to terrestrial crops (Lorbeer, Tham, & Zhang 2013).

Eco-Friendly Products: Seaweed meets the demands of environmentally conscious consumers as a vegan and recyclable marine-based component, offering eco-friendly alternatives to conventional materials and promoting sustainability (El-Beltagi et.al. 2022).

Biomaterials and Cosmeceuticals: Seaweed-derived polysaccharides have been explored for various applications in biomaterials, cosmetics, and pharmaceuticals, offering biodegradable and biocompatible alternatives to synthetic materials and contributing to the economy (Ali, Ramsubhag, & Jayaraman 2021).

Economic Advantages for Coastal Communities

Additional Income: Seaweed cultivation provides an additional source of income for fishermen during off-seasons and offers economic diversification opportunities for traditional fishing communities, oyster, mussel, and fish farmers (Bolduc, Griffin, & Byron 2023).

Economic Diversification: Seaweed farming can serve as an economically viable alternative to traditional fisheries, providing opportunities for rural coastal areas to diversify their economies and mitigate the impacts of climate change on seafood industries (Lawrence 2023).

Market Opportunities: Advanced aquaculture techniques enable seafood companies to meet the rising demand for shellfish products both domestically and globally, creating new market opportunities and fostering economic growth in the seafood industry.

Seaweed and Shellfish Challenges:

Pollutants-related Challenges

Seaweed consumption must be approached with caution due to the potential presence of hazardous pollutants such as heavy metals and toxic compounds, which can pose health risks to consumers (Circuncisao, Catarino, Cardoso, & Silva, 2018). Contamination of seaweed biomass by pollutants threatens its use in agricultural applications, highlighting the need for stringent quality control measures (Kulsreshtha, Hincke, Prithiviraj, & Critchley 2020). In addition, High sodium levels in seaweed consumption raise concerns, particularly in regions where dietary sodium intake exceeds recommended levels.

Production-related Challenges

Seasonal variability impacts the nutritional profile of seaweeds, posing challenges in maintaining consistency in bioactive compounds for feed supplements. Harvesting, processing, and storage of seaweed biomass also present significant logistical challenges, necessitating advancements in technology and infrastructure. Inadequate technology and unpredictable biomass volume and quality also hinder large-scale seaweed production, limiting its commercial viability.

Consumer and Technological Challenges

Consumer Perceptions and Knowledge: Limited public awareness and misconceptions surrounding seaweed aquaculture hinder market growth and consumer acceptance. Concerns about aesthetic pollution and potential conflicts with existing ocean resource stakeholders contribute to apprehension towards seaweed farming. In addition, lack of consumer understanding and familiarity with seaweed products impedes market expansion and adoption (Bolduc, Griffin, & Byron).

Quality and Authenticity Concerns**:** The proliferation of spurious seaweed products containing synthetic components undermines consumer trust and highlights the need for strict quality standards and certification processes. Technological solutions such as iodine reduction and purification processes can mitigate the impact of pollutants and ensure product safety and authenticity.

PRODUCT MARKET SECTORS

Identification of Market Sectors

Our initial task as identified in the Quality Assurance Project Plan was to perform a market potential analysis for eight different market sectors: fresh food, dried food, fertilizer for both food and non-food, animal feed, cosmetics, pharmaceuticals, and biofuels. Based on a combination of interviews, survey data, and secondary research we recommend biostimulants, pet food, and cosmetics as the product market sectors with the most potential for the short term. Other market sectors may be considered for the medium- or long-term depending on the level and direction of development of the seaweed industry in the Long Island

Sound. The rationale and the analysis that led to our recommendation is detailed in the following sections of this report.

Technology

Seaweed and its products like agar and carrageenan are well established in the food market sector. However, the use of seaweed and its extracts in market sectors beyond food is continuously evolving and likely to continue to grow in the future. Given the multiple species of seaweed, the variations in composition, variations in the conditions for growing seaweed, and the evolving nature of the industry, it is beyond the scope of this report to comment on the technology required for the processing of seaweed in a specific sector. However, in certain market sectors such as biostimulants, fresh food, dried food, animal feed, pet food, and cosmetics, the technology for processing mainly consists of drying, milling, fermentation, extraction, and purification. It is recommended that future research include the use of technology experts who can more appropriately comment on processes that take raw seaweed and convert them through extractive methods into downstream products that can serve as inputs across multiple market sectors.

Key Factors to Consider in Market Sector Evaluation:

The key variables that we considered in evaluating different market sectors include the following:

Market size: While some sectors we examined are in the initial stages, we obtained estimates of market size from secondary sources such as the World Bank research report on seaweed.

Value addition: To penetrate market sectors, seaweed must be able to add value to the product compared to other products available in the market sector. For example, the benefits to pet owners provided by adding seaweed to pet food must be substantial enough to consider pet food as a potential market.

Price realization: The marketing of seaweed without value addition will result in much lower price realizations for the seaweed farmer adversely affecting the economic feasibility of growing seaweed. In evaluating a market sector, we consider the level of possible price realizations for seaweed in that sector.

Demand levels: Given the uncertainty of production quantities of seaweed in the Long Island Sound, the potential of a particular market sector would depend on the quantity of seaweed that can be produced. For example, sectors such as fabrics may require quantities of seaweed that may not be feasible to produce in the Long Island Sound region, at least in the short term.

Processing complexity: While details of processing complexity and technology for each market sector are beyond the scope of this report, we rely on secondary sources to identify market sectors that have relatively lower barriers to entry and are more feasible in the short term.

GLOBAL OVERVIEW OF SEAWEED MARKET SECTORS

The global market for seaweed is indeed promising and the global production of seaweed is estimated at 36 million tons wet weight (FAO 2022). The largest genera by tons of wet weight include *Saccharina*, *Encheumatoids*, *Gracilaria*, *Pyropia*, and *Undaria*. Currently, more than 90 percent of the seaweed produced globally is produced by four countries: China (56% of global supply), Indonesia (27 % of global supply), South Korea (4% of global supply), and the Philippines (4% of global supply).

While commercial seaweed production has grown substantially over the last fifty years, and by some estimates tripled over the last twenty years, there has been relatively little innovation in the farming of seaweed. In addition to the lack of innovation in farming and environmental factors, such as climate change, some estimates suggest a stagnation in seaweed production unless environmental and technological factors are addressed for both seaweed production and downstream products in various market sectors that could use seaweed. There are some nascent signs of technological investment with current estimates of 200 startups related to the downstream use of seaweed in Europe, North America, Australia, and New Zealand (Hermans 2023).

The estimates of global market potential for seaweed by 2030 in various sectors beyond the more mature sectors of food and food additives, projected by the World Bank are as follows (World Bank Group, 2023):

Table 3.1: Global Market Potential by Sector

Product Market Sector	2030 Global Market Potential
Bio stimulants	$1875 million
Animal Feed	$1122 million
Pet Food	$1078 million
Nutraceuticals	$3954 million
Alternative Proteins	$448 million
Fabrics	$862 million
Bioplastics	$723 million
Pharmaceuticals	Potential unknown
Construction	$1396 million

Next, we consider the market for seaweed in the United States and the Long Island Sound region.

Market for Seaweed in the United States and the Long Island Sound

In the United States, the seaweed industry is very much in the introductory stage, with seaweed farming in Maine and Alaska accounting for the bulk of seaweed production. In comparison to the global production of 36 million tons of wet weight seaweed, the current production in the United States is less than 1000 tons. Clearly, the industry has a long way to go in the US.

While the current level of production is low, seaweed farming is an emerging industry in the United States, with significant growth potential and large exclusive economic zone in the USA as compared to other nations (Bolduc, Griffin, & Byron, 2023). Currently in the US, there are two major areas of industry growth: Maine and Alaska (Kim et al. 2019). Since 2010, commercial cultivation of kelp *(Saccharina latissima, Laminaria digitata,* and *Alaria esculenta*) and other seaweeds (*Palmaria palmata* and *Porphyra umbilicalis*) began in the Gulf of Maine and in Alaska. Seaweed aquaculture, while tiny from a global perspective, is nevertheless a fast-growing maritime industry, with much potential in the United States (Kim, Stekoll, & Yarish, 2019). Steps are also underway to identify other economic zones that have significant potential for producing seaweed, such as those in California.

The seaweed industry in the US does face many challenges to scale up to a competitive level with other major seaweed producers such as China, Indonesia, Korea, and the Philippines. The primary challenge is the low prices at which seaweed is currently available in the global marketplace. For example, one of our interviewees based in Singapore mentioned that the average seaweed farmer in Indonesia would make a net income of less than $10,000 annually. It would not be feasible for seaweed farmers based in the United States and around the Long Island Sound to create a viable business proposition on such low levels of potential income. Hence, alternate business models that add value to the seaweed may be necessary to create a profitable business proposition. The addition of value will entail additional costs for processing and marketing. However, given the nature of the price competition, a value-added approach with innovation in technology and marketing seems more likely to be sustainable.

Given the difficulty competing on price with imports, producers in the United States must be able to compete on value addition through technology and marketing, or to compete in regional markets where they may be able to add additional value by virtue of location and time to market.

MARKET SECTOR ANALYSIS FOR THE LONG ISLAND SOUND

Based on interviews that we conducted and the secondary research, it appears that the most promising sectors that are worth further exploration in Long Island and the Connecticut and New York region include biostimulants, pet food, and cosmetics.

We expand below on the use of seaweed in each of the product market sectors and the reasons why we recommend a focus on biostimulants, cosmetics, and pet food. In evaluating the sectors, we examine the market potential, potential for value addition in Long Island, and the competitive advantage, if any, offered by farming in the Long Island region. In addition to issues of value addition, competitive advantage, and demand, it is important to realize that given the nature of regulations, the nature of the species grown, and differences in the type of farming techniques, it is hard at this initial stage to estimate the total possible production capacity of seaweed in the Long Island Sound.

The production capacity of seaweed is a critical factor that impacts the potential for downstream industries. For example, one of our interviewees mentioned that for a fabric producer to consider Long Island as a source of supply for seaweed, they would eventually need a guaranteed supply of 1500 tons of seaweed.

Given that the current total production of seaweed in the United Sates is less than 1000 tons with most of that production in Maine and Alaska, it would be premature for us to consider the feasibility of large-scale production of seaweed without additional research on the extent of the Long Island Sound available for farming, the growth rates of viable species, and potential innovations in production techniques. In addition, it is important that we establish reliability, consistency, and quality of supply for business to consider sourcing seaweed from the Long Island sound.

The market sectors for seaweed that we examined in our secondary research include fresh food, dried food, fertilizer for food and non-food, animal feed, cosmetics, pharmaceuticals, and biofuels. As we conducted our secondary research, we came across other promising sectors, such as the use of seaweed biomass in building materials in Mexico. Given this project's scope, however, and the lack of accurate data on current technology and value chains for potential new sectors, the examination of potential new sectors must be addressed in follow-up projects.

Market sectors with short-, medium- and long-term prospects

The World Bank (2023) comprehensive analysis of the global seaweed industry classified the viability of market sectors as short-, medium-, and long-term. The identification of market sectors as short-term, medium-term, or long-term by the World Bank was based on two factors: the “viability of market establishment” and “estimated market size.” The two factors in turn were based on variables such as the value addition enabled using seaweed in the industry, the availability and competitiveness of substitute products, the complexity of processing required in a particular market sector, regulations, and the likelihood of overcoming these challenges.

The classification is as follows:

Short-Term (before 2025): animal feed, biostimulants, pet food

Medium-term (2024-2028): alternative proteins, nutraceuticals, bioplastics, and fabrics

Long-Term (after 2028): pharmaceuticals and construction

In deciding on the market sectors to target for the Long Island Sound region, we decided to focus on market sectors with short-term prospects. Consequently, we began with an analysis of animal feed, biostimulants, and pet food. However, the low-price realizations and the need for potentially large quantities to meet the demand for animal feed led us to eliminate detailed consideration of the animal feed sector as well.

As we explored other potential sectors, we included the cosmetics sector which was not part of the World Bank classification but was part of the market sectors to include as part of the original project scope. In addition, preliminary analysis of the seaweed industry in Maine indicated that small businesses in Maine were already marketing cosmetics that included seaweed (Planet Botanicals, 2024).

Besides cosmetics, in our initial analysis, we did include the food sector. However, the low-price realizations for seaweed marketed as food led to focus on other sectors with more value adding potential. Processed food based on seaweed, such as seaweed snacks, may offer potential in the future. However, the difficulty of competing with imported products makes this a difficult proposition without processing and marketing investments. An interview with a local seaweed marketer based in Long Island, who has been trying to market seaweed as food for many years with great difficulty, also reinforced our decision to focus on other potential sectors.

In deciding on the sectors to identify for further interview-based research based on our secondary research and preliminary analysis, we narrowed down the list of market sectors with short-term potential to pet food, cosmetics, and biostimulants. In the following section, we discuss the potential of these three market sectors in more detail followed by a brief discussion of sectors that are not as promising in the short-term.

While the global market for some sectors, such as pharmaceuticals or nutraceuticals, are much larger, the level of processing needed for seaweed to be used in these products is not feasible with the current value chain infrastructure in the region of the Long Island Sound. In addition, pharmaceuticals and, to an extent, nutraceuticals require a higher level of technology, capital, and time and the use of seaweeds in these sectors must necessarily be a longer-term project. The use of seaweed in pharmaceuticals, for example, would need field trials and FDA approval, all of which involves a multi-year investment horizon.

Market Sectors with short-term prospects

Biostimulants

The use of seaweed-based bioproducts has been gaining momentum in crop production systems owing to their unique bioactive components and effects. Types of biostimulants include seaweed-derived fertilizers, plant performance boosters, and plant meals.

The use of seaweed as a biostimulant stimulates plant growth and development, reduces plant stress, and protects plants from disease (Sujeeth et al. 2022, Mukherjee and Patel 2020, Salehi et al. 2019). The major benefits of seaweed as a biostimulant include helping soils and crops overcome challenges from environmental stresses like heatwaves, droughts, and soil exhaustion; ensuring balanced nutrition, preventing nutrient deficiencies, and promoting overall plant health; increasing water and nutrient holding capacity; and increasing fertility (Joshi et al. 2018, Ali et al. 2021).

Other properties and benefits of seaweed include phytostimulatory properties that result in increased plant growth and yield parameters in several important crop plants and phytoelicitor activity that evoke defense responses in plants that contribute to resistance to several pests, diseases, and abiotic stresses, including drought, salinity, and cold (Ali et al. 2021). This is often linked to the upregulation of important defense-related genes and pathways in the plant system, priming the plant defenses against future attacks.

Seaweeds also evoke phytohormonal responses due to their specific components and interaction with plant growth regulation. Treatment by seaweed extracts and products also causes significant changes in the microbiome components of soil and plant in support of sustainable plant growth. Since seaweed extracts are highly organic, they are ideally suited for organic farming and environmentally sensitive crop production (Ali et al. 2021).

The types of seaweed that could potentially serve as biostimulants are a range of species including species identified in chapter one as viable in the Long Island Sound region:

- Brown macroalgae - *Ascophyllum nodosum* (rockweed), *Fucus vesiculosus* (rockweed), *Sargassum spp., Ralfsia spp., Laminaria digitata* (horsetail kelp), *Fucus spiralis* (rockweed)
- Green macroalgae - *Ulva lactuca* (sea lettuce) and *Ulva prolifera* (branched string lettuce)

The level of processing required to produce seaweed for biostimulants is typically farming of seaweed, followed by drying and extraction. Techniques for extraction from wet biomass also exist with enzymatic extraction, followed by acidic or alkaline extraction. Co-products from the process of making biostimulants may also be sold as animal feed or pet food.

Biostimulants are applied either as a powder or in liquid form. The price for biostimulants in the US ranges between $8 to $20/liter. We were unable to find data on the quantity of seaweed required to produce a liter of biostimulant and this may be an area for further research. Note to reader that the quantity of seaweed needed to produce a liter of biostimulants would likely vary depending on the seaweed genus.

A search on Amazon for seaweed biostimulants yielded many brands, most of which had positive consumer ratings of higher than 4.0 on a 5.0 scale. Our interviewees also suggest that seaweed as a biostimulant has potential in horticulture and agriculture in Long Island, especially in the luxury home sector, wherein homeowners and landscapers are willing to pay higher prices to landscape their properties. For example, one business owner reported that they are having more success selling seaweed as a biostimulant than as food for human consumption. In addition, anecdotal evidence suggests that seaweed-based biostimulants may also have potential markets in the vineyards and golf courses of Long Island if their value proposition is realized in the form of easier to maintain landscapes and enhanced vineyard productivity.

The possibility of using seaweed as a source of nitrogen-based fertilizer would be worth further exploration. Given the high level of nitrogen present in the Long Island Sound, the ability to reuse that nitrogen in the form of a biostimulant would help in recycling nitrogen for productive use as well as enhancing water quality in the Long Island Sound.

Overall, we would recommend further exploration of this market sector as this might be suitable for smaller- to medium-sized firms. The price realization is reasonable if marketed to premium market segments and small businesses regionally are seeing positive responses from customers to their marketing efforts.

Pet Food

According to the World Bank 2023 research report on the use of seaweed in the pet food industry, the global pet food market was $115.5 billion in 2022 and the projected share of seaweed-based pet food market is projected to be $1.08 billion in 2030. Claims made by marketers regarding pet food are indicative of what marketers think that consumers value in their products. While these claims are not necessarily supported by scientific evidence, they are nevertheless useful in enhancing our understanding of marketing strategy and product positioning in the pet food market. Some of the health benefits as *claimed* by marketers are as follows (*Can Dogs Eat Seaweed?* - Supreme Source, 2024):

- For pets with sensitive stomachs, seaweed is easier to digest, and may help firm their stool, regulate their digestion and improve their metabolism.
- Seaweed is loaded with antioxidants. Antioxidants aid heart health, which increases longevity and may lower risk of infections.
- In addition to fiber, seaweed is full of prebiotics which help sustain good bacteria in the gut.
- Seaweed may help reduce skin dryness, redness and decrease inflammation.

The global pet food industry is dominated by large multinational firms, such as Mars Petcare and Nestlé Purina Petcare. There is growing interest from firms, such as Nestlé, to explore the potential for seaweed to support regenerative agriculture, and for Nestlé to source ingredients from products produced from regenerative agricultural practices. As an example, Purina announced in March 2023 that it has extended support for a three-year study to "explore the role of seaweed in regenerative agriculture" (*Purina Supports Three-year Research to Explore the Role of Seaweed in Regenerative Agriculture*, 2023).

There are many examples of the use of seaweed as a pet food additive. Purina Mills, which was originally a part of Nestlé Purina, produces "Purina Outlast" that contains a seaweed-derived calcium. Regional examples of firms using seaweed as an additive for pet food include Vitamin Sea from Maine and Supreme

Source based in Utah. Supreme Source *claims* that its organic seaweed is sourced from Nova Scotia and their products are "USDA Certified Organic" (Seaweed Superfood - Supreme Source, 2021).

For seaweed sourced in the Long Island Sound, it may be possible, with the right extraction methods, to use the seaweed as an additive for small businesses that are involved in producing gourmet pet food on a small scale and as a niche market. The technological and economic feasibility for extraction that includes drying, milling, fermentation, and other possible methods needs further examination. However, the level of processing required to process seaweed as an additive for pet food is not complex in comparison to other product categories, such as pharmaceuticals. One interviewee working in the pet food industry mentioned that typically, in their manufacturing process, it would not be difficult to add seaweed in powdered form to their ingredient mix. They are in fact considering the addition of seaweed powders to their chewable dog treats. The seaweed powder would enable better dental health for dogs due to anti-bacterial properties.

The prices for seaweed-based petfood products are higher than for seaweed itself sourced as a raw material. A search on Amazon (on January 3, 2024) for example indicated that Raw Paws Pet Food's organic kelp for dogs and cats in dry powder form sold at $22.99 for 16 ounces (Raw Paws Pet Food, 2024). There were 1062 consumer ratings for the product with an average rating of 4.4 on a 5.0 scale, and there were 300 of these products sold in the last month. While such evidence does not indicate the range on the entire market beyond this paper's scope, the search revealed several different brands of seaweed- based petfood products.

Based on our interview data, a small- to medium-sized pet food manufacturer was willing to pay around $75/kg for seaweed powder, which would be equivalent to approximately $34/lb. Another mass market pet food manufacturer sells their pet food "Reveal Tuna with Seaweed in Broth" on Amazon and in retail stores at a price closer to $9/lb. for their product. This product is sourced from Thailand and sold in the United States. Adding seaweed to Reveal enhances the ocean flavor of the product, making it more attractive to cats. Vitamin-Sea from Maine (Vitamin Sea Seaweed, 2024) sells their seaweed for horses at $56 for three pounds, which works out to a price of approximately $19/pound. Prices vary quite substantially depending on the perceived value add.

There is also wide variation in the percentage of seaweed used in products, ranging from 4% for pet food ingredients in treats to 100% when fermented seaweed is sold as a prebiotic fermented supplement. Pet food is subject to both federal and state regulations in New York and Connecticut (NYS Department of Agriculture and Markets, 2024; Connecticut Department of Agriculture, 2018). While we have not examined the regulations as it pertains to pet food and animal feed, a more detailed study of the pet food market would need to consider federal and state regulations.

Overall, the pet food industry is a promising market sector for seaweed with relatively less complex technology, higher than average prices, and consumer perceptions of value. We would recommend further research on the types of seaweed suitable for pet food, the need for third-party certification of quality, and feasibility of establishing at least some part of the value chain in the Long Island Sound region.

Cosmetics

Cosmetics is a well-established global industry. The size of the cosmetics worldwide was close to $43 billion dollars in 2022 according to McKinsey, a major management consulting firm (The Beauty Market in 2023: A Special State of Fashion Report, 2023). Continued economic expansion and the rise of the global middle class will likely result in increased growth of the cosmetics industry, and the revenue of the industry is projected to reach $580 billion by 2027. The sectors of the industry as identified by McKinsey include fragrance, makeup, hair care, and skin care, with skin care as the largest segment of the market. In addition, e-commerce shares in the industry now exceed 20 percent, which would imply a growing market for the direct-to-consumer market with potential opportunities for small businesses as well.

An increasing trend in the cosmetics industry according to McKinsey is also the growing interest in wellness and the content of the cosmetics that consumers consume. Nearly half of the Gen Z population (people born between 1981-1996), one third of the Gen X population (people born between 1965-1980), and one fifth of the Baby Boom population (people born between 1946-1964) were concerned about the ingredients in cosmetics.

The advantages of seaweeds in cosmetics arise from both their chemical composition as well as their physical properties (Lopez-Hortas et al. 2021). Useful features include proteins, lipids, amino acids, peptides, vitamins and minerals, polyphenols, and polysaccharides. Seaweeds also help in thickening, gelling, emulsification, and moistening. Research on the benefits of using cosmetics for seaweed indicate that seaweed is being used in diverse cosmetic products as a reliable organic ingredient and to add value to them (Joshi et al. 2018). Macroalgae-derived compounds are natural, renewable cosmeceutical ingredients that can be easily and cost-effectively extracted. Due to their abundance, chemical diversity, biocompatibility, desirable bioactivities, and physical properties, seaweed extracts are ideal for developing safe and effective skincare products. Clinical studies to date demonstrate the skin- moisturizing, anti-melanogenic, and anticellulite (slimming) benefits of topical macroalgae extracts.

The diversity of macroalgae species and their widely ranging biochemical composition also represent an important source of ingredients in skincare products. The importance of seaweed in the cosmetics industry is highlighted by the estimation that it makes up almost 40% of the world's hydrocolloid market. Macroalgae extracts can have one of three main functions in cosmeceutical formulations: (1) as additives that improve product stabilization, preservation, and/or organoleptic properties; (2) as excipients that constitute the transport medium for bioactive ingredients; and (3) as true functional compounds with cosmeceutical effects (Murphy & Dow 2021).

The cosmetics industry is always searching for new ingredients for two main reasons: (1) marketing advantage, (2) a need to replace raw materials that have either been banned or become less trusted by consumers. Macroalgae is the target of the moment when it comes to innovation in ingredients and efficiency in this area (Hempel et al. 2023).

The main constituent of the algal product are the pigments produced by the photosynthetic organisms. The algal metabolites, such as polysaccharides and proteins, have diverse functions and applications. They enhance the health of the skin by acting as anti-aging, antioxidant, anti-inflammatory, anti-wrinkling, and collagen boosting agent. Polysaccharides, such as alginates, carrageenan, and agar derived from macroalgae, act as gelling agents in various cosmetics like shampoos and lotions. Apart from this, the ingredients of macroalgae possess stabilizing, preserving, and organoleptic (substances that can be perceived through senses involving smell, touch, and sight) properties (Joshi et al. 2018). In addition, when exposed to UV radiation, macroalgae synthesize different defense mechanisms to deal with the radiation. This characteristic makes them suitable as an option for sunscreens and provides additional protection as antioxidants (Hempel et al. 2023).

Macroalgae contain a broad range of photosynthetic pigments, which have an attributed antioxidant function of interest to cosmetics. They have also been used as stabilizers and as preservatives in creams and lotions for solar protection. These pigments are algae-derived metabolites creams and lotions for solar protection.

Some macroalgae species and applications/products include (Joshi et al. 2018):

- *Chondrus crispus* (Irish moss) - Emollient, moisturizing, sheaths damaged or dry hair, nutritive, skin soothing, anti-inflammatory
- *Ulva lactuca* (sea Lettuce) - Antioxidant, anti-inflammatory, skin elasticity, collagen synthesis, anti-wrinkle, emollient, moisturizing
- *Fucus vesiculosus* (rockweed) - Tightening effect and stimulates metabolism
- *Porphyra umbilicalis* (laver/nori)- Skin-conditioning agent
- Red macroalgae, such as *Chondrus crispus* (Irish moss), *Gracilaria tikvahiae* (graceful red weed), *Porphyra* spp. (laver/nori) - food products

Cargill, for example, is using seaweed to extract carrageenan for supply to major cosmetics manufacturers like L'Oréal (Seaweed: L'Oréal's Answer to Sustainability, 2015). Examples of smaller scale efforts to develop technology to use seaweed in cosmetics include the collaboration between National Oceanic and Atmospheric Administration (NOAA) and SOLSEA Ltd. (Bryant, 2023). This collaboration involved the growth of seaweed in tanks and the use of the seaweed in developing high-value skin care products.

Interviews with businesses also suggest a growing interest in the use of natural ingredients from consumers, especially millennials. The largest application of seaweeds in cosmetics is likely to be in the skincare segment of the cosmetic industry in comparison with fragrance, haircare, and makeup. In the use of seaweed in cosmetics, one interviewee suggested that it is also necessary to mask the smell of seaweed in the formulation.

Prices for seaweed in the cosmetics industry are similar to that of pet food. One price quoted to us was around $35/pound. Two major suppliers of seaweed-based ingredients indicated by an interviewee included Active Organics (Botanical Extracts and Natural Performance Ingredients - Lubrizol, 2024) and CP Kelco (CP Kelco, 2024).

Overall, cosmetics represent an attractive market sector with higher perceived value addition, enhanced price realizations, and good marketing prospects based on an enhanced understanding of the technological product benefits of seaweed, such as sugar kelp (*Saccharina latissima*) and *Gracilaria* grown in the Long Island Sound.

Market sectors with low potential

Animal feed

The current main sources of animal feed include soybeans and corn. The benefits of adding seaweed to animal feed have been shown to be multifold, including better digestive health, enhanced immunity potentially reducing the need for antibiotics, increased egg production for poultry, enhanced milk yield, higher birth weight for pigs, and as a meal for abalone. A range of green, brown, and red seaweeds have been shown in seaweed studies to be beneficial for animal feed. In the New York region, potential markets include horse ranches and cattle farmers, especially in upstate New York.

The level of processing required to use seaweed as an additive for animal feed is not complex, depending on the level of extraction needed. Processing techniques include enzyme-based extraction, microwave-assisted extraction, and screw-press dehydration. The economic feasibility of different processing techniques in Long Island needs to be examined further. Seaweed can be consumed as animal feed in both processed and unprocessed ways. Fermented seaweed adds beneficial effects for animals in enhancing digestibility of food and increasing the stability of storage of the product, adding shelf life.

The global market for animal feed additives and nutritional supplements is estimated to generate a net revenue of $64 billion by 2025, growing at a compound annual growth rate (CAGR) of 2.7%. Worldwide, the animal nutrition market is largely driven by a rising demand for poultry feed, which constitutes about 47% of the total consumption. The combined seaweed market for agriculture and animal feed applications is anticipated to reach much higher values by 2024 due to the impacts of current research and development targeting enhanced animal health and productivity.

In terms of market size, livestock and dairy production in New York was estimated at $3.2 billion in 2017 (Your Dollar Does: In New York, 2023) with over one million head of cattle. Ninety-two percent of New York farms are family owned and any potential to enhance farm productivity and lower costs would be an attractive proposition for New York farmers. Research studies also show that the typical level of seaweed additives for animal feed should not exceed 80 g/kg of feed, i.e. not more than 8% by weight. The use of seaweed as an additive for animal feed does require FDA approval.

While seaweed has been shown to be beneficial as an animal feed in many ways, the market sector is unattractive for seaweed produced in the Long Island Sound. The supply of seaweed for the animal feed sector is considered a high volume, low margin business. A large buyer would need at least two thousand tons of seaweed annually (World Bank 2023).

The business case for seaweed produced in the Long Island Sound as animal feed is not strong. Typically, given the size of cattle farms, the quantity of seaweed needed, even as an additive, is large and much beyond the current production capacities in the Long Island Sound. In addition, the expected price realization for seaweed sold in this sector is low and varies from one dollar to five dollars per pound for dry seaweed depending on the species. Overall, animal feed is not an attractive sector by itself for a seaweed farmer in the Long Island Sound.

Nutraceuticals

The perceived benefits of seaweed in nutraceuticals include improved bone and joint health, improved health of the digestive tract, immune support, energy boost, weight management, weight loss, and thyroid support (Ganesan et al. 2019, Lozano et al. 2022, Shannon and Abu-Ghannam 2019).

The nutraceutical value chain consists of seaweed farmers, ingredient manufacturers of seaweed extracts, and nutraceutical manufacturers. Nutraceuticals may be in the form of capsules, gels, powders, or drinks and may include seaweed in its original form or as extracts added as ingredients to the nutraceutical.

Nutraceuticals are considered a potential market sector in the long-term (World Bank 2023). Brown and red macroalgae possess a good nutritional quality and can be used for an alternative source of diets (İrkin & Yayintaş, 2018). Despite the widespread use of seaweed in the food industry and their antioxidative qualities, they are untapped as a nutraceutical and medicinal product (Pradhan et al. 2022).

Nutraceuticals as dietary supplements with claims to enhance health are widespread. Estimates put the global market size of nutraceuticals at $450 billion in 2021. However, there are many barriers to the use of seaweed in nutraceuticals and they include regulatory compliance needs, capital requirements to establish a manufacturing facility, relatively low consumer awareness of the benefits of seaweed, and the marketing costs involved in enhancing awareness. Given the barriers, even though the sector has long-term potential, nutraceuticals would not be a viable sector to target for seaweed produced in the Long Island Sound, at least in the short-term. Although nutraceuticals may not have the same level of regulatory requirements as pharmaceuticals, they are likely to receive a high level of scrutiny and any claims regarding the health benefits of specific products using seaweed or seaweed extracts would need to be supported by scientific research.

Bioplastics, Biofuels, and Bio-packaging

Biofuels: There are many advantages to using seaweed as biofuel. An excellent summary of the pros and cons of biofuel is also provided by Bellona.org, a non-profit organization based in Europe established to fight climate change (Bellona, 2017).

Some of the benefits of seaweed as summarized by Sharmila et al. (2021) is given below:

- Macroalgae is perhaps the most potential non-consumable biofuel source as it can grow exponentially in saline water and in adverse conditions. The algae biofuel is safe and extremely compostable and contains no sulfur.
- Algae can be transformed into a variety of fuels, depending on the technique and algal species used. Biofuels from algae are considered as third generation fuels and has advantages, such as rapid growth, high CO_2 capture, and ease of cultivation even in barren lands which has the potential to meet energy crises. The oil extracted from algae can be used for biodiesel production and the residual biomass obtained are rich in sugar content that can be used for bioethanol production.

- Algal growth rate is about 20–30 times faster than fodder crops, and the oil content present in macroalgae is around 30 times more than the conventional feedstocks. The algal source is completely biodegradable and sulfur-free, and the oil derived from algae has better quality. Further, the absence of lignin makes the macroalgae easy to digest by microbes in the biorefinery process and makes it easier to convert into a biofuel than land-based plants. Biomass residues after the conversion processes can be used for heating purposes, fertilizers, and other types of fuel production.
- Biofuels are capable of being used in automobiles and a variety of industrial activities. Biofuels can be derived from macroalgae through various biochemical and thermochemical methods.
- Types of biofuel production from various macroalgal species include:
    - Biodiesel - *Ulva intestinalis* (gut weed) and *Ulva prolifera* (branched string lettuce)
    - Bioethanol - *Chaetomorpha linum* (green thread), *Laminaria digitata* (horsetail kelp), *Ulva linza* (mini sea lettuce)
    - Biohydrogen – *Laminaria digitata* (horsetail kelp)
    - Biomethane - *Palmaria palmata* (dulse) and *Laminaria digitata* (horsetail kelp)
    - Bio oil - *Ulva lactuca* (sea lettuce)

Despite the potential for seaweed as biofuel, the cost of algae-based biofuel is still too high at over $5/gallon and cannot compete with gasoline. According to an article in Popular Science, the business case to mass-produce biofuel from algae is not strong (Amir, 2022). In addition, given the lack of certainty regarding high-volume production of seaweed in the Long Island Sound, biofuels are not a promising market.

Bioplastics and Bio-packaging: The World Bank research report (2023) estimates that it will take five to ten years to realize the potential of seaweed for bioplastics and biopackaging. Constraints include the need for high research and development budgets, high levels of capital investment, the need for large quantities of seaweed, and high production costs which make it uncompetitive with existing substitute products.

Overall, the market potential for seaweed produced in the Long Island sound to supply biofuel, bioplastics, and biopackaging industries is low due to uncertain demand, high costs, and large quantity of product that would be needed to supply this market sector.

Fresh and Dried Food

Seaweeds are easy for people to digest and add a variety of vitamins and minerals to their diet. Because of the rising interest in non-animal protein, macroalgae have also been explored as a renewable source of protein and is forecasted to have a market value of $1.51 billion by 2030 (Naga et al. 2022). A comprehensive identification of the benefits of seaweed as a food is beyond this paper's scope. However, some of the benefits of seaweed as food include the following (İrkin & Yayintaş, 2018; Circuncisão et al. 2018; Rocha et al. 2019; Raposo et al. 2016):

- Seaweeds, especially brown macroalgae species, may accumulate exceptional levels of iodine, which is a vital nutrient required for growth for all age groups and essential for the regulation of thyroid function, which involves the brain and pituitary gland.
- Considering that iodine deficiency is a common disorder in 11 European countries and most of the remaining countries are using iodized salts to supplement iodine in their diet, the introduction of seaweeds in population eating habits could be a valid alternative to ensure intake of the optimal daily requirement of iodine.
- Seaweeds have generally high amounts of sodium. This characteristic may be advantageous if considering seaweeds as a salt replacer in processed foods since their high mineral content would contribute to the maintenance of foods’ salty taste without adding sodium in the form of table salt.

- Agar is a derivative of seaweed widely used in the food industry for many purposes. An example of the benefits of agar include its unique gelling properties, which make it particularly suitable for food applications. Its gelling strength is high, even at low concentrations. Gelation is reversible, though it only melts above 80 °C, avoiding the need for refrigeration (an advantage over gelatin), and it can retain its gelling ability even at high temperature, allowing proper sterilization. Furthermore, its high temperature resistance widens its usability, allowing its use as a thickening or stabilizing agent in the baking industry. In addition, it is tasteless and does not need the presence of extra reagents to induce gelation, which is preferred over a wide range of other phycocolloids or gums.
- Ninety percent of the produced agar is used for food applications. Its price is generally higher than for other food-grade phycocolloids.
- Emerging food applications include its use in low-fat food as a fat replacer, in prebiotics, and as an edible film- forming or coating-forming agent.
- The consumption of fibers obtained from algal biomass has demonstrated physiological effects that confer health benefits.
- Some of the products produced by marine algae (alginates, agars, carrageenan, fucoidan, mannitol, laminaran, ulvan) and/or their biomass can be considered as functional foods, as they confer specific health benefits other than the "simple" nutrition. These benefits include antiviral capacity; prevention of cancer, obesity, and diabetes; decrease of total and LDL cholesterol and postprandial glucose levels, which are some of the chronic diseases associated with a low consumption of dietary fibers.
- Macroalgae mineral supplementation of food and drinks, such as milk, dairy products, and more recently, plant "milks" (e.g., soy, almond, oat, and rice), are another segment of food products that occupy a highly significant position in some dietary routines. In fact, patents for dairy products and plant beverages fortified with seaweed-derived minerals have already been registered.

Fresh food and dried food are among the most common uses of seaweed in the global marketplace, particularly in East Asia. Food is the most established sector for seaweed. However, based on an interview with a business that has attempted to market seaweed as food for many years on Long Island, the potential for seaweed grown in Long Island Sound to compete with global suppliers of seaweed is very low due to the low prices at which the product is available from the global marketplace. In addition, consumer demand for seaweed as food within the Long Island region and neighboring states is not widespread but growing. Our consumer survey results also indicate that awareness of the benefits of seaweed is not high, with an average rating of less than 4.0 on a 7.0 scale: 7.0 indicating a high level of awareness and 1.0 indicating a low level of awareness. Furthermore, the quantity of seaweed currently produced in the Long Island Sound will not make it viable to serve as a source or raw materials for medium- and large-scale manufacturers of seaweed product used in the food industry, such as agar and carrageenan, most of which is currently produced in China and Indonesia.

The US currently imports about $250 million dollars of seaweed each year, while the domestic production of seaweed in comparison is negligible. While we do not have specific data, given the low level of domestic production, it would not be unreasonable to assume that a large quantity of processed seaweed sold as food in the United States is primarily imported from Asia. The price of seaweed in Asian markets, such as Indonesia, the Philippines, China, and Korea, is much lower than the current market price of seaweed in the United States. In addition, without significant value addition, it is not clear that the product grown domestically offers significant quality or other advantages over seaweed grown in other parts of the world.

However, seaweed produced in the Long Island Sound as a new entrant into the marketplace would need and benefit from further third-party certifications and substantial marketing to establish themselves in the Business to Consumer (B to C) marketplace for food. Similar in principle to the labelling of foods as “organic,” for example, consumers may perceive higher quality when the seaweed is certified by a third-party laboratory or government agency to attest to the quality of the product.

Pharmaceuticals

The use of seaweed in pharmaceuticals is a long-term prospect and there are currently no seaweed-based pharmaceuticals in the marketplace (World Bank 2023). The use of seaweed-based pharmaceuticals will require much scientific testing and a lengthy regulatory process for approval. Consequently, without the current existence of any seaweed-based pharmaceutical in the marketplace, it is premature for us to consider pharmaceuticals' potential as a market sector for seaweed grown in the Long Island Sound. There is, however, literature on the medicinal properties of seaweed, which may in the long-term, yield to the development of seaweed-based pharmaceuticals. Examples of some of the medicinal properties are given below (Pradhan et al. 2022, İrkin & Yayintaş, 2018, Patel 2012, Gheda et al. 2016, Kandale et al. 2011):

- Seaweeds are effective as therapeutic pharmacological entities for various disorders, including dyslipidemia, obesity, diabetes, cancer, and hypertension. Along with individualized health care, a regular diet rich in seaweeds can boost the nutritional content of food.
- Seaweeds are also an abundant source of all the known vitamins, chlorophylls, lignans, polyphenols, and antioxidants, which may have their potential in human health.
- Marine macroalgae have the potential utilized in the treatments of cardiovascular diseases, diabetes, obesity, viral diseases (especially HIV and HPV), cancers, disorder of the gastrointestinal tract, hepatic diseases, and anti-inflammatory issues.
- Some seaweeds, especially coralline algae, have high levels of calcium carbonate and are thus applicable to treat osteoporosis.
- Fucoxanthin, a marine carotenoid found in edible brown seaweeds, helps reduce the accumulation of fats and aids in weight loss. Due to its ability to promote the oxidation of fats, it is

used in making prescription diet pills and gastric banding pills. Seaweeds have a laxative effect that is useful in maintaining healthy digestion. It helps in stimulating the release of digestive enzymes, supporting the absorption of nutrients, and facilitating the metabolism of fats.

- Alginate, a salt of alginic acid extracted from seaweeds, is useful in the production of dental molds. It also has preventative effects in the growth of dental cavities with anti-inflammatory properties
- Seaweeds possess antioxidant and anticoagulant properties. Anticoagulants, known as blood thinners, prevent the occurrence of blood clots and vascular occlusion, and decrease the threat of stroke and cardiac failure. Seaweed has been used for sustaining lower levels of triglycerides and cholesterol. This helps in maintaining a healthy heart, smooth circulation in the blood vessels, and prevents fatal conditions. Seaweeds also possess the ability to detoxify and facilitate the excretion of toxic waste.
- Seaweeds have antiviral properties proven in providing an effect against influenza virus. Its extracts prevent the absorption of harmful viral particles and prevent the body from getting infected.
- Macroalgal lectins, fucoidans, kainoids, and aplysiatoxins are routinely used in biomedical research.
- Seaweed has been used as an herbal medicine for treatment for cough, asthma, hemorrhoids, boils, goiters, stomach ailments, and urinary diseases, and for reducing the incidence of tumors, ulcers, and headaches.
- Red macroalgae seaweeds have a great variety of halogenated alkanes, saturated and unsaturated ketones, aldehyde, alcohols, epoxides, and halogenated derivatives of acetic and acrylic acids. These bioactive compounds have been used for antibiotic activity against bacteria, such as *Bacillus subtilis*, *Staphylococcus* sp., *Fusarium* sp. and *Vibrio* sp.

In summary, we do not recommend the market sectors of animal feed, nutraceuticals, bioplastics, biofuel, biopackaging, pharmaceuticals, and food as attractive market sectors in the short-term for seaweed produced in the Long Island Sound.

Shellfish Markets

We did not find data on market sectors as it specifically relates to ribbed mussels (*Geukensia demissa*) except for an article outlining the environmental benefit that ribbed mussels provide for salt marshes (*UNH Researchers Examining Use of Ribbed Mussels in Marsh Restoration*, 2023).

We did not find immediate product applications for ribbed mussels in secondary research. The primary market sectors for bivalves other than ribbed mussels are in food and we did not find relevance to other product sectors identified within the scope of this project. The economics of bivalves as food is discussed in detail in Chapter four.

Biorefining:

The concept of biorefining involves the use of seaweed to produce and extract multiple products simultaneously (Bigersson et al. 2022; Yun et al. 2023). Products that could be produced simultaneously include alginates, fucoidan, laminarin, cellulose, protein, and peptide biomass. These seaweed extracts could be used in multiple industries including construction, biofuels, and food products. A company based in the Netherlands, Weedware, uses biorefining in a 5,000-liter capacity tank to split macroalgae cells and extract components. "The output is typically divided into three or four streams, from which liquid extracts are derived that can be used by certified organic farmers as natural biostimulants and to prevent waste. The remaining components of the biomass are used in a variety of products for the homeware industry through a process of mincing, blending, grinding, and extruding" (Worldbank 2023).

The concept of biorefining as it applies to seaweed is in the early stages. However, more advances are expected with further research to enhance the value added from the extraction process and to reduce waste materials as well.

Consumers and markets

Consumer survey findings on seaweed and shellfish usage:

239 consumers were surveyed online with the help of Qualtrics, a market research firm (see Table 3.2). At the time of the consumer survey, we were focused on food, nutritional supplements, and cosmetics. Pet food was not included in our consumer survey but was added later as a part of our interview panel as we gathered additional information on potential market sectors. Our consumer survey did not include questions on pet food.

Table 3.2: Demographics Overview:

Total respondents	239
Age distribution:	
18-34 years old	30%
35-54 years old	41%
55 and over	29%
Gender distribution:	
Male	48%
Female	52%
Ethnicity distribution:	
White	73%
African American	14%
Hispanic	6%
Asian American	5%
Mixed race	2%

Product Category Consumption

Consumption of products with seaweed and shellfish:

We asked consumers about whether the product categories of food, cosmetics, food and nutritional supplements, or fertilizer that they use involve seaweed and/or shellfish. Food dominates the category of products both for seaweed and shellfish (Table 3.3).

Table 3.3: Product Category Consumption

Food:	
Seaweed involved	54%
Shellfish involved	60%
Food/Nutritional supplements:	
Seaweed involved	46%
Shellfish involved	30%
Cosmetics:	
Seaweed involved	17%
Shellfish involved	7%
Fertilizer:	
Seaweed involved	11%
Shellfish involved	8%
No involvement in seaweed-containing products	29%
No involvement in shellfish-containing products	27%

In general, consumers were more aware of the use of seaweed and shellfish as food or as a nutritional supplement, rather than as a product that could be used in fertilizer or cosmetics.

Consumer perceptions:

Consumer perceptions of seaweed and shellfish were gathered using a series of statements with a seven-point Likert scale (1- Strongly disagree, 2- Disagree, 3- Somewhat disagree, 4- Neither agree nor disagree, 5- Somewhat agree, 6- Agree, 7- Strongly agree). An average score above 4.0 would indicate a level of agreement with the statement, and a score below 4.0 would indicate disagreement with the statement. Below in Table 3.4 are the average scores indicating the level of agreement/disagreement with the statements:

Table 3.4: Consumer Agreement Ratings	
Statement	**Average Rating**
Seaweed makes products better	4.39
Shellfish makes products better	4.18
Consumption of seaweed is good for health	4.88
Consumption of shellfish is good for health	4.62
Awareness of seaweed benefits is high	3.85
Awareness of shellfish benefits is high	3.80
Seaweed makes products more natural	4.75
Shellfish makes products more natural	4.27
Seaweed benefits the environment	4.80
Shellfish benefits the environment	4.25
Presence of seaweed in current products	3.75
Presence of shellfish in current products	3.72
More likely to buy if seaweed present	4.00
More likely to buy if shellfish present	3.82
Willing to pay more if seaweed present	3.63
Willing to pay more if shellfish present	3.61
Seaweed improves products compared to non-seaweed products	4.00
Shellfish improves products compared to non-shellfish products	3.91
Importance of environmental care	5.52

***Consumer comments*:**

In addition to the Likert-scale questions, some consumers wrote comments. Some consumers mentioned that they would use seaweed or shellfish if they better knew the benefits and how to use them. They mentioned the lack of advertisements for seaweed and shellfish ingredients in products. Some consumers appreciated how informative the survey was. One questioned why it is important to be aware that seaweed and/or shellfish are in more things than consumers realize, especially when it comes to the fertilizer category. One comment questioned whether using seaweed would destroy marine habitats. Another comment highlighted that a barrier to shellfish-use by consumers is shellfish allergy.

Overall, among the consumers we surveyed, consumer ratings as well as additional comments indicated a lack of consumer awareness about the benefits and uses of seaweed and shellfish, with many of the scores close to an average of 4.0, indicating a neutral response. However, the scores related to seaweed as natural (4.75), good for health (4.88), and important for environmental care (5.52) are higher and indicate a moderate level of consumer awareness of some of the potential benefits. This indicates an opportunity to use these ingredients and promote the health and environmental benefits of products that involve seaweed and shellfish.

Interview Findings

As part of the research project, we conducted twelve interviews with businesses (in food, cosmetics, pet food/supplement, and biostimulant industries), consultants, business executives, seaweed farmers, and other market players, such as researchers, related to the algae industry. The interviews offered insights on both the opportunities and the barriers for utilization of algae in various products, as well as on the potential of sourcing algae from Long Island Sound.

The opportunities and barriers that interviewees mentioned evolved mainly around consumer demand, reliability and cost of supply, product differentiation in the market, environmental and health benefits, and sustainability. We provide below a summary of the major insights from the interviews.

Consumer demand and market perceptions:

Informants from every sector stressed the importance of consumer demand in deciding to use algae as an ingredient in their products. Most of the interviewees emphasize that they have started to utilize algae and do more research on incorporating algae into more products, as it has become the trendy ingredient that consumers seek. Businesses from all industries also emphasized that they sometimes use seaweed as an ingredient, not only for the functional benefits or extra quality value it adds to the products compared to some other ingredients, but also as a marketing tool for the sake of making their products more appealing and different than alternatives on the market. Many informants suggested the need for more research to support the benefits of seaweed in various applications. However, all the informants are still confident in the high quality of the algae because they trust that it is a natural and raw ingredient, not a synthetic one.

Informants discussed that the increasing consumer demand in algae is closely related to the emphasized environmental and health benefits that consumers perceive. According to the experiences of the informants, algae as an ingredient in products is a bigger deal for environmental- and health-conscious consumers. An important potential that businesses see in this segment is that since consumers perceive algae food as high quality and sustainable, they are likely to pay a premium cost. Most of the products that involve algae are priced higher than their competitor products. One theme that occurred in every discussion is the importance of targeting very specific, niche segments of consumers even within the group of environmental and health-conscious consumers. Our informants emphasized this because they are functioning in an industry that is still in its infancy but is very competitive. Businesses need to find their niche to be able to have a place in the market. Some businesses are not yet very profitable and are stable rather than thriving. These businesses are focused on doing good for specific groups of consumers. An example of niche targeting is one of the businesses that we interviewed that focuses on helping pre-menopausal and menopausal health-conscious women who need a natural food supplement, rather than the synthetic supplements available in the market, to ease their symptoms.

Interviewees also mentioned that not every consumer is aware of the significance of algae. The market is still yet to be developed. Consumer demand for algae is complex and shaped by multiple things, such as a growing interest in media, industry buyers, and other players in the industry. For instance, as one interviewee in the pet food industry mentioned, veterinaries shape the demand for pet foods that incorporate algae. Businesses also emphasized the significance of growing interest in the media. They mentioned that more articles about the benefits of seaweed in big news outlets, such as the New York Times and the Washington Post, are educating and creating a demand. People are becoming more open to using algae.

Businesses believe that their responsibility is not only to sell their products, but also to create a demand for algae products in general, but this is not an easy task. Developing consumer demand is challenging due to taste-related matters for food businesses. Some of the informants from food businesses emphasized that most American consumers do not necessarily like the taste of the seaweed or are not ready to eat more of it yet. However, all informants from food businesses see the potential for growth in the market as algae has its own umami flavor profile, and consumer taste is changing. They also talked about the importance of continuously working on product development to create tastes that American consumers may enjoy more easily.

Indeed, continuous research and product development is something that almost every informant from every industry stressed for the success of their endeavors. For instance, the owner of a biostimulant business discussed how they also developed a small cosmetic line with products targeting consumers with very specific skin conditions. They believe that their biostimulant business is doing well, but they need to also offer their cosmetic products because it is much more profitable. This demonstrates that local and small businesses incorporating algae into their products can be successful if they have diversified product development, as well as well-researched niche marketing.

Sustainability and the Environmental concerns:

Our informants mentioned that there are a significant number of businesses that use algae because they prioritize the environment and human health. Small local companies are especially action-oriented and visionary in terms of being sustainable. One of the food businesses talked about their interest as “finding hope in seaweed.” One food business, one biostimulant and cosmetics business, and a group of environmental researchers and documentary makers mentioned their interest in seaweed is due to its beneficial qualities, such as its ability to sequester carbon, clean waterbodies, provide habitat, help minimize pH changes in water, and promote biodiversity. Another important point from food and biostimulant businesses and seaweed growers is that seaweed can grow with little or no additional resources and can be grown sustainably.

Product development and differentiation:

Interviewees from different industries mentioned that incorporating algae in products is simple and straightforward. This helps businesses develop cost-effective products that consumers seek with minimal effort. In the pet food market, especially cat food, use of algae is more straightforward as pet food businesses mentioned their research shows that cats enjoy ocean flavors, and use of seaweed intensifies the ocean flavor in cat food. In addition to food for pets, seaweed (especially brown algae) is also used as an ingredient in products for pet supplements due to their antimicrobial and antibacterial properties. Our informants mentioned that using algae in this industry is a good way to compete and differentiate.

Informants in the food industry specifically highlighted that more information sharing and education are needed for seaweed to gain mass market appeal. For Western diets specifically, it is just not well known. For a lot of American people, it is a new food they have not often experienced before, and they do not perceive its “oceany” taste to be pleasant. Also, there are consumer misconceptions about seaweed, such as people thinking they are carrageenan or thinking of only kelp when they hear seaweed. There is a general misconception as to what seaweed is. Yet, every food business we talked to emphasized the unique nutritional density of algae for healthy plant-based products. All these businesses are very knowledgeable about the unique qualities of algae and developing unique products based on research. In a market that is competitive, businesses use algae as an ingredient that would differentiate their products from their competitors across multiple sectors including pet food, biostimulants, and cosmetics.

International Sourcing vs. Domestic Sourcing:

The reliability and cost of supply is another consideration mentioned for businesses, as production largely depends on independent contractors for different aspects of processing, innovation, and manufacturing. Businesses said they need a reliable, low-cost supply of algae to be able to use it as an ingredient. Most businesses that use algae in their products rely on other suppliers that grow or process algae. Finding a reliable supplier is important for any food, cosmetics, pet food, and pet supplies business. When businesses talked about reliability, they mentioned both the quantity and quality of the supply. All interviewees from the food industry mentioned transparency and quality testing, such as strict lab testing, as important criteria when sourcing algae. These interviewees prefer domestic suppliers for quality reasons and believe that businesses and consumers should focus on local ingredients and products for various reasons, such as caring about equal treatment of people in the supply chain and the environmental benefits, taste, and effectiveness of local products. One interviewee in the food industry also mentioned that growing algae is an economic opportunity for small fisheries. Fisheries can grow seaweed in the offseason or when these fisheries shut down. Yet, some food businesses find not having their own equipment for processing algae as a barrier for the expansion of algae used in their products. One of the informants in the food industry suggested that developing an open-source model when it comes to some of the algae processing equipment will help grow the industry and innovative seaweed processing. However, they also mentioned that this is capital intensive and not a simple task. Interviewees in the cosmetics and pet food industry did not mention supply as a concern because some of them also source internationally from firms that sell algae extracts or seaweed.

Overall, most interviewees emphasized that domestic algae industry is in its infancy. The US industry is still figuring out the most applicable and cost-effective methods of drying, and this has an impact on the reliability perceptions of using algae as a main ingredient in products. Additionally, some of our informants highlighted that there is a supply limit to what they can source domestically. This issue was specifically discussed by our food industry informants. According to them, there are a couple of constraining factors for the reliability of supply, especially domestically, for the food industry. For instance, when businesses want to supply organic seaweed, businesses in the supply chain do not have the capacity to support this demand.

There are variability and seasonality issues for wild harvested algae. Drying facilities are not sufficient and there is a very short window of time to dry algae. Once it's out of the water, it needs to be dried within 24 hours for up to five days to be a high-quality food grade product. Another point mentioned by a few of our informants is that setting up a processing facility is very capital intensive and challenging for small farmers. Cost of equipment is another significant consideration for the food industry as seaweeds are so corrosive that a lot of equipment that is built for food processing does not last very long.

As a result, businesses have a smaller range of products because they try to focus on ones that they know they have sufficient supply to produce. Another constraining factor in using algae for food is that some easily found species in the US, such as kelp, have high iodine content. One informant suggested that an option is to find partners to balance the kelp by eliminating or lowering iodine content. The final limiting factor that we heard from our informants is that there are desirable species that currently cannot be cultivated in the US (e.g. cultivated nori, dulse). When seaweed is grown or farmed and processed in an area, it is important to ensure that all other fisheries are not damaged because most of these seaweeds are also habitat for important species. One critical point mentioned by the informants is that the industry is moving towards more tank-grown species because it is more controllable, predictable, and easier to grow and harvest.

Interviewees in the pet food and cosmetics sectors indicated that sourcing from both domestic and international sources are feasible, and they need product certifications from their suppliers. The product certifications are typically provided by the manufacturers themselves or by third-party laboratories. In addition, the seaweed powder or extract is further tested in-house by the pet food or cosmetics manufacturers.

Shelf stability and Nutritional Benefits:

Another benefit of algae that was mentioned by interviewees in different industries is that dried algae is very shelf-stable. It can be stored for three to five years without any issue. This facilitates the use of algae in production in many industries. For food products, algae do not require much volume in any form to add a high concentration of nutrition to any food. According to our interviewees, that is the main reason for its increasing use in food products, such as snacks and supplements. Algae has been used as a stabilizer and preservative for a long time, but according to our interviewees in the food industry, algae is now also offered as a nutritional enhancement as opposed to a lot of the chemicals that are currently used. In addition, focusing on the health aspects of algae offer a lot of opportunities. These interviewees predict that the nutritional quality of seaweed will make it an even bigger impact as consumers become more aware of these benefits.

Pricing

An important variable in the viability of any market sector is the potential price at which products can be sold. Our interviewees in the pet food and cosmetics sector said they source seaweed in dry or extract form at prices that range from $35/lb. to $100/lb. The possible price realizations are much higher than the price for seaweed sold directly as food in dry form, in which the price realization is less than $5/lb. Selling seaweed as an extract may involve further processing, and supply chains currently in Long Island may not be fully developed. However, even with higher processing costs of seaweed, the additional price realizations make the biostimulant, cosmetics, and pet food sectors the most attractive markets.

Considerations for sourcing seaweed from the Long Island Sound:

One of the discussions we had with industry informants was on their perceptions of supplying algae from Long Island Sound. The discussion was focused on the barriers that the informants perceive, rather than the opportunities. Some informants expressed concern about water quality in the Long Island Sound. However, others mentioned that product certifications from the producer or a third-party lab would serve to satisfy the customer. Interviewees in the cosmetics and pet food industries mentioned that current suppliers provide testing certificates along with products. These certificates attest to the contents of the product. In addition, some cosmetic manufacturers who typically source seaweed extract retest the product in their own facilities to ensure the integrity and quality of their cosmetic formulations.

Regulatory Analysis

Federal Government Overview

Under federal law, aquaculture is defined as the propagation and rearing of aquatic species in controlled or selected environments, including, but not limited to, ocean ranching (except private ocean ranching of Pacific salmon for profit in those States where such ranching is prohibited by law) (National Aquaculture Act of 1980). Federal law acknowledged the potential for commercial value in cultivating aquatic species and directed the drafting of the National Aquaculture Development Plan (NADP) to identify species for cultivation, recommend public and private sector cultivation related activities, and give regulatory authority to federal agencies (National Aquaculture Act of 1980). It also called for a study of regulatory restrictions at the federal and state levels and authorized the random selection of five states based on geographic region for that study, which would culminate in a Regulatory Constraints Plan. This plan listed steps the federal government could take to "to remove unnecessarily burdensome regulatory barriers to the initiation and operation of commercial aquaculture venture." (National Aquaculture Act of 1980). In 1983, the National Aquaculture Development Plan (NADP) was completed.

In 2022, the federal Subcommittee on Aquaculture sought public comment on a draft document intended to update the NADP as well as several existing related documents (Agricultural Research Service, 2022). Of the four goals identified in that draft document, the third sought to expand market opportunities for U.S.

aquaculture products (Agricultural Research Service, 2022). Additional federal efforts to reduce regulatory limitations on the aquaculture industry include the National Science and Technology Subcommittee on Aquaculture's 2022 plan to help improve the efficiency of the aquaculture regulatory environment (Agricultural Research Service, 2022). That plan identified three goals addressing regulatory improvements in permitting, management of aquatic animal health, and tools used to support regulatory management (Agricultural Research Service, 2022).

Another broad step by the federal government is in Executive Order 13921 which authorized the creation of ten Aquaculture Opportunity Areas (AOA) nationwide by 2025 (Exec. Order No. 13,921, 2020). The AOAs are defined as geographic areas suitable for commercial aquaculture which will support multiple farm sites with varying marine species including shellfish and seaweed (National Oceanographic and Atmospheric Administration, 2020). The Executive Order's express purpose includes the removal of "outdated and unnecessarily burdensome regulations" as a means, in combination with other steps, to protect aquatic environments and strengthen the seafood industry in the United States (Exec. Order No. 13,921, 2020). Although the first two AOAs were designated in federal waters off Southern California and in the Gulf of Mexico, the executive order does not prohibit AOAs located in state waters and Alaska is currently in pursuit of AOA designation for invertebrate farming, including shellfish and seaweed farming (National Oceanographic and Atmospheric Administration, 2023). States, such as Connecticut and New York, can benefit by observing AOA operations and any implemented regulatory changes.

Since 1980, the federal government has demonstrated an interest in establishing and maintaining a robust aquacultural industry. This has allowed states with coastal regions to pursue aquacultural endeavors with success. Washington state and California are leaders in shellfish production with a reported $475 million in annual aquaculture sales ("U.S. States with the Largest Aquaculture Industry," 2021). Production of seaweed, a species commanding more attention worldwide, is dominant in Maine, with other

New England states and the Pacific Northwest actively engaged as well (National Oceanographic and Atmospheric Administration, 2020).

Many, but not all, species of seaweed thrive in the colder waters of Maine. This presents an opportunity for states with coastal waterways south of New England. Connecticut and New York recognize the environmental and commercial importance of the aquaculture industry as it relates to shellfish and seaweed species that can be farmed in the waters of and near Long Island Sound. A great deal has been done in these states to establish a regulatory structure for the aquaculture industry and preserve the aquatic system within which it operates. Entrepreneurs and established businesses would benefit from understanding the regulatory environment, which is complex. Explanatory documents exist in both states and at the federal level. In Connecticut, interested parties should review *A Guide to Marine Aquaculture Permitting in Connecticut*, while interested parties in New York should review *A Guide to Shellfish Aquaculture Permitting in New York* (Getchis, et al., 2019). These guides offer links and references to specific federal, state, and local statutory law, as well as identify the numerous agencies with regulatory authority. Another helpful guide geared toward seaweed aquaculture is the National Oceanographic and Atmospheric Administration's State by State Summary of Seaweed Aquaculture Leasing/Permitting Requirements (2021).

In addition, not-for-profit organizations in both states offer a great deal of assistance to those interested in growing and farming seaweed and shellfish. In Connecticut, GreenWave Organization Corp. (GreenWave) is a nonprofit in New Haven with a self-described mission "to train and support regenerative ocean farmers" to yield positive environmental and economic outcomes. In New York, Lazy Point Farms has a similar goal. Both organizations' websites offer information, education, and support for those working in the aquaculture industry. GreenWave provides self-guided courses on their website for Ocean Farming and Kelp Hatchery. These courses include topics ranging from an industry overview, equipment, and location considerations as well as detailed regulation and permit information. There is also an Ocean Farming Hub that gives access to farmers and others working each day with seaweed and shellfish. Lazy Point Farms places a focus on kelp and offers information and operational support to existing and potential farmers. Both organizations are valuable points of contact for those entering the aquaculture industry in the waters of Long Island Sound.

New York Regulations

New York State statutory law gives authority to the New York State Department of Environmental Conservation (NYS DEC) over matters related to shellfish cultivation and harvest and seaweed cultivation. Post-harvest activity for shellfish involves several state agencies including the DEC, the Department of Health, and the Department of Agriculture and Markets. Post-harvest activity for seaweed intended for human consumption is regulated by the New York State Department of Agriculture and Markets in the Division of Food Safety and Inspection.

New York State owns the water from Long Island's north shoreline to the mid-point of Long Island Sound. New York Environmental Conservation Law (ECL) § 13-0301 (1996) authorized leasing of underwater lands "within the marine and coastal district" for shellfish farming. Commercial off-bottom shellfish cultivation is possible through a Temporary Marine Area Use Assignment issued by the DEC for state-owned land in the waters of Long Island Sound, Gardiners Bay, and Block Island Sound. The circular shaped parcel of underwater land is limited to slightly less than 5 acres and must be a minimum of 1,000 feet from shore. Authorized use expires annually with renewal options and the Off-Bottom Culture permit must also be obtained. State-owned waters have not been authorized for seaweed farming. ECL § 13- 0301's general authorization was followed by ECL § 13-0302 (2004), which designated specific underwater land in Suffolk County for shellfish cultivation and called for the establishment of a Shellfish Aquaculture Lease Program within Gardiner's Bay and Peconic Bay, waters once owned by New York State but previously ceded to Suffolk County for oyster cultivation. Pursuant to ECL §§ 13-0302(4) and (8), Suffolk County enacted regulations establishing a shellfish cultivation zone~~s~~ as part of the leasing program within these two bays and developed a map designating the zone (Suffolk County, NY, Ch 475, Art. II and Art. III, of the 2011 Code). Beyond these approved bays are miles of Long Island Sound shoreline with additional bays and harbors that are not part of Long Island Sound waters. Some of these bays and harbors are engaged in aquaculture activity. Local towns regulate shellfish and seaweed activities within their bays and harbors on the north and south shores of Suffolk and Nassau Counties. These counties have a combined thirteen townships with three currently engaged in commercial aquaculture programs.

In addition to these local and state regulations, including New York Environmental Conservation Laws and New York State Department of State's Division of Administrative Rules laws found in in the New York Code of Rules and Regulations (NYCRR) that pertain to shellfish and seaweed farming, several federal agencies including the U.S. Army Corps of Engineers (USACE), National Oceanographic and Atmospheric Administration (NOAA) and the U.S. Coast Guard (USCG) are involved in the regulatory environment of shellfish and seaweed farming in New York.

Businesses interested in shellfish and seaweed cultivation in county and local waters need to understand the differentiation of legal rights of access and use through leases, licenses, and permits. Leasing, the grant of authority to access underwater land, is always controlled at the local level. Some townships control use of leased land by issuing licenses. Permitting, the grant of authority to use and conduct activity on the leased land is controlled at the state level through the NYS DEC. Another notable aspect of New York law is its site-specific nature. Suffolk County's shellfish leasing is limited to Gardiner's and Peconic Bays, which sit at the eastern end of the county. Regulatory authority rests with the county. In other parts of Long Island, townships possess regulatory authority. Such is the current practice in the townships of Brookhaven, Islip, and Oyster Bay. -

Once access to underwater land is lawfully established, a permit for aquaculture activity is needed, unless regulations allow for waiving the permit by the respective town. Permit applications were created by the NYS DEC and are subject to review and approval by the DEC. Accessible electronically, applications contain a significant level of detail and incorporate requirements from other state agencies such as the NYS

Department of State and relevant federal agencies including the U.S. Army Corps of Engineers and the U.S. Coast Guard. While electronic access is convenient, and the NYS DEC processes completed applications in a timely manner ranging from a few days to a few months, acquiring federal agency approval is recognized as a time-consuming process that can take well over a year or more. This is largely due to the USACE conducting biological assessments of the permitting site. NYS DEC's aquaculture fee for on/off bottom culture is $100.00 with additional fees for specific activities such as shellfish digging, harvesting, and shipping. Businesses seeking permits must identify their business organization form and submit proof of their good standing annually. The New York State Department of State website provides necessary guidance for businesses. Permits can be renewed, and the NYS DEC sends out renewal applications in the mail to existing permit holders to streamline the renewal process for them.

Shellfish History

Shellfish cultivation has a long history in New York. From 1884 through 1914, thousands of acres of underwater land grants were issued by Suffolk County, but the practice ended in 1915 when most land grants reverted to the county or state (Suffolk County Shellfish Aquaculture Lease Program Overview and History, n.d.). New York State made those land grants available for lease for the cultivation of shellfish through ECL §13-0301(1) and later via ECL §13-0302(1) and (4), which authorized the lease of up to 110,000 underwater acres for shellfish cultivation in Suffolk County's Peconic Bay and Gardiner's Bay, with a portion of those underwater lands designated and mapped for leasing known as The Shellfish Cultivation Zone. In compliance with state law, the Suffolk County Shellfish Aquaculture Lease Program in Peconic Bay and Gardiner's Bay was created to establish access to shellfish leases for cultivation on Long Island's east end.

Suffolk County shares regulatory authority with the state and the federal government. The county may issue leases for access to underwater land, but the state and federal government regulate activity that takes place on the leased land via permits. Regulated activity includes types of species cultivated and methods of cultivation and harvest. The Suffolk County Shellfish Aquaculture Lease Program consists of two Phases, each with ten-year terms and a review process. The review process for Phase I occurred in 2021 with continuation of the lease program into Phase II recommended (Suffolk County, NY L.L. No. 9-2021). Currently, 40 leaseholders are part of Phase II, and all cultivate shellfish. There are approximately 17,000 acres in Suffolk County designated for leasing for shellfish cultivation (Suffolk County Shellfish Aquaculture Lease Program Overview and History, n.d.).

Nassau County does not have a shellfish leasing program, but local towns have authority to determine whether to designate~~d~~ acres to support leasing for shellfish. Suffolk County shoulders an enormous responsibility to the researchers and farmers striving to explore the commercial and environmental value of aquaculture activity in local waters with legitimate interests from other groups. According to a Suffolk County environmental analyst, use of Long Island Sound waters requires balancing aquaculture interests and recreational interests. Suffolk County has received objections from yacht clubs and waterfront homeowners concerned about their rights of use in relation to underwater aquaculture land use. In response, local laws contain public notice and hearing requirements following the submission of an application. The addition of time in the application process ensures the public is informed about intended use of waterways allowing for objection and review at the application stage. The state also required public notice for leasing of state-owned land for shellfish cultivation, as well as a bidding process (ECL §13-0301(2)(b), 2014). In 2022, a more detailed public notice requirement was enacted requiring shellfish lease applications to be posted in offices with the state, county, and local government for a two-month period along with notice placed in the official county newspaper (ECL §13-0302). Suffolk County also provides for review of shellfish cultivation leases applications by the Suffolk County Aquaculture Lease Board, which has authority to conduct meetings as needed (Suffolk County, NY, Ch 475, Art. II, of the 2011 Code).

Seaweed History

Statewide recognition of seaweed cultivation came in 2016 when ECL § 13-0302 was amended to authorize Suffolk County to conduct a pilot program for scientific research and assessment of the feasibility of seaweed, specifically kelp, cultivation on 5 one-acre parcels on existing shellfish leases. The ECL was amended again in 2021 to provide Suffolk County with the expanded authority to lease lands for kelp farming.

In 2022, ECL § 13-0302(1) was amended to replace "kelp" with "seaweed cultivation" as an authorized purpose to the leasing of underwater land in Gardiner's Bay and Peconic Bay. This law also authorized the establishment of a Seaweed Cultivation Zone to be used for implementation of a seaweed cultivation leasing program (ECL § 13-0302(8), 2021). Persons with existing Suffolk County issued shellfish leases were eligible to lease up to five acres in the cultivation zone with no more than one acre set aside for seaweed cultivation and permit applications were waived. In compliance with ECL § 13-0302, Suffolk County authorized the creation of a Seaweed Cultivation Pilot Program and reporting of results to the County by January 2026 (Suffolk County, NY Ch. 475, Art. III, §§ 24 to 32).

The addition of a role for seaweed was welcomed by researchers interested in the potential for use of locally cultivated seaweed and shellfish farmers looking to add to their existing species and continue farming in multiple seasons. However, the limited acreage for seaweed and the state's two-month public notice period, applicable to shellfish and seaweed lease applications alike, impacts farmer's ability to transition quickly from seaweed cultivation for research and scientific purposes to the development of a commercial seaweed industry (ECL §13-0302(7)(c)).

In 2022 Governor Hochul vetoed a bipartisan bill that called for amending ECL 13 § 13-0301 to increase the amount of underwater land made available for seaweed cultivation, including Long Island Sound waters (A04817, 2021). In *Hochul Vetoes Seaweed Bill to Help New York Oyster Farms*, the governor characterized her veto as prudent considering the totality of the circumstances (Voelker, 2022). "Assessing potential environmental conflicts, commercial and recreational user conflicts and spatial planning must be undertaken before further leasing is considered. It is premature to consider a broader leasing program for seaweed aquaculture on state-owned lands currently, as the state is still considering the pilot program." (Voelker, 2022) In contrast, the bill's co-sponsor, Assemblyman Fred W. Thiele, Jr. said in a press release, "This bill would have allowed more kelp farmers and local enterprises to participate in a growing industry that can provide substantial environmental benefits for the state" (Thiele, 2021).

No other seaweed cultivation is occurring in Gardiner's and Peconic Bays at the present time. However, efforts persist and A04817 was referred to the Standing Committee on Environmental Conservation in the New York State Assembly in January 2024 (Permits the Leasing of State-owned Underwater Lands for Seaweed Cultivation, A.B. A04817, 247th Legislative Session, January 3, 2024). With an eye toward the future, researchers and farmers continue to work together, cultivating sugar kelp in the waters near Long Island Sound to explore its water quality improvement properties and commercial value.

In June 2023, NYS DEC unveiled its Off-Bottom Macroalgae Culture Permit issuing the state's first permit to a non-profit organization to study the potential environmental benefits of seaweed *Gracilaria tikvahiae* as a bioextraction species for improving water quality in the Bronx River. The Off-Bottom Macroalgae Culture Permit Application Instructions detail the process for obtaining a permit to cultivate native sugar kelp or other native species of macroalgae in the state's tidal waters. The first commercial seaweed permit was issued to a New York business operating in the Town of Brookhaven's Moriches Bay for cultivation of sugar kelp. Additional commercial permit applications have been submitted for review. In addition, the townships of Huntington and Hempstead each received permits for research efforts. A permit is required whether the purpose of cultivation is research, environmental or commercial. Below is a summary of existing permit regulations for shellfish and seaweed cultivation based on NYS DEC applications.

Table 3.5 Summary of New York Permit Regulations – Shellfish

Lease/Access	Regulatory Agencies	Application Documents	Distribution
Suffolk County Aquaculture Lease Program – Peconic Bay and Gardiners Bay Town of Islip Bay Bottom Licensing Program in Great South Bay Town of Brookhaven Mariculture Leasing Program NYS DEC Temporary Marine Area Use Assignment – state owned underwater lands in LI Sound and Block Island Sound	United States Army Corps of Engineers (USACE), New York District United States Coast Guard (USCG) New York State Department of State, Office of Planning & Development NYS Department of Environmental Conservation (DEC)	Joint application USACE and NYSDEC Environmental Questionnaire Project Drawings Federal Consistency Assessment Form USCG Private Aids to Navigation (PATON) Permit NYS Environmental Quality Review Act (SEQR) Forms Short Environmental Assessment Form (SEAF) Part I Supplementary Information from All Applicants - copy of written authorization for land access (lease); aerial view site map or survey of cultivation location; Site photos (4); Nautical aids to navigation specifications for buoys and markers; vessel information; Cultivation/Operational Plan. Off-bottom culture applicants: detail regarding gear; deployment system and gear quantities with details regarding anchoring, buoying and marking of gear on underwater land parcel; drawings of off-bottom culture gear and deployment systems as it will appear on the site; bird mitigation for floating gear to address potential bird pollution problem. On-bottom culture applicants - planting design and activities; drawings of on-bottom planting design; mechanical harvesting gear and activities.	Completed applications must be sent to: NYSDEC Shellfish Management Unit of the Division of Marine Resources. USACE NY District; and NYSDOS Office of Planning & Development.

Table 3.6 Summary of New York Permit Regulations – Seaweed/Macroalgae

Lease/Access	Regulatory Agencies	Application Documents	Distribution
Township programs exist in Brookhaven, Islip and Oyster Bay. Currently no state lease programs exist.	United States Army Corps of Engineers (USACE), New York District United States Coast Guard (USCG) New York State Department of State, Office of Planning & Development NYS Department of Environmental Conservation (DEC)	Joint application USACE and NYSDEC Environmental Questionnaire Project Drawings Federal Consistency Assessment Form USCG Private Aids to Navigation (PATON) Permit NYS Environmental Quality Review Act (SEQR) Forms Short Environmental Assessment Form (SEAF) Part I Supplementary Information from <u>Off-bottom culture applicants</u>: copy of written authorization for land access (lease); aerial view site map or survey of cultivation location; Site photos (4); Nautical aids to navigation specifications for buoys and markers; vessel information; Cultivation/Operational Plan; detail regarding gear; deployment system and gear quantities with details regarding anchoring, buoying and marking of gear on underwater land parcel; drawings of off-bottom culture gear and deployment systems as it will appear on the site; and purpose of the cultivation activity as commercial or non-commercial.	Completed applications must be sent to: NYSDEC Shellfish Management Unit of the Division of Marine Resources. USACE NY District; and NYSDOS Office of Planning & Development, Consistency Review Unit.

Interview Data Analysis

Against the backdrop of a multi-tiered regulatory landscape, researchers and farmers are forging a path for shellfish and seaweed cultivation for commercial purposes. In addition to the 40 permits for shellfish cultivation as part of Suffolk County's Phase II program, shellfish and seaweed cultivation is taking shape in other parts of Long Island. NYS DEC created a separate permit application for macroalgae and reported that the first Off-Bottom Macroalgae Culture Permit Application received approval in Spring 2023 for environmental research by a non-profit organization that intends to grow *Gracilaria tikvahiae* in the Bronx River. Eight additional Off-Bottom Macroalgae Culture Permits applications were submitted to NYS DEC by mid-June 2023 for cultivation of sugar kelp. Three applications are from commercial oyster farms in the Towns of Islip to operate in specific bay areas. Three applications are from shellfish hatcheries and seeding programs in East Hampton, Islip, and Hempstead. Two applications are for non-commercial use involving education and research in New York Harbor and Jamaica Bay. The Town of Huntington reported plans to expand its seaweed cultivation pilot program, which initially operated in one harbor last season that concluded with a harvest in April 2023, to now all five harbors within the township. Those applications are currently being prepared for submission to NYS DEC for the upcoming season.

Finally, NYS DEC reported permit applications to produce sugar kelp spools and kelp strings have also been submitted for both commercial and non-commercial purposes from marine hatcheries in Hempstead, West Sayville, Southold, and a few other towns. In spring of 2023, the first commercial sugar kelp permit was issued for cultivation and harvest in Moriches Bay. The permit process spanned a two-year period. As this was the first permit of its kind in New York State, extensive work by the USACE was done as part of the biological assessment to ensure preservation of marine life and of navigable waters. Since that time, Hempstead and Huntington received permits for non-commercial kelp cultivation.

Sugar kelp cultivation was a success in Huntington, according to an interview conducted with their Deputy Director Department of Maritime Services. The town's pilot program, using pre-seeded kelp lines in four town harbors, concluded successfully in April 2023. As a result, a decision was made to expand the pilot program to all six harbors in the township in the 2024 season. To prepare for the expansion, the town completed the permit process in summer 2023. One of the most intricate parts of the application process was mapping the sites where the 100-foot seeded kelp lines will be anchored to mooring balls on either side. Photos and GPS coordinates of the harbor sites were required. Each site was selected based on minimal intrusion into active harbor areas even though the growing and harvesting season for sugar kelp does not coincide with busy summer use months. Another notable regulatory experience was the need to obtain approval to access the land at the local level from the Huntington Board of Trustees.

A non-profit organization who participated in an interview for this project dropped lines to grow *Gracilaria tikvahiae* in the summer of 2023. This youth advocacy non-profit organization includes educational programs in environmental science, where the seaweed cultivation efforts are managed. They hope to understand how seaweed absorbs nitrogen to improve water quality in the Bronx River, with a goal toward restoration of the river. They laid four moorings in Long Island Sound just off Hunts Point with two long seeded lines in between the moorings. The Director of Environmental Science and Justice at the non-profit acknowledged that obtaining a permit was an involved process. To complete the application, they provided detailed information about the site of the seaweed lines and communicated with both NYS DEC and USACE as they conducted a biological assessment of the water site. Despite the time and effort, the Director of Environmental Science and Justice stated "the permitting process was not going to stop us from getting involved in seaweed farming. We hope the renewal process is straightforward so that we can continue this work."

While growth and harvest of shellfish and seaweed are two commercial endeavor options, there are other business opportunities after harvest. One processing company located on the east end of Long Island works with wet kelp, which they dry, grind, mill, package, and sell to customers. According to a co-owner, the company receives kelp from Connecticut, Rhode Island, New Hampshire, and Maine. They purchase the kelp and process it on Long Island in compliance with regulations from the New York State Department of Agriculture and Markets. This company is a licensed commercial fertilizer distributor. Part of their regulatory activity includes product testing for impurities and label testing to ensure accuracy of labeling information. They must report to the Department of Agriculture and Markets on the amount of kelp processed and sold for compliance with state recordkeeping on kelp imports and exports.

A second interview with a Long Island processor of kelp was conducted, but this business is a relative newcomer to aquaculture processing. This company began growing hops for craft breweries on Long Island, and their transition to kelp processing was relatively easy because the equipment once used for drying and processing hops was easily converted to drying and processing sugar kelp. Contacts from farming resource Cornell Cooperative Extension put the company in contact with the east end processor referenced above. The two businesses collaborated on opportunities and best practices for sugar kelp processing, forming a business relationship between the two processors. For the past two years, they have received raw kelp grown and harvested in New England from the east end business. They dry and grind the kelp into a powder in their mills and deliver bulk packages of the dried, ground kelp back to the east end processor for packaging and commercial sale. While sugar kelp is a small percentage of their current business operation, they are open to expanding sugar kelp processing in the future. Recently, they processed kelp from the Town of Huntington's pilot sugar kelp program by drying it over a four-to-five-day period in their mills and delivering the ground powder back to the Town of Huntington. The co-owner hopes the regulatory environment does not become overly burdensome because he sees this as an industry with promise for entrepreneurs.

Regulatory Landscape in Connecticut

Connecticut's authority over shellfish and seaweed rests with the Connecticut Department of Agriculture, Bureau of Aquaculture (DA/BA). Shellfish farming dates back hundreds of years, and today, approximately 70,000 acres of shellfish farms exist (CT.gov Home/Department of Agriculture/Shellfish Industry Profile, 2011). Connecticut General Statutes §§ 22 and 26 detail the regulation of shellfish and seaweed farming. In June 2023, new legislation was signed that called for the development and expansion of small-scale aquaculture operations for shellfish in the state (State of Connecticut, Substitute House Bill No 6725, Public Act No. 23-184, 2023). Seaweed cultivation has been a legal activity in the state for more than a decade.

Additional regulatory authority exists within several state agencies including the Connecticut Department of Energy and Environmental Protection (CT DEEP), which has a major role in the permitting process. The state has authority to issue shellfish aquaculture leases in state waters, including the waters of Long Island Sound. In general, towns retain leasing authority for shellfish and seaweed cultivation in their harbors. With respect to seaweed licenses, regardless of whether the cultivation site is owned by the state or town, issuing authority lies solely with the Connecticut DA/BA. Compliance with federal law is required for post-harvest activities involving seaweed. Federal regulatory agencies are also involved, including the U.S. Army Corps of Engineers, National Oceanographic and Atmospheric Administration, and the U.S. Coast Guard.

Shellfish

Connecticut has a rich shellfish farming history, distinguished in the 1890's with the largest fleet of oyster steamers in the world (CT.gov Home/About Connecticut/State Symbols/The State Shellfish, n.d., para 3). Shellfish leases in state waters must be between fifty to two hundred acres, which is relatively large compared to other New England states (Schulter, 2021). Shellfish licenses are issued through a competitive bidding process and there is no public notice requirement under state law although some towns have implemented such a provision (Schulter, 2021). While there is a distinction between state owned and municipal owned underwater land, several towns in Connecticut are under state control. Waters in the towns of Bridgeport, Milford, West Haven, New Haven, Westport, and the Branford Initiative Area are regulated by the state.

Seaweed

Connecticut recognizes two approved species of seaweed, *Gracilaria tikvahiae* and *Saccharina latissima* (sugar kelp) for commercial cultivation, but only sugar kelp can be grown for commercial sale in Connecticut waters (Connecticut Sea Grant, 2024). Kelp is approved for human consumption and regulated for food safety by the state in compliance with federal regulations, but the state acknowledges the possibility of other uses, including fertilizer, biofuel, animal feed, or cosmetic ingredients (Kelly, 2019, para. 8).

The Connecticut Department of Agriculture, Bureau of Aquaculture has numerous resources for licensure. Interested parties should review materials on their website, including a guide for completing license applications electronically (ELicense Online, n.d.). The Department of Agriculture, Bureau of Agriculture established a set price of $25.00 per acre of underwater land and offers a license term of five years. License fees are waived if the site location for seaweed cultivation is on an existing shellfish aquacultural space. On its website, the Connecticut Department of Agriculture reported kelp farms in, or proposed in, Greenwich, Stamford, Norwalk, Fairfield, Milford, Branford, Groton, and Stonington (Kelly, 2019, para 1). Connecticut Sea Grant records indicate four commercial permits have been issued for the cultivation and harvest of seaweed. For one of the permit holders, sugar kelp cultivation is part of a larger business, which includes the operation of a marina from May to November. A valuable resource for farmers is the Sugar Kelp Cooperative, which was established in 2022 by several regional aquaculture farmers with expertise they share in support of their belief that the aquaculture industry holds commercial promise (Shirvell, 2023).

The Department of Agriculture's website contains links to various resources available to the public. The *2019 Guide to Marine Aquaculture Permitting in Connecticut* by Connecticut Sea Grant, explains the state's permitting process in five steps with information about site selection, intended use, planting and cultivation, production, as well as handling, harvest, and sale to the public. Each step identifies the various permit/license applications that must be prepared for the regulatory agencies involved. Below is a summary of the five steps, highlighting relevant agencies and applications.

Table 3.7 Summary of Connecticut Permit Regulations - Shellfish and Seaweed

Step	Required Application	Government Agency & Notes
Step 1 Site Selection & Designation: To obtain access to approved underwater land		
State Waters	Shellfish Lease Application	CT DA/BA – competitive bidding process exists with successful bidder paying legal notice fees and costs for necessary equipment used
Town Waters – excluding Bridgeport, Milford, West Haven, New Haven, Westport and Branford Initiative Area	Town-specific application	Contact local shellfish commission or town selectman/mayor
Town Waters of Bridgeport, Milford, West Haven, New Haven, Westport (under state control)	Shellfish Lease Application	CT DA/BA
Branford Area Initiative – state owned 900 acres of commercial shellfish ground in Town of Branford	Branford Area Initiative License	CT DA/BA
Seaweed	Seaweed Area License	CT DA/BA – Nontransferable license for a term of 5 years issued by Dept. of Agriculture. $25.00 per acre unless applicant has active shellfish lease.
Step 2 Use of Aquaculture Organisms Only native species sources from Long Island Sound. Native shellfish are oysters (Crassostrea virginica) and clams (Mercenaria mercenaria), and native seaweed is kelp (Saccharina latissima)	Scientific/Resource Assessment License	DA/BA If for non-commercial uses such as research, education, habitat restoration, stock enhancement project.
Step 3 Planting and Cultivation Permission to plant & cultivate & use gear/facilities		For commercial and non- commercial uses Local, state and federal agencies are involved.
Bottom Culture Molluscan shellfish only – No gear/facilities State waters	Shellstock Shipper License	DA/BA
Bottom Culture Molluscan shellfish only – No gear/facilities		Relevant town requirements

Town waters – Bridgeport, Milford, West Haven, New Haven, Westport and Branford Initiative Area		
Shellfish & Seaweed Using Aquaculture Gear/Facilities	Joint Agency Application for Marine Aquaculture	DA/BA CT DEEP Land & Water Resources Division USACE
	CT DEEP General Permit or Certificate of Permission or Structures, Dredging & Fill and Tidal Wetlands Permit	CT DEEP Only if potential interference with navigation in customary boating & shipping lanes and channels exist as determined by agency review above.
	CT DEEP Regulatory Buoy Marker	CT DEEP
	Surface Water Discharge Permit Program; Ground Water Discharge Permit Program; Pre-treatment Permit Program	CT - Only if project will discharge water, substances or materials into state waters
	Department of Army CT General Permit	Only where activity results in no more than minimal adverse environmental impact
	Department of Army CT Individual Permit	Only where state and/or federal agencies have identified concerns for other than minimal adverse environmental impact
Town Waters	Written approval from CT DA/BA, CT DEEP, USACE	
	Possible additional agency involvement	Ct Department of Public Health; CT Department of Consumer Protection; CT State Historic Preservation Office; U.S. Food and Drug Administration; U.S. Coast Guard; Bureau of Ocean Energy Management; Northeast Fishery Management Council; and Atlantic States Marine Fisheries Commission
		Successful compliance = Certificate of Aquaculture Operations issued by CT
	Seafood Sanitation & Training Plan	Only if intent to harvest and sell product for public consumption
Step 4 Production Only licensed commercial businesses may cultivate, harvest		

and sell aquaculture products to the public.		
Shellfish	Shellstock Shipper 1 License	DA/BA
	Seafood Sanitation & Training Plan	DA/BA
Seaweed – Raw Unprocessed = fresh seaweed sold by agricultural unit and in an unsealed bag or box. Seed source must be CT hatchery and utilizing spawning stock harvested from LI Sound waters	Aquaculture Seaweed Producer License	DA/BA
	Seafood Sanitation & Training Plan	DA/BA
Seaweed – Processed = cut, blanched, cooked, dried, frozen	Seaweed Producer License	DA/BA
	Food Manufacturing Establishment License	
	Seafood Sanitation & Training Plan	DA/BA
	Food Labeling compliance is required by CT law.	Compliance with the following agency rules: Federal Food, Drug and Cosmetic Act; Federal Fair Packaging and Labeling Act; and Uniform Packaging and Labeling Regulation
Step 5: Handling, Harvest and Sale		
Safe Seafood Harvest		DA/BA is responsible for classifying aquaculture growing waters, monitoring water quality, identifying pollutants and taking corrective actions as needed. DA/BA ensures CT complies with federal regulations on shellfish sanitation.
Shellfish & Seaweed Producers	Take Hazard Analysis and Critical Control Point Training	DA/BA: CT Sea Grant Course offered 2-3 times annually FDA Seafood Regulation requirements
Shellfish & Seaweed Producers	Develop Hazard Analysis and Critical Control Point Plan	DA/BA: CT Sea Grant Course offered 2-3 times annually FDA Seafood Regulation requirements
Shellfish Producers	Inspections at least twice annually	DA/BA
Seaweed Producers	Inspection once annually due to seasonal nature of crop	DA/BA

Interview Data Analysis

Per the Department of Agriculture, Bureau of Aquaculture, there are four active commercial seaweed permit holders in Connecticut, but only one agreed to participate in an interview. This business is a not-for-profit organization focused on marine resource education and sustainability, which shared that they hold a 5-year license for their cultivation location and comply with annual permit renewal requirements that they described as not overly burdensome. They are not engaged in commercial activity, but instead donate harvested kelp for use as a biostimulant. In future seasons, they hope to expand post-harvest use by drying and grinding the kelp in-house.

Impact of Water Quality in New York and Connecticut

In New York, water quality sampling is conducted year-round by the DEC to classify shellfish harvest areas that are safe for post-harvest use. According to the DEC, shellfish may only be harvested, whether for commercial or recreational purposes, from open or "certified" waters. Certified waters are those meeting strict state bacteriological standards. The DEC maintains a Shellfish Public Mapper with updated information on certified areas and uncertified areas throughout the year. Title 6 of the Department of Environmental Conservation Chapter I, Subchapter F Marine Fisheries provides information on sanitary conditions of waters along the Long Island coast in Suffolk and Nassau counties and beyond (6 NYCRR §§41.1-41.5).

The DEC identifies three methods that enable shellfish from closed areas to be used, including for human consumption. Conditional certification, transplanting, and depuration offer the necessary cleansing environment and time. Conditional certification is useful when closure is due to temporary conditions and the shellfish can be cleansed over a seven-day period. Transplanting allows for the removal of shellfish from a closed area with placement in an open area for at least 21 days. Depuration occurs when shellfish are removed from a closed area and placed in tanks of seawater that cleanses them for a period of 48 hours. Regulations, including DEC approval and permits, govern these processes. For example, shellfish from uncertified areas may be transplanted between April 1st and October 10th for cleansing and eventual marketing as a food product. Shellfish of less than marketable size (seed) may be transplanted between March 1 and October 31 (6 NYCRR §45). Transplanting is subject to DEC approval and permit conditions. Currently there are no DEC regulations on seaweed cultivation in uncertified waters.

Connecticut identifies five classifications of water quality. State monitoring is an on-going process. The public is made aware of water quality status and changes through the state's Shellfish Area Classifications & Maps. The five classifications are: Approved, Conditionally Approved, Restricted Relay/Depuration, Conditionally Restricted, and Prohibited (Ct.gov Home/Department of Agriculture/Shellfish Area Classification & Maps). Shellfish intended for human consumption must be harvested from Approved or Conditionally Approved waters. Harvesting shellfish from the remaining classification areas is permissible for limited purposes other than human consumption and may require state licensing. There are no water quality classifications specific to seaweed, however the current shellfish water quality classifications are applicable to seaweed. Seaweed may only be cultivated in Conditionally Approved or Approved waters. Changes to classifications are made by the state. Any request for reclassification is weighed against data compiled over a three-year period as well as the actual or potential pollution risk in the water area.

Current regulations in Connecticut and New York on the use of shellfish or seaweed from unapproved or uncertified waters refer to end use for human consumption. At the present time, no regulations specific to other end uses from such waters have been issued.

Emerging Markets

Federal law is often a primary source of regulatory guidance in post-harvest market considerations. At the state level, the New York State Department of Agriculture and Markets regulates post-harvest shellfish activities. However, this agency does not regulate the cultivation or harvest of seaweed at the present time. The NYS Department of Agriculture and Markets recommends compliance with all applicable federal regulations for use of seaweed to ensure product safety. The Connecticut Department of Agriculture has similar regulatory authority.

This report has identified potential markets for shellfish and seaweed post-harvest, including as food for human consumption, biostimulants, cosmetics, pet food, animal feed, and potentially as a nutraceutical. Express federal regulation of seaweed as a food product is lacking in part because seaweed is not included in the definition of fish or fishery products in current regulations (Janasie, 2023).

Federal regulations on sanitary conditions are not directly applied to seaweed, but many states rely on the system for food safety in the federal Hazard Analysis Critical Control Points (HACCP) and their state regulations reflect that. In Connecticut, the permitting process identifies several steps, which incorporate requirements for food safety training and planning (*Seaweed Production and Processing in Connecticut: A Guide to Understanding and Controlling Potential Food Safety Hazards*, 2019). New York Sea Grant is currently working to produce a guidance document to address food safety best practices for seaweed grown in New York waters and identified a need to develop regulations over seaweed as a raw product, given a concern for the presence of chemical contaminants.

Biostimulants are a possible market for shellfish and seaweed use. Biostimulants are not fertilizers that provide nutrients directly to plants, but they can help plants acquire nutrients by supporting various metabolic processes (Madende, 2020). The Environmental Protection Agency (EPA) and U.S. Department of Agriculture (USDA) are two agencies involved in regulatory considerations and review of biostimulants. The EPA has prepared a guidance document addressing plant regulator products and claims including plant biostimulants, which can be consulted by processors and end users (U.S. Environmental Protection Agency, 2020).

Use of seaweed as a cosmetic component has been researched. Seaweeds are the most extensively studied marine organisms since they are a biodegradable and non-toxic source of natural compounds with a vast array of benefits, such as delaying skin aging, providing antioxidants, and immunomodulatory benefits (Fonseca, 2023). The Federal Food, Drug and Cosmetic Act of 1938 regulates ingredient use in cosmetics by prohibiting misbranded or adulterated cosmetics in interstate commerce (21 U.S.C. § 301 et seq.). Under federal law, raw materials making up the ingredients in cosmetic products are also treated as cosmetics (21 U.S.C. § 201(i)). Businesses utilizing seaweed as a raw material in skin creams, lotions, makeup, and other products are subject to Federal Food, Drug and Cosmetic Act packaging regulations and future regulatory actions.

When considering pet and animal feed markets, businesses should be aware of regulations at the federal and state levels. Under the Food and Drug Administration, the Federal Food, Drug, and Cosmetic Act requires safety of pet and animal food, sanitary manufacturing conditions, and truth in labeling. Connecticut's Department of Agriculture oversees pet and animal food through their Food Safety and Agricultural Commodities Unit, Bureau of Regulatory Services, which regulates the safety and sanitary nature of pet and animal food. In New York, Article 8 of the Agriculture and Markets Law: Manufacture and Distribution of Commercial Feed is the source of pet and animal food safety and sanitary regulations.

Seaweed has also been explored for possible effectiveness as a nutraceutical. In the United States, nutraceutical products are regulated as drugs, food ingredients, and dietary supplements (Chauhan, 2013). While nutraceutical compounds may have use in disease prevention and treatment, only pharmaceutical compounds have governmental sanction (Chauhan, 2013). Food and Drug Administration regulations over dietary supplements apply after products have entered the marketplace. The Food and Drug Administration works to ensure that dietary supplements meet applicable safety standards and that they are well-manufactured and accurately labeled (U.S. Food and Drug Administration, 2023).

Regulatory Conclusions

The aquaculture industry is at the center of anticipated environmental benefits and promising commercial opportunities. Interests such as improving water quality, preserving marine habitats, maintaining safe recreational uses, and exploring commercial avenues come together in a single industry. The aquaculture industry is heavily regulated in Connecticut and New York. Multiple federal agencies also impose regulations on aquaculture activities conducted within each state. Regulatory compliance is a component of the business environment for parties seeking to cultivate shellfish and seaweed. Connecticut and New York have guidance documents and continue to implement programs that help support those seeking entry into the industry. In addition, non-profit organizations exist in both states that offer a wide range of assistance to businesses, including assistance navigating the regulatory requirements. The current regulations are intended to address the interests of many stakeholders, but they should be examined at all levels to create an efficient and business-friendly point of entry to the aquaculture industry. Expansion of seaweed cultivation in New York state-owned waters as well as expanded acreage in county waters can support industry growth.

Value chains

In examining value chains or the value proposition offered by seaweed, it would be necessary to examine the value added at multiple stages, including farming the raw material, processing the raw material for manufacture and packaging, value added by advertising, logistics, and brand marketing, and environmental and societal value addition. Clearly, the value chain is complex and for a product like seaweed, which is in the initial stages of development as a non-food-based product, any analysis at this stage is by necessity preliminary. In many ways, the directions in which seaweed could develop will depend on innovations in research and technology, in farming, in manufacturing, and in marketing. However, for our purpose, we perform a preliminary value chain analysis based in many ways on the complexity of the product market in general. For example, the use of seaweed as food is well-established and accepted by consumers, at least in East Asia and Southeast Asia. Thus, the value chain for seaweed in food is relatively less complex and already exists. However, in a product market like pharmaceuticals, much more research and technology investments are needed before the use of seaweed in pharmaceutical can be established. The values chain for seaweed in pharmaceuticals is therefore both uncertain and complex.

In deciding the short- and medium-term market sectors to focus on, we need to consider the complexity of the value chain, the capital and investment involved in setting up a value chain, and whether it would be possible to use existing value chains to support the production and marketing of seaweed. Our perceptions of the value chain are preliminary and based on secondary research and interviews.

Table 3.8: Value Chain Analysis

Product	**Manufacturing complexity**	**Value chain complexity**	**Capital and investment**	**Level of technology**	**Volume requirements**	**Overall feasibility**
Biostimulant	Low	Low	Medium	Low	High	High and Short term
Animal feed	Low	Low	Low to Medium	Low	High	Low
Pet food	Low to Medium	Low	Low to Medium	Medium	Low to high	High and Short term
Cosmetics	Medium to High	Medium to high	Medium	Medium	Low to High	High and short term
Nutraceuticals	Medium to High	Medium to Hhigh	High	Medium to High	Low to High	Long term
Fabrics	uncertain	Medium to High	Uncertain	High	Medium to High	Long term
Bioplastics	Uncertain	High	Uncertain	High		Long term
Construction	Uncertain	Medium to High	High	High	High	Long term
Pharmaceuticals	Uncertain	High	High	High	Uncertain	Long term

Overall Conclusions and Recommendations on Product Market Sectors

The conclusions and recommendations from our research on markets and regulations are as follows:

a) Product market sectors that are promising in the short-term for seaweed farming in the Long Island Sound include biostimulants, pet food, and cosmetics.

b) Product markets that are not viable in the short-term either due to low price realizations, need for large quantities of seaweed, severe price competition, or complex regulatory and technological requirements include animal feed, bioplastics, biopackaging, biofabrics, and biofuels, and fresh food.

c) Nutraceuticals and pharmaceuticals offer long-term potential due to the possibility of higher value addition and price realization. However, these sectors are in the nascent stages, and it may be many years before they may be considered viable markets.

d) The concept of biorefining by which multiple products can be extracted from seaweed simultaneously is worth exploring further, especially as technology develops to biorefine seaweed.

e) The economic and environmental impacts of growing seaweed in controlled containers may be worth exploring as it would add production capacity for seaweed production on Long Island.

f) Further research on the feasibility of market sectors would benefit with the addition of technical expertise focused on the conversion and processing of raw seaweed into downstream products.

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CHAPTER 4. ECONOMIC FEASIBILITY OF NITROGEN BIOEXTRACTION THROUGH AQUACULTURE IN LIS

1. INTRODUCTION

The following genus and species of macroalgae and bivalves were identified as possible candidates for cultivation in LIS including: *Porphyra* (*umbilicalis*), *Ulva* (*prolifera, lactuca, rigida*), *Cladophora* (*sericea*), *Gracilaria*, *Chondrus*, *Saccharina latissimi*, *Mya arenaria*, *Geukensia demissa*, and *Argopectin irradians*. In the case of macroalgal species, studies such as Buschmann et al. (2017), McHugh (2003), Porse and Rudolph (2017), and Garcia-Pozo et al. (2020) have identified multiple uses for cultivated seaweed and biomass in the market. The commonly identified uses for seaweed include food, food additives and ingredients for cosmetics (such as agar and carrageenan, or extracts), conversion into biofuels and energy, and fertilizer/biostimulants for agricultural and landscaping uses. While the biology team has identified viable candidates for use in aquaculture bioremediation, the key question is whether it is feasible to produce these species profitably. Addressing this question is the focus of the rest of this study.

Long Island has a long history of commercial marine based economic activity from oysters, bay scallops, other shellfish like lobsters, and a commercial fishing industry. One study by Li et al. (2016) found that the island's marine economy, a sector defined as "living resources, tourism and recreation, construction, minerals, and transportation" was responsible for approximately 13 percent of the region's gross domestic product of $170 billion. Within this sector, living resources accounted for $31 million in output and 468 jobs. The introduction and expansion of additional aquacultural activity, such as macroalgae farming in Long Island Sound, would add to this sector's output and contribution to employment and regional GDP. More importantly though, the production of these various macroalgae and bivalves may also lead to improved water quality, which would enhance the attractiveness of Long Island as a tourist destination, a much larger sector of the region's GDP.

It is important to note that from the standpoint of the individual firm, profitability implies generating enough revenue to cover all costs of production, including capital costs. This situation would occur through several scenarios: firms produce and sell their product directly in the market (e.g., industrial, wholesale, and retail users), they contract with the government (state and local) to engage in aquaculture at pre-established prices or output levels, or aquaculture is supported through some type of subsidy or water quality trading program (see Mascia and Gildesgame 2021; Racine et al. 2021; and Morgan and Wolverton 2005 for more discussion of water quality trading programs).

There is ample evidence in the literature that macroalgal species like *Saccharina latissimi*, *Gracilaria*, or bivalve species, such as *Geukensia demissa*, can be effective species for bioextraction (see for example Kim, Kraemer, Yarish 2017; Galimany et al. 2017). **The greater issue though is whether raising these species through aquaculture can be profitable. Our analysis suggests that it is possible that over time, this type of aquaculture could be profitable. Achieving profitability will likely require growers to find ways to process and market their output beyond its ordinary commodity uses of food and food additives.** In the next section of this report (Section 2), we review the relevant literature related to the economic aspects of the various species identified in Task 1. Following that (Section 3) is a discussion of data sources and data collection methods, and then a discussion (Section 4) of the method and process used to construct the cost models for the identified species of bivalves and macroalgae. In section 5, we present the cost tables and initial feasibility analysis. Section 6 presents the sensitivity and elasticity analysis. In Section 7, we discuss and present the overall results of the feasibility analysis. The conclusions are presented in Section 8.

2. THE ECONOMICS OF BIOEXTRACTION AND LONG ISLAND SOUND

Literature collection was conducted following the process identified in the approved QAPP. Academic databases including EconLit, ProQuest, Academic Search, ABI/Inform, Applied Science and Technology Source, Biological and Agr Index Plus, JSTOR, and Science Direct were searched using multiple keywords to identify the academic literature relating bioremediation and aquacultural practices to economics including production costs, processes, market demand, and similar terminology. Boolean keyword searches (depending upon database used) could result in as many as 8000 to 9000 peer reviewed articles, depending on the terms used. For example, a search using the terms “aquaculture and economics” resulted in 8200 possible articles. Other keyword term searches using more specific terminology (e.g. *Mya arenaria* and economics) resulted in as few as 7 articles. Closer inspection of the results for each Boolean keyword search by article titles, inspection of the paper’s abstracts, and the specific species or scope of the study resulted in the collection of 175 articles.

An additional snowball approach was followed, in which more literature was identified from the references of relevant articles and studies from the keyword searches. This process resulted in the collection of 28 additional articles. The literature collection was further supplemented through Google Scholar and internet searches to identify additional non-academic studies and reports available through non-profit organizations, state and local government, and similar authorities, yielding an additional 135 studies, reports, and data sources. Overall, 338 academic articles, organization reports, and studies were collected and reviewed. The literature reviewed in this section comprises the most relevant to the analysis conducted (and are included in the references to this report). The full list of literature collected is included as an attachment to the final report.

Over the past three decades, numerous studies and reports have been generated, highlighting the economic and market potential for aquaculture. These studies fall into a broad range of areas including production methods and costs including multitrophic production (see for example Tabrizi 1992; Ladner et al. 2018; or Szuster et al. 2008), technical studies with a focus on applications and uses for seaweed and shellfish products (see for example Arakaki et al. 2021; Baghel et al. 2020; Arbia et al. 2013), the demand for and marketing of aquacultural products (see for example Charles and Paquotte 1999; Chidmi, Hanson, and Nguyen 2012; Getchis et al. 2020), and a broad range of other topics such as agglomeration economies in aquaculture, and environmental policy, and the economic impacts of improved water quality (see for example Nepf and Walsh 2022; Sudhakaran et al. 2021). Many of these studies are beyond the scope of this study, and we will concentrate on a discussion of the most relevant literature related to the production, costs, and market related issues of macroalgae and bivalve aquaculture for bioremediation.

At the outset, it should be noted that improving water quality through aquaculture may have very positive benefits in the community. A recent study by Nepf and Walsh (2022) using a hedonic model of the housing market found that improved water quality may improve property values on Long Island within a 2000-meter distance from the coast by as much as $30,000. While they focus on water quality improvements arising from infrastructure improvements such the installation of improved household sewage treatment and handling systems, their analysis strengthens arguments to find appropriate methods to improve water quality in the area. Sudhakaran et al. (2021) using a hedonic analysis framework examine the impact of aquaculture (oyster farms) on property values in Rhode Island. Overall, they found that proximity to oyster farms tended to increase the value of homes. However, they also found that the value of luxury homes located near aquaculture operations fell significantly.

Studies such as Lee et al. (2006) focus on evaluating the demand for aquaculture products and identifying the various factors underlying that demand. Their study in particular focuses upon a range of species commonly sold in Taiwan. They found that price elasticities varied significantly across different species of aquaculture-raised products, including milkfish, tilapia, shrimp, shellfish, and carp. A demand study by Brayden et al. (2018) focusing on product attributes and characteristics found that while consumers appeared to prefer wild harvest for shellfish and seaweed products, they were willing to pay higher prices for products produced within their home state or bearing certification labels. Capps and Lambregts' (1991) study evaluated the retail demand for finfish and shellfish sold through markets using scanner data. Using a linear demand model in a seemingly unrelated regression (SUR) framework, they estimated the demand elasticities for fresh shellfish (shrimp, crab, lobster, oysters, and scallops) and a broad range of fresh finfish sold through a single multi-location retail market, finding elastic demand across almost all products. Girard and Mariojouls (2003), in their marketing and demand study of French mussel and oyster markets found quality to be an important factor impacting consumption. Lucas and Gouin (2019) use a multinomial probit model to analyze consumer preferences to consume seaweed products in France differentiating between traditional consumers of Asian seaweed products and other consumers willing to consume other products based on other attributes.

Many studies have focused directly on the production and costs associated with macroalgae and shellfish. Kite-Powell et al. (2022) developed a model for large scale seaweed aquaculture to produce biomass for conversion into biofuel. Their analysis focused on open ocean growing using large arrays of seeded line using cost parameters derived from previous studies and applied to farm sizes of 10 square-kilometers. They estimated the costs of production for *Saccharina latissima* produced in temperate waters to be in the range of $250 to $300 per dry ton for farms located 200 kilometers from shore and could also potentially fall to $100 per dry ton for farms located closer to shore. It should be noted that the model is hypothetical, and farms of this magnitude would likely be difficult to operate in some environments, such as Long Island Sound.

Campo and Zuniga-Jara's (2018) study focused on finding and evaluating the appropriate weighted cost of capital (WACC), the discount rate used to evaluate the net present value of an investment, that should be used as a baseline for profit analysis. Drawing on 80 previous academic studies evaluating various aquaculture investments, their analysis focuses on quantifying the long-run return rate for aquaculture. They found that across all the aquaculture studies analyzed (fish, bivalves, algae, and crustaceans), researchers have used an average rate of 10.6 percent. For seaweed and shellfish aquaculture projects to prosper and attract the necessary capital, they must compete with other investment opportunities.

In their study on the feasibility of producing seaweed in the North Sea, van den Burg et al. (2016) found that potential revenues were not high enough to make it profitable. Using revised and updated data from previous studies and a simulated profit function for a large-scale macroalgae operation in the open spaces around North Sea wind turbines and assuming seaweed farms managed by windfarm operators, they modeled potential output and profitability for seaweed going into alginate and animal feed uses. They identified alternative uses for seaweed but found that European markets would need to grow for the product to be used for human consumption and become profitable. In their economic simulation, Perreira et al. (2020) evaluated the production of *Hypnea pseudomusciformis* in Brazilian waters for small (150 long- lines) and medium-sized farms (450 long-lines). They constructed their model in a similar fashion as van den Burg et al. (2016) and found that for this species to be profitable, its market for human consumption and as an input into nutraceuticals would need to expand.

Unlike the other studies, Redmond et al. (2014) provided an overview on culturing and growing most of the taxa identified in Chapter 2, including *Gracilaria tikvahiae*, *Saccharina latissima*, *Chondrus Crispus*, and *Porphyra*. They noted methods for cultivating each of these species for either line or net culture, growth rates, temperature ranges, and other similar variables of interest. Similarly, Flavin et al. (2013) detailed aquaculture farming methods and techniques for three kelp species including *Saccharina*. It described in greater detail kelp farming from culturing and seeding line to farm set-up and operation. The authors note that 10-foot line spacing resulted in higher yields than 5-foot spacing. Radulovich et al. (2015) similarly describes cultivation methods for various seaweed species including longline and raft methods. In the Maine Seaweed Benchmarking Report (Brayden and Coleman 2023), they provide significant and recent details on the production costs and pricing of kelp grown in the Northeast. Brayden and Coleman found that larger farms (harvesting 75,000 wet pounds or more) were more profitable than smaller farms, the potential for scale economies as break-even price decreased with farm size, and that seaweed farming provided a second source of income for fishers (p. 2). Their analysis serves as both a valuable source for secondary data and means to benchmark and crosscheck data collected from the interviews conducted in this study. Hasselstrom et al. (2020), using a cost-benefit analysis methodology in which they estimate the net present value of large-scale kelp aquaculture in coastal Sweden, found that it could be profitable. Their initial starting point is the cultivation of *Saccharina latissima* for bioremediation. However, just as van den Burg (2016) concluded, Hasseltrom et al. (2020) also suggest that the Swedish and European market for seaweed as food and biomass (biofuel and similar uses) will need to further develop for the industry to be successful.

The Edible Seaweed Market Report provides additional detail to the industry in the Northeast (Piconi et al. 2020). Their study includes both pricing and cost data for both *Saccharina latissima* (sugar kelp) and *Alaria* produced in Maine waters, as well as general market analysis and an economic impact study of the industry on the state. Secondary data from this study has been used for both cross-checking other data as well as input in some cases directly into some cost tables for our study. Kim et al. (2017) provides additional discussion of production techniques for various macroalgae species.

Wu et al. (2023) evaluate the costs associated with alternative methods of growing seaweed (*Saccharina latissima* and *Gracilaria tikvahiae*). Their analysis is based upon trials of several methods of production, single-layer and dual-layer longline, single-layer and dual-layer strip process. They found that dual-layer methods and strip methods of production were lower cost than single-layer production methods. In addition, they also found that rotating between *Saccharina* and *Gracilaria* produced significant savings as well.

Samonte-Tan and Davis (1998) focuses on the production of oysters in the Philippines. While oysters are outside of the scope of our analysis, their study provides some cost modeling that can be applied to other shellfish processes. Their study identifies differences in efficiencies and costs between different growing techniques. Galimany et al. (2013, 2017) presented the results of two separate research designs with ribbed mussels (*Geukensia demissa*) for bioremediation. While these two studies do not address the economic costs or commercial viability of the ribbed mussel, they both provide some detail on several methods for its cultivation and its habitat suitability. In the case of Galimany et al. (2017), ribbed mussels were cultivated using a commercial mussel raft. The authors found that ribbed mussels could be successfully grown with this method. Filipelli et al. (2020) in their study found that cultivating blue mussels could be a cost-effective method for bioremediation in Denmark. Processing costs and marketing limitations on converting cultivated mussels into animal feed was a limiting factor on cost effectiveness. Lindahl et al. (2005) similarly evaluated the effectiveness using mussels for remediation of Swedish waters and found that it could be an effective and valuable method.

In a recent study of aquaculture in New York State, Forbes et al. (2022) documented the status of shellfish and macroalgae operations in and around Long Island Sound (LIS). As of 2022, 1694 acres of underwater land in LIS was leased and under cultivation. Thirty-four hundred acres of underwater land was under private lease for cultivation (Forbes et al. 2022, p. 10). Long Island was an important source for hard clams through the 20th century, but the fishery went into decline during the 1970s and early 21st century from overharvest and algal blooms. Over the past decade, hard clam production has increased resulting from water quality improvements and increased aquaculture. However, it is still well below historic production levels (p. 12). Bay scallops have also been an important commercial product in the region. The fishery went into decline through the 20th century due to multiple factors but in recent years bay scallop populations increased. However, in 2019, the fishery experienced another setback, and efforts continue to try and revitalize the industry (p. 13).

Forbes et al. (2022) also documented the recent introduction of macroalgae aquaculture in the region through the launch of the Nitrogen Bioextraction Initiative, an EPA, NYS DEC and NEIWPCC project, with experimental projects conducted through groups, such as Stony Brook University and Cornell Cooperative extension. They noted that permitting for macroalgae in the region remains limited and is under the purview of multiple entities including the Army Corps of Engineers, New York Department of Environmental Conservation, Suffolk County, and potentially other local government entities (p. 17). The report documented other aspects of aquaculture, including restoration projects, various aquaculture methodologies, and recommendations for expanding aquaculture in the state, such as addressing regulatory hurdles and supporting education to develop the workforce.

A recent study by St. Gelais et al. (2022) identifies macroalgae aquaculture (*Saccharina latissima*) as a valuable addition for Maine fishers to engage in as a method to enhance sales and revenue. Their focus is on using a low-cost mobile seaweed platform for fishers to use with their other marine-based activities, creating a second revenue stream and minimally impacting their primary fishing operations. In their study, St. Gelais et al. (2022) identify a ten-year range for kelp prices from $1.10 to $2.20 per wet kilogram with a median price of $1.65 per wet kilogram.

It is clear from the literature that aquaculture bioremediation is a viable means to address some pollutants such as excess nitrogen in Long Island Sound. The question, however, is whether it is an economically viable option or not. That issue is the concern of the rest of this study.

3. DATA COLLECTION AND INTERVIEW PROCESS

Following the QAPP (B3.3, B4.3, B9.3), data was collected through several methods. Primary data was collected through virtual interviews, though one interview was conducted by email. These interviews were initially recorded and automatically transcribed using Microsoft Teams. Transcripts were then stored in a password protected shared drive for use by the research team. As per the process description in the QAPP, a log of contacts with dates and response rates was maintained, but IRB confidentiality rules limit the sharing of this information, and only deidentified data extracted from the interviews can be shared and utilized (see Tables 4.1 and 4.2). An initial target of 20 industry-related interviews was established. However, with revisions to the QAPP, and as embodied in the approved revised schedule (revised QAPP approved October 5, 2023), this target was revised to 12-15 interviews. Several joint interviews were conducted with Task 2 members, as several industry individuals overlapped. In addition, primary data was collected directly from community hatchery websites, direct inquiry with sellers regarding retail sales prices and seeded line costs, and the use of tools such as the nonprofit GreenWave seaweed hub.

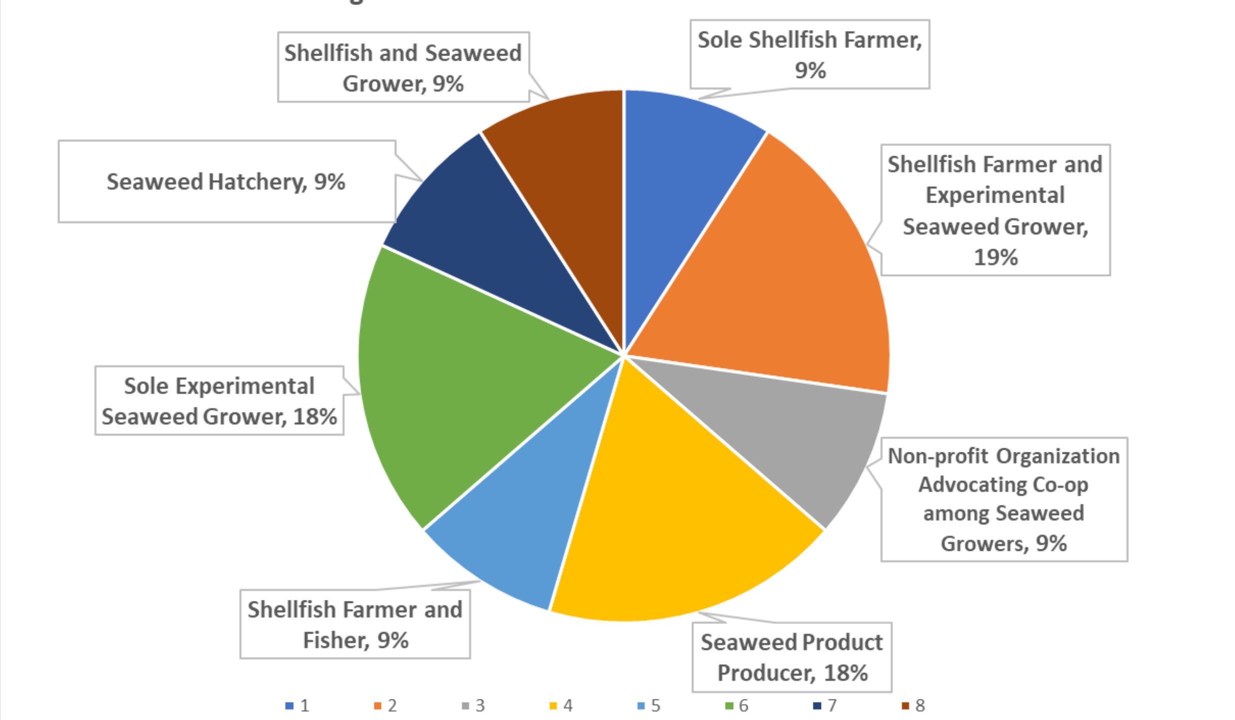
Table 4.1: Contacts and Interview Participation

Metric	Value
Initial contact list (#)	34
Not in business	0
Final list (#)	34
Rejected (#)	3
No response (#)	16
Completed interviews (#)	15 (4 experts)
Participation rate (%)	44.12%

While the QAPP was still under development and undergoing approval (July 2022-February 2023), the Economics team prepared and submitted its materials, including an interview script and informed consent form for participants (both instruments are included in the appendix to this document), to the Farmingdale

Institutional Review Board. These instruments were approved in March 2023, just before the QAPP was approved (March 2023). In May 2023, the Economics team, led by Dr. Zhang, began to contact industry stakeholders and shellfish and seaweed growers to discuss and arrange interviews. This process continued over a seven-month period, with the first stakeholder meeting conducted on May 15, 2023, and the final interview conducted on November 8, 2023. The interviewee's profile is attached below (Figure 4.1). As Figure 4.1 demonstrates, the sample of interviewee represents a good breadth of stakeholders of the aquaculture business in shellfish and seaweed in terms of relevant species and different stages of operation. There are 9% of shellfish and seaweed growers, 9% of sole shellfish farmers, 19% of shellfish farmers and experimental seaweed growers, 9% of non-profit organization advocating co-operatives among seaweed growers, 18% of seaweed product producers (using seaweed as ingredients for final products), 9% of shellfish farmers and fishers, 18% of sole experimental seaweed growers, and 9% of seaweed hatchery owners.

Figure 4.1 Interviewee's Profile



Secondary data was collected from multiple sources. As outlined in the QAPP, several federal government data sites were reviewed (USDA, US Commerce Department, BEA) as well as state databases for aquaculture and marine production. Much of the information collected from these sites was aggregated at too great a level to be useful. Most secondary data (both input into the cost tables and used as reference for cross-verification of cost structure) was extracted from several sources including the Maine Seaweed Benchmarking Report (2023), an investment study by BlueYou Consulting (2016), a study produced by Sea Grant (State of the States – Status of U.S. Seaweed Aquaculture, 2023), and Piconi et al.'s Edible Seaweed Market Analysis (2020). Additional data was collected from several academic studies, including Ladner et al. (2018), Kite-Powell et al. (2022), Campo and Zuniga-Jara (2018), and Pereira et al. (2020). Data from primary sources were cross-checked against values from secondary sources before being entered into and used in the cost tables for analysis.

Table 4.2: Contacts and Interview Timeline

Contact Code	Request Date	Interview Date
Stakeholder 1	5/12/2023	5/15/2023
Stakeholder 2	5/12/2023	5/16/2023
Stakeholder 3	5/12/2023, 8/11/2023	implicitly rejected
Stakeholder 4	5/30/2023	5/31/2023
Stakeholder 5	5/30/2023	never responded
Stakeholder 6	5/30/2023, 8/9/2023	never responded
Stakeholder 7	5/30/2023, 8/9/2023	never responded
Stakeholder 8	5/31/2023	never responded
Stakeholder 9	6/2/2023	6/2/2023
Stakeholder 10	6/9/2023	never responded
Stakeholder 11	6/9/2023	6/13/2023
Stakeholder 12	6/9/2023, 10/6/2023	11/8/2023
Stakeholder 13	6/9/2023, 8/9/2023	never responded
Stakeholder 14	6/9/2023, 9/28/2023	never responded
Stakeholder 15	6/15/2023	6/20/2023
Stakeholder 16	7/19/2023	never responded
Stakeholder 17	7/19/2023	rejected
Stakeholder 18	7/27/2023	never responded
Stakeholder 19	7/27/2023	never responded
Stakeholder 20	7/27/2023	9/1/2023
Stakeholder 21	8/3/2023	never responded
Stakeholder 22	8/17/2023	8/20/2023
Stakeholder 23	8/21/2023	rejected
Stakeholder 24	8/22/2023	9/6/2023

Stakeholder 25	8/23/2023	no response
Stakeholder 26	8/24/2023	never responded
Stakeholder 27	8/24/2023	10/11/2023
Stakeholder 28	8/31/2023	never responded
Stakeholder 29	9/5/2023	10/19/2023
Stakeholder 30	9/6/2023	9/15/2023
Stakeholder 31	9/7/2023	11/5/2023
Stakeholder 32	9/7/2023, 9/12/2023	no response (disconnected)
Stakeholder 33	9/28/2023	10/10/2023
Stakeholder 34	10/2/2023	never responded
Stakeholder 35	11/6/2023	11/7/2023

The global market for commercial seaweed was estimated at $15 billion in 2021 and predicted to rise to $24.9 billion by 2028 (Statista 2023). According to the most recent census of aquaculture (USDA 2018, p. 15), there were 26 saltwater farms in Connecticut with 26,884 acres in use, and 21 saltwater farms in New York with 2,102 acres in use. Robidoux and Chadsey (2022) reported that there were 15 permitted sites for the cultivation of sugar kelp in Connecticut with 4 farms under operation. Combined, these operations produced 3,800 pounds of *Saccharina latissima* (sugar kelp). In New York, there was no commercial cultivation of seaweed (*Saccharina latissima* or *Gracilaria tikvahiae*) in 2022, but 1,000 pounds of sugar kelp was grown under research licenses at 3 commercial oyster farms. This is in contrast with Alaska, where over 536,000 pounds of seaweed, primarily sugar kelp, was produced in 2021. Similarly, Maine produced 500,000 pounds of seaweed (*Saccharina latissima*, *Saccharina angustissima*, and *Alaria esculenta*) in 2020. The first commercial license for seaweed cultivation in New York was approved in summer 2023.

4. MODELING/INITIAL COST ANALYSIS

Following economic conventions, profits and costs are modeled as a function of price (P), output (Q), and inputs (quantity of input i, x_i; cost of input i, w_i): Profit = PQ - $\sum w_i x_i$. Profit maximizing firms will seek to minimize costs at various production levels. A recent econometric study by Gren and Tirkaso (2021) estimated a cost function for growing mussels in a meta-analysis using data from across 23 previously published studies. They modeled costs as a function of output level, wage rate, interest rate, salinity, temperature, consumption type (for human consumption), technology (production technology), mussel type, and several other variables (related specifically to the meta-analysis). Their study resulted in a stylized general cost function specifically focused on mussels (they include in their analysis blue mussels, zebra mussels, Mediterranean mussels, and green mussels). Other studies related specifically to macroalgae, such as Piconi, Veidenheimer, and Chase (2020), and Brayden and Coleman (2023), developed cost functions directly from reported survey data.

In the analysis that follows, we assume that aquaculture firms engaging in the production of one of the identified macroalgae or bivalve species operate under a set of constraints in which they invest a certain level of capital and enter into acreage lease agreements. While in the long run, all costs are variable, the firm will find its actions in the short run limited by these constraints. Thus, the total costs of seaweed and shellfish production depend on fixed costs (e.g., short-term constraints that may include fees for coastal land usage or license fee, fixed capital currently in place, and capital depreciation) and variable costs, including costs of seeds, labor, gear, fuel, service related to production (transportation, disease diagnostic services), maintenance and repairs, sales, and marketing. Data collected from interviews with growers, processors and relevant industry representatives was used to obtain the most up-to-date information on costs and revenues. In addition, interview data was combined with data collected from secondary sources (identified in Section 3). Cost and revenue tables presented in Section 5 follow the basic structure shown in Table 4.3.

The cultivation of macroalgae in Long Island Sound is new and not widespread, except for some experimental and demonstration sites in New York and 4 farms in Connecticut waters. Similarly, the cultivation of ribbed mussels in New York waters has primarily been for demonstration or experimental projects with no commercial applications. The closest commercial analog for the ribbed mussel in terms of cultivation techniques and some potential markets is the blue mussel. Consequently, we modeled ribbed mussel aquaculture using blue mussel cultivation as a proxy. The other two identified bivalve species (soft shell clam and bay scallop) have demonstrated commercial application. Soft shell clams historically were wild harvested from the intertidal zones, but in states such as Maine, they are increasingly cultivated through aquaculture (see Hagen and Wilkerson 2018). The bay scallop has a long history of production and harvesting in Peconic Bay. However, as noted in studies such as Forbes et al. (2022), the fishery has experienced significant decline due to disease and pathogens. Given its past commercial exploitation, it falls outside of the scope of this study.

The production cost of macroalgae is modeled in the following form:

1. $C = C_{cap\&material} + C_{operation} + C_{harvest} + C_{others}$, and
2. $C_{cap\&material} = C_{capital} + C_{seededline}$

Where $C_{capital}$ denotes the annualized equipment cost per acre, including vessels, vehicles (if applicable), buoys, anchors, and supplies such as ropes; $C_{seededline}$ is calculated as the cost per foot of seeded line times the length of seeded line per acre.

3. $C_{operation} = C_{insurance} + C_{license} + C_{op*labor} + C_{op*\ other}$.

$C_{operation}$ represents the annual cost of operating and maintenance cost per acre, including the business insurance cost, business license cost, business entity structuring fees for startups, labor cost attributed to farm operation (opportunity cost of owner's time), and other operating and maintenance costs. It should be noted that insurance costs identified from interview data and other primary and secondary sources does not include crop insurance. Bowen (2019) noted that crop insurance for aquaculture is included as part of the national crop insurance program. However, it is underutilized, with policies generally only available for oysters and cultivated clams. $C_{harvest}$ represents the annual harvest cost of harvesting seaweed per acre, which depends on $C_{har*base}$, the annual harvest cost of harvesting seaweed per harvest per acre, and $n_{harvest}$, the number of harvests in one year. C_{others} represents the annualized financial cost (if applicable) and miscellaneous costs per acre. It is assumed the owner's time, and other (financial) cost are not included in the calculation throughout this report.

Table 4.3: Structure breakdown of Cost Table (macroalgae)

Item	Cost Category
1	**Capital & Material Cost**
	Annualized Equipment Cost
	Expendable & Misc. Supplies
	Seeded Line Cost
2	**Operating & Maintenance Cost**
	Operation Labor Cost (Owner)
	Farm Setup Labor Cost
	Maintenance Labor Cost
	Business Operation expenses
	Other operating expenses
3	**Harvest Cost**
	Harvest Labor Cost
4	**Other Costs**

The production of shellfish, specifically ribbed mussels and soft-shell clams, is modeled similarly. Mussels are assumed to be cultivated using raft culture and we used blue mussel raft culture as a proxy for ribbed mussel cultivation. It should be noted that some towns and villages on Long Island have participated in projects for seeding sections of Long Island Sound waters with ribbed mussel spat as part of a plan to clean up the water (Lindner 2013; Town of Huntington 2013).

Mya arenaria (soft-shell clams) can be cultivated in intertidal zones in which aquaculture farmers seed juvenile clams in 14 by 20-foot plots to protect the clams from predators (Hagan and Wilkerson 2018). The specific number of plots will vary depending upon the size of the acreage lease granted to the farmer. Once the plots are seeded, the farmer will need to monitor the cultivated area. Hagan and Wilkerson note that it may take up to three years before the clams have grown to harvestable sizes (2 inches or more) and suggest that allowing more growth time could increase growers' income substantially. Since cultivating *Mya arenaria* takes place close to shore, this activity may face a greater level of regulation and local community restrictions than cultivating some of the other identified species.

Equipment needs and start-up costs for raising seaweed, mussels, and soft-shell clams may vary based upon location of operations. Kelp can be grown in a range of depths, from close to shore to deeper water.

Mussels can be grown in deeper water using raft culture. Soft-shell clam culture will likely only take place in shallower intertidal zones. Aquaculture activities taking place in shallower waters may have lower startup costs as capital expenditures on boating equipment may not be as extensive. On the other hand, existing fishers and aquaculture farmers, such as oyster farmers, may already have much of the necessary capital equipment in place and will only need to purchase a modicum of additional equipment and supplies to cultivate these species. Piconi et al. (2020), Engle et al. (2020; 2023), and Brayden and Coleman (2023) all note that expansion into kelp aquaculture has enabled existing Maine fishers to enhance their annual income potential. Cost tables for macroalgae and bivalves are presented in the next section (Section 5) of this analysis.

5. COST TABLES

Following the framework outlined in the previous section, production and revenue tables for macroalgae, soft-shell clams, and ribbed mussels were constructed. Both the costs and revenue are assumed to be linear within the space for cultivation along Long Island Sound. Bricker et al. (2015) estimated the value of nitrogen reduction in Long Island Sound to range between $17.4 million to $469.3 million. Their analysis was based upon using eastern oysters under several scenarios: (1) changes in harvest densities, and (2) the relaxation of legal constraints that could potentially increase the allowable acreage for cultivation. Their focus was primarily to estimate monetary values of nitrogen bioextraction to fit into a water quality trading regime.

Our analysis is directed towards bringing non-traditional species under cultivation in the Long Island Sound, with an orientation to whether it is feasible for aquaculture farmers to engage profitably in these activities. Aquaculture operations may be able to produce both shellfish and macroalgae in tandem with each other, in a rotational cycle (some species of macroalgae are primarily winter crops and would not interfere with other marine uses), or in a multi-trophic process.

For kelp production, we estimate costs primarily in terms of number of acres or the number of lines under cultivation. It is up to the individual aquaculture operation to determine their specific scale of operation. Previous studies, such as the *Maine Seaweed Benchmark Study* (2023), noted the presence of scale economies indicating per unit production costs may fall over some range of production. They also noted that many seaweed farms were engaged in other fishing and/or aquaculture endeavors. While it is impossible to capture all these variants in the cost table, we provide cost estimates for several different levels of production. These tables are not meant to serve as complete financial planning models for aquaculture farmers, but instead to provide a vehicle for overall feasibility analysis. (Individuals interested in entering directly into the industry can consult planning tools such as those found at GreenWave's Regenerative Ocean Farming Hub). Sales revenue for break-even analysis in Table 4.4 is determined as market price (p) times the yield (y) in pounds per lineal foot times the total footage under cultivation.

Table 4.4 presents the basic set of costs for macroalgae production. While growers may produce different species (*Saccharina latissima*, *Porphyra*, *Chondrus*), many of the costs for these species will overlap. Most of the production of macroalgae in the Northeastern U.S. has been sugar kelp (*Saccharina latissima*). Equipment costs of production are very similar, with the primary differences between them are in the growing season and the number of times annually that farmers may be able to harvest their crop. Following previous studies, such as those by Engle et al. (2023) and Brayden and Coleman (2023), we use sugar kelp as the base species for analysis, and where possible, use sales prices for the other species in the break-even and sensitivity analysis.

Table 4.4: Macroalgae annualized Cost Table, one-acre farm.*	
Item	**Value**
Total Revenue ($)	12705.50
Market Price ($)	0.60
Yield (lb ft^{-1})	7.70
Total Cost ($)	14687.26
Fixed Cost ($)	9764.76
Variable Cost ($)	4922.50
Total Profit ($)	(1982.26)
Startup Cost ($)	9764.76
Break-even Price for Total Cost ($)	**0.69**
Break-even Price above Variable Cost ($)	**0.23**
Capital & Material Cost ($)	11191.26
Annualized Equipment Cost ($)	6959.76
Material Cost	
Expendable & Misc. Supplies ($)	931.50
Seeded Line Cost ($)	3300.00
Unit price --Seeded line ($ ft -1)	1.20
Total length per acre (ft)	2750.00
Operating & Maintenance Cost	3018.00
Operation Labor Cost (Owner)**	0.00
Farm Setup Labor Cost (hired)	213.40
Maintenance Labor Cost (hired)	0.00
Business Operation expenses	2805.00
Harvest Cost	477.60
Harvest Labor Cost (hired)	477.60
Other Costs* (e.g. financial cost)**	0.00

* Assumes 15-foot line spacing with 250-foot-long lines, 11 lines total per acre.
** Assumes the compensation to an owner's time can be recouped through the profit.
***Assumes an owner owns the necessary funds to start the business. If, otherwise, other costs such as financial costs through a loan will be added to the cost table.

The production costs presented in Tables 4.4 and 4.5 show that at current prevailing prices for seaweed, farmers face significant hurdles to achieving profitability, especially if kelp is their only source of income. Macroalgae aquaculture is a nascent industry for Long Island Sound. The fact that only a few commercial farms in Connecticut are currently in operation should not be taken as anything other than representative of this fact. It took close to twenty years for the industry to grow to its current size in Maine. Only a few facilities such as one east-end processing firm currently exist in the Long Island Sound region.

Table 4.5: Costs and Revenues for different average yields per lineal foot based on one-acre farm.			
Scenario	1	2	3
Item	Value	Value	Value
Total Revenue	12705.50	4339.50	10312.50
Market Price ($)	0.60	0.60	0.60
Yield (lb ft^{-1})	7.70	2.63	6.25
Total Cost ($)	14687.26	14687.26	14687.26
Fixed Cost ($)	9764.76	9764.76	9764.76
Variable Cost ($)	4922.50	4922.50	4922.50
Total Profit ($)	(1982.26)	(10347.76)	(4374.76)
Startup Cost ($)**	13064.76	13064.76	13064.76
Break-even Price for Total Cost ($)	**0.69**	**2.03**	**0.85**
Break-even Price above Variable Cost ($)	**0.23**	**0.68**	**0.29**

*Scenarios vary based upon reported average yields from interviews and literature, with 15 foot line spacing.

** Startup costs includes annualized equipment cost, business operation costs and seed cost.

New entrants with startup and initial investment costs operating a one-acre farm will face some significant hurdles. As shown in Table 4.5, with a market price of $0.60 per wet pound, they would not be able to operate profitably, regardless of productivity level. Table 4.6 provides a comparison of costs and revenue potential at different levels of productivity, 2.63 and 6.25 pounds per lineal foot, with 5 and 10-acre farms. Operating at productivity levels of 6.25 pounds per lineal foot, when farm size is increased to 5 or 10-acres, at a price of $0.60 per pound, aquaculture farmers would be able to operate at a profit. For existing aquaculture or marine companies already in operation for other marine species (e.g., oysters), their startup costs to enter macroalgae cultivation may be much lower as they likely would have much of the capital equipment already in place.

Table 4.6 Comparison of Costs/Revenue for different yields and farm size.

Scenario	4 (5 acres)	5 (5 acres)	6 (10 acres)	7 (10 acres)
Item	Value	Value	Value	Value
Total Revenue	21697.5	51562.5	43395	103125
Market Price ($)	0.60	0.60	0.60	0.60
Yield (lb ft^{-1})	2.63	6.25	2.63	6.25
Total Cost ($)	34,377.26	34377.26	58989.76	58989.76
Fixed Cost ($)	9764.76	9764.76	9764.76	9764.76
Variable Cost ($)	24612.5	24612.5	49225	49225
Total Profit ($)	(12679.76)	17185.24	(15594.76)	44135.24
Startup Cost ($)*	26264.76	26264.76	42764.76	42764.76
Break-even Price for Total Cost ($)	0.95	0.40	0.82	0.34
Break-even Price above Variable Cost ($)	0.68	0.29	0.68	0.29

* Startup costs include annualized equipment cost, business operation costs, and seed cost.

Given that one of the goals of the introduction of these species for aquaculture is bioextraction, farmers may face some hurdles in finding potential markets for their products. Only products grown and harvested in "approved waters" will be allowed to be used for human consumption (e.g. direct sales to restaurants and consumers for food). Products produced in unapproved waters, if regulators allow them, will likely require substantial processing to convert biomass from kelp and seaweed or shellfish into commercially saleable products. The predominant seaweed crop under aquaculture cultivation in Maine, Connecticut, and New York is sugar kelp during the winter growing season, yielding one harvest a year.

If the aquaculture operation is engaged in other aquaculture and marine based activities, such as oysters or fishing, then firms may already have much of the capital needed to operate, and a seaweed operation may enhance the firm's revenue opportunities with minimal impact to other activities. Some of the other macroalgae species, such as *Porphyra*, *Gracilaria*, and *Chondrus*, can be grown year-round and harvested multiple times during the year. While multiple harvests a year may enhance revenue possibilities, for the multi-product aquaculture firm, it may also have more impact on other firm operations.

Table 4.7: Seaweed Cost table with two harvests per year on a one-acre farm.

Item	Value
Total Revenue ($)	22869.00
Market Price ($)	0.60
Yield (lb ft^{-1})	7.70
Harvest Cycle	2.00
Total Cost ($)	15378.26
Fixed Cost ($)	9764.76
Variable Cost ($)	5613.50
Total Profit ($)	7490.74
Startup Cost ($)	13064.76
Break-even Price for Total Cost ($)	**0.40**
Break-even Price above Variable Cost ($)	**0.15**
Capital & Material Cost ($)	11191.26
Annualized Equipment Cost	6959.76
Material Costs	
Expendable & Misc. Supplies ($)	931.50
Seeded Line Cost ($)	3300.00
Unit price --Seeded line ($ ft -1)	1.20
Total length per acre (ft)	2750.00
Operating & Maintenance Cost ($)	3231.80
Operation Labor Cost (Owner)**	0.00
Farm Setup Labor Cost (hired)	426.80
Maintenance Labor Cost (hired)	0.00
Business Operation expenses	2805.00
Harvest Cost ($)	955.20
Harvest Labor Cost (hired)	955.20
Other Costs*** (e.g. financial Costs)	0

* Assume the second harvest is about 80% of the first harvest.
** Assumes the compensation to an owner's time can be recouped through the profit.
***Assumes an owner owns the necessary funds to start the business. If, otherwise, other costs such as financial costs through a loan will be added to the cost table

Table 4.7 provides an overview of costs for the multiple harvest product. With multiple harvests, capital and fixed expense costs per pound of output will fall as the firm spreads these out across overall production, and operators will need to be able to cover the variable costs from additional labor and other associated expenses.

Soft-shell clam aquaculture requires a much lower level of capital equipment for firms to enter the industry since it takes place in intertidal coastal zones. Table 4.8 outlines the basic cost structure for net aquaculture (Hagan and Wilkerson 2018). The number of nets a farmer can install is a function of the acreage they may be able to lease to operate. Hagan and Wilkerson (2018) suggest that individual farmers can oversee up to 240 fourteen by twenty-foot netted plots. The costs for soft-shell clam operations are all upfront and it will take two to three years before a new operation will be able to begin harvesting clams for sale. The predominate market for soft-shell clams has been for foods in restaurants and private households. Soft-shell clams grown in unapproved waters may in some cases be able to be moved to approved waters for grow-out. Otherwise, as will be the case with ribbed mussels (discussed below), they will need further processing to be converted into non-food commercial products. Table 5.6 presents costs based upon the number of netted plots. The number of plots is based upon Hager and Wilkerson's (2018) estimate of what would be effective for an individual farmer who can manage "a 25-to-150 net farm" to handle several different sized farms.

Table 4.8: Cost of one seeded-net, Soft Shell-Clam farming

Item	Value ($) in 2018	Value ($) in 2023
14' x 12' net with floats and zip ties	$32	$38.72
10,000 Seed Clams @ $25 / 1000	$250	$302.50
Hired labor cost to install and seed the net *	$20	$24.20
Total Cost per seeded net	$302	$365.42

* Assuming 3 people (including the owner) take 10 minutes to install one net. The hourly wage is assumed to be $100/hr for an experienced and $20/ hr for a helper. 10 minutes of the labor cost of two people will be $20.

** CPI inflation $1 in 2018 = $1.21 in 2023 (July in each year, BLS CPI inflation calculator).

The key part of the analysis for all cost tables is the per unit variable cost of production, the term labeled as the break-even price above variable costs. Capital costs and other initial funds that owners invest to start up their business are long term investments that will be expensed over the life of the operation or investment. Owners recoup their investments if the firm is profitable, and capital equipment costs (boats and other potential long-lived assets) will be expensed through depreciation. If the firm cannot cover its variable costs, it will not operate. When the market price is above the firm's variable costs, the firm can cover production costs and profit. In the break-even and sensitivity analysis that follows, we will convert the costs from Tables 4.3 - 4.10 into linear cost functions to evaluate the feasibility of the identified species.

Table 4.9: Soft Shell Clam Cost Table per net*, in one acre and 1.5 acre

Item	Value per net	Value in one acre (83 nets)	Value in 1.81 acre (150 nets)
Total Revenue	680.00	56440	102000
Market Price ($)	2.72	2.72	2.72
Survival Rate	0.30	0.3	0.3
Planting density per net	10000.00	10000	10000
Harvested Clams (lb)	250.00	20750	37500
Total Cost ($)	416.11	34537.36	59020.5
Fixed Cost ($)	50.69	4207.5	4207.5
Variable Cost ($)	365.42	30329.86	54813
Total Profit ($)	263.89	21902.64	42979.5
Break-even Price for Total Cost ($)	**1.66**	1.66	1.57
Break-even Price above Variable Cost ($)	**1.46**	1.46	1.46
Material Cost			
Cost per seeded-net ($)	365.42	30329.86	54813
Operating & Maintenance Cost			
Operation Labor Cost (Owner)**	0	0	0
Business Operation expenses	50.69	4207.5	4207.5
Harvest Cost			
Harvest Labor Cost (owner)	0.00	0	0
Other Costs * (e.g. financial cost)**	0.00	0	0

* It is assumed seed clams can be harvested to commercial legal size (2'') after 2 growing seasons, approximately one year and a half. Initially, 10,000 seed clams are planted, and 12 harvested clams per pound.

**One person can manage a soft-shell clam farm with 25 to 150 nets (Hagan and Wilkerson, 2018). Assumes the compensation to an owner's time can be recouped through the profit.

***Assumes an owner owns the necessary funds to start the business. If, otherwise, other costs such as financial costs through a loan will be added to the cost table

The costs to produce mussels are presented in Table 4.10. Ribbed mussel production is modeled using raft culture with the costs associated with blue mussel (*Mytilus edulis*) aquaculture as a proxy. While production costs between these two different mussels would be very similar, markets in which these products could be sold will differ significantly. Blue mussels have a long history of commercial exploitation and are restaurant and household food staples. Ribbed mussels currently have limited market appeal, though they may find their way into alternative uses such as animal feed or processed into various constituents for use in other products. Although it is difficult to predict what type of market price growers may receive for ribbed mussels, growers will face a minimum estimated break-even threshold of $0.56 per pound.

Table 4.10: Mussel Cost table per raft*

Item	Value	Value (in-kind boat)
Market Price @ $0.72 in 2022	0.7488	0.7488
Yield (lb / raft) @130 bu / raft)	7800.00	7800.00
Harvest Cycle per 18 months	1.00	1.00
Total Cost ($)	6677.5	4357.54
Fixed Cost ($)	3069.96	750.00
Variable Cost ($)	3607.54	3607.54
Total Profit ($)	(836.86)	1483.10
Startup Cost ($)	22364.77	12364.77
Break-even Price for Total Cost ($)	**0.86**	**0.56**
Break-even Price above Variable Cost ($)	**0.46**	**0.46**
Capital & Material Cost ($)	3927.5	1607.54
Annualized equipment cost ($)	2319.96	0.00
Material Costs		
Raft, mooring, net, and socks ($)	1334.54	1334.54
Seed Cost ($) @ $9.1/ bu (30 bu/raft)	273.00	273.00
Total length of socks (ft)	2196.00	2196.00
Operating & Maintenance Cost		
Labor to build, stock and harvest raft	2000.00	2000.00
Business Operation expenses (legal and lease fees)@$500/year	750.00	750.00
Other Costs (e.g. financial costs)**	0.00	0.00

* 18-month turnaround based on a 22' x 22' raft, assuming 7 years of useful life for the raft and nets. Data are converted from the Island Institute's *Mussel Raft Guide* (1999). $1 in 1999 = $1.82 in 2023 BLS CPI convertor
**Assumes an owner owns the necessary funds to start the business. If, otherwise, other costs such as financial costs through a loan will be added to the cost table

6. FEASIBILITY ANALYSIS

6.A.1. Feasibility based upon costs and projected revenue

The cost tables presented in Section 5 reveal that production of the identified macroalgae and bivalve species can be economically viable over a range of output levels. Two factors will impact economic feasibility: the level of necessary post-harvest processing that growers will need to engage in to sell their product, and the market price these products will sell for. **The key issue for feasibility is whether the aquaculture farmer can cover their variable cost or not. If the firm can sell their product at a price (market price) equal to or above variable cost, it can operate and has a potential path to profitability.**

For seaweed culture, the base variable cost (Break-even Price above Variable Cost) is estimated at $0.23 per wet pound if aquaculture farmers produce 7.7 wet pounds per lineal foot. If yields are only 2.63 pounds or 6.23 pounds, the decrease in productivity results in a significant increase in variable cost to $0.68 and $0.29 per wet pound respectively. For macroalgae with multiple harvests in the year, the cost structure looks more favorable, with variable costs dropping as low as $0.15 per wet pound and a break-even price of $0.40 per wet pound (Table 5.4). In the case of soft-shell clams, the variable cost is $1.46 per pound. For mussels, the variable cost of production is $0.46 per pound. Market price, based upon Maine data for the value of landed product, was $0.61 (2020) for farm-raised seaweed, $2.72 per pound for soft-shell clams, and $0.72 per pound for raft cultured mussels.

Based upon these prices, macroalgae and soft-shell clam aquaculture are both viable and potentially profitable options for farmers. While the price for mussels is well above the variable cost of production, we are skeptical about ribbed mussel aquaculture as there does not appear to be a currently operable commercial market for this output. Studies, such as Filipelli et al. (2020), noted a similar concern in terms of finding additional uses and markets for other mussel species if they are going to be exploited for bioremediation purposes.

Piconi et al. (2020), Engle et al. (2020; 2023), and Brayden and Coleman (2023) all allude to the possibility of the existence of scale economies in the production of these various species, especially seaweed. It will take time for new industry entrants to fully develop the expertise and master the skills that are necessary for the cultivation of these products. Yields for new aquaculture farmers may not hit the targets identified in the cost tables. Data from interviews of regional growers who conduct a few test and demonstration projects suggest that yields for seaweed may be as low as 2.5 wet pounds per lineal foot. As growers mature, their yields are likely to increase from “learning by doing.” As new aquaculture farmers enter the industry, this action likely will attract more support services and greater local production knowledge spillovers that lead to economies of aggregation.

6b. Elasticities and Sensitivity Analysis

6b.1. Prices

Market prices for macroalgae and shellfish were collected from multiple sources and span multiple years. Our focus is on regional price levels and the revenue that aquaculture farms in the Northeast may be able to obtain. Where possible, recorded prices were also cross-checked against sales data reported from local producers and collected from the interviews that were conducted. In some cases, prices for specific genera and species were not readily available and noted in the tables below. Prices realized at the regional level reflect not only local demand and market conditions for macroalgae and shellfish, but global markets and prices. Regional producers may find some local and niche markets for their products resulting from actual or perceived quality differences, buyer preferences, and similar concerns. However, regional producers will ultimately need to demonstrate that they are competitive with globally sourced output.

Engle et al. (2020, 2023) and Brayden and Coleman (2023) provide the most current pricing for *Saccharina latissima* (sugar kelp) and macroalgae in general. Production costs for other macroalgae species in an aquaculture setting are similar, with the primary differences of seeding costs and the number of harvests annually. Tables 4.11 through 4.16 report prices culled from commercial websites, academic papers, and industry reports. The reported prices for kelp are primarily Northeastern U.S. regional prices, while the prices for other species such as *Gracilaria* reflect international price levels. Regional, U.S. national, and world prices are noted in each table.

Prices for commodity products, such as kelp, seaweed, and shellfish can vary significantly from year to year based upon growing conditions, harvest yields, and market factors. Seaweed and kelp may be sold either completely unprocessed (wet/farmgate), or with varying levels of processing. One of the issues that aquaculture producers in Connecticut and New York will face is the limited number of processing facilities. It has taken close to two decades for the industry to develop in Maine where there are now over 30 commercial seaweed farms and processing facilities (Robidoux and Chadsey 2022). Processing may be as simple as drying harvested kelp and seaweed which will allow the finished product to be stored more easily and broaden distribution beyond the region.

Table 4.11: Prices for *Saccharina latissima* (sugar kelp)* (Northeastern U.S.)

Year	Price	unit	source
2020	0.48	wet lb.	Engle et al. 2020
2023	0.45-8.00	wet lb	GreenWave
2020	0.40 - 0.70	wet lb.	Piconi et al. 2020, p.7
2023	0.60-2.20	wet lb.	Brayden and Coleman 2023.

* Prices for *Porphyra umbilicalis* produced regionally were not found.

Table 4.12: Prices for *Gracilaria tikvahiae* (international prices)

Year	Price	unit	source
1999	$1,260.00	per dry ton	Bixler and Porse, 2011
2009	$1,300.00	per dry ton	Bixler and Porse, 2011
2015	$735.00	per dry ton	Porse and Rudolph, 2017, p. 2194
2023	$5.00-7.00*	kilogram	FAO, Cultured and Aquatic Species Information Programme https://www.fao.org/fishery/en/culturedspecies/gracilaria_spp/en

*Price in select Asian countries (e.g. Japan)

The most recent Maine Seaweed Benchmarking study (Brayden and Coleman 2023) suggests that in general, seaweed farmers receive between $0.60 to $2.20 per wet pound of seaweed, and do not distinguish between the three predominant crops (sugar kelp, skinny kelp, and *Alaria esculenta*). Most of the crop is sold at the lower end of the price spectrum. The prices for *Alaria esculenta* (Table 6.1.3.) are similarly amalgamated prices for seaweed or kelp grown and sold from Maine waters (Piconi et al. 2020). Prices for *Gracilaria* have varied over the past twenty-five years. The price shown for 2024 is drawn from an FAO report and primarily reflects the use of *Gracilaria* for food in several Asian countries.

Table 4.13: Prices for *Alaria esculenta* (Northeastern U.S.)

Year	Price	unit	source
2020	0.40 to 0.70	wet lb - Typical	Piconi et al. 2020
2020	6.00 - 8.00	per dry lb	Piconi et al. 2020

Table 4.14: Prices for *Chondrus* (International prices)

Year	Price	unit	source
2009	$3,400.00	per dry ton	Bixler and Porse, 2011; Porse and Rudolph, 2017
1999	$1,800.00	per dry ton	Bixler and Porse, 2011

Reported prices for mussels (Table 6.1.5) are for blue mussels. Blue mussels are not the primary focus of this study, but they are perhaps the closest analog to *Geukensia demissa* (ribbed mussel) in terms of cultivation. Ribbed mussels were ranked very highly by the biology team as one of the target species with high nitrogen extraction potential and have been identified in several studies (see for example Galimany et al. 2013, Galimany et al. 2017) for use in bioextraction in the Long Island Sound. They can also be cultivated using raft cultures like blue mussels. There does not appear to be an existing commercial market for ribbed mussels in the region. While reports in the popular press (The Economist 2017) do not suggest that ribbed mussels will ever be used for human consumption, they may find their way into other uses such as animal feed. Over a thirty-year period, the nominal price of mussels has varied from as low $1 per pound to $2.18 per pound in 2020. Across 2018 to 2022, the landed price of mussels in Maine has ranged from $0.28 to $0.72 per pound. Though blue mussels are a food staple eaten in homes and restaurants, they are also used in animal feed. Filipelli et al. (2020) notes that expansion of the animal feed market would be one possible means of exploiting mussels for bioextraction. The key for this market is whether ribbed mussel aquaculture can be achieved at low enough costs.

Table 4.15: Prices for mussels* (Northeastern U.S. and U.S. National prices)

Year	Price	unit	source
1993	$1-1.50	lb	Brooks 1993
2020	$2.18 (+/- .08)	lb	Engle et al. 2020.
2019	$1.61	lb	USDA Aquaculture Trade Tables, Value of exports
2018	$2.09	lb	USDA Aquaculture Trade Tables, Value of exports
2013	$2.17	lb	Washington Sea Grant 2015. page 3

* Using price of blue mussels as a proxy for ribbed mussels

Table 4.16: Prices for *Mya arenaria* (U.S. national prices and Northeastern regional prices)

Year	Price	unit	source
2018	$100.00	bushel	Hagen and Wilkerson, 2018, p. 14
2014	$220.00	bushel	Hagen and Wilkerson, 2018, p. 14
2023	$18.99	lb (retail prices)	Fulton Fish Market website
2023	$18.95	2 lbs	Intershell Seafood, 2023. www.intershellseafood.co m
2011	$80.00	bushel	Homer et al. 2011, p. 2
2009	$5.28	lb	National Marine Fisheries Service, 2010. p. xii
2008	$5.67	lb	National Marine Fisheries Service, 2010. p. xii
2010	$5.52	lb	Weston, Buttner, and Beal, 2010.
2002	$1.65-1.95	kilogram	Beal 2002.
2002	2.80 -4.00	kilogram	Beal 2002.
2013	$8.30	lb	Cygler 2014, p. 227

Nominal prices for *Mya arenaria* (soft-shell clams) (Table 6.1.6) have varied significantly over time. Current retail prices and direct sales to households range from $9.48 to $18.99 per pound. The wholesale price reported as of 2018 (Hagen and Wilkerson) was $2.08 per pound. As described in Hagen and Wilkerson (2018), *Mya arenaria* can readily be exploited for commercial aquaculture production. It was also identified as the top bivalve species for nitrogen extraction potential by the biologists (Task 1).

Sales data for all the identified species is very limited. Global production and in some cases, regional production levels of both kelp and shellfish are available, specific sales data for these products is not. Data collected from regional stakeholders provided only limited information on output. National statistics on shellfish and seaweed report aggregated total production and value of that production annually. While in some cases, this data has allowed us to estimate an average market price for some products, it does not lend itself well to estimating price elasticity for all the specific species. Studies, such as Lee, Liao, and Hwang (2006), used aggregated quarterly time series data for seafood products (finfish, shrimp, and shellfish) to estimate market demand functions and elasticity. Chidmi et al. (2012) used supermarket scanner data to evaluate elasticities. Both studies provide some indication of household and retail level price elasticity and cross-price elasticity. A study by Gallet (2009) and cited by EMLab (2019) indicates that the price elasticity of demand for shellfish (undifferentiated) is $0.86 (in absolute terms). This figure was estimated using a meta-analysis from the literature.

Table 4.17: Prices and Quantity sold – Maine Soft-Shell Clams (per lb)

Year	Price	Quantity
2018	$1.80	7,188,354
2019	$2.33	7,833,329
2020	$2.39	6,611,139
2021	$3.36	7,533,724
2022	$2.72	6,141,166

Table 4.18: Prices and Quantity sold – Maine Mussels (per lb)

Year	Price	Quantity
2018	$0.28	9,805,365
2019	$0.30	11,506,077
2020	$0.29	9,185,540
2021	$0.42	8,026,592
2022	$0.72	5,562,720

Table 4.19: Prices and Quantity sold – Maine Farm Raised Seaweed (wet lbs)

Year	Price	Quantity
2015	--	14,582
2016	--	24,004
2017	--	45,023
2018	$0.71	53,564
2019	$0.63	280,612
2020	$0.61	497,146

Using time series data collected from the Maine Department of Marine Resources database on historical landings and sales value, we were able to collect selling price and quantities for mussels, soft- shell clams, and non-differentiated farm-raised seaweed. It should be noted that data for mussels and clams covered a period from 1950 to 2022. The data for farm-raised seaweed covered a 5-year period from 2015-2020. Using additional times series data collected from the St. Louis Federal Reserve Economic Database for U.S. Real Disposable Personal Income per capita, and the Personal Consumption Expenditures index both indexed to 2017, we were able to estimate long-run elasticities for mussels and clams using a cointegration model like that used by Tatli and Barak (2018). Many of the marine-product elasticity studies that we reviewed utilized direct consumer sales and expenditure data, or expenditure share data, as well as retail scanner data. None of this type of data was public for the species under analysis.

Tables 4.17 to 4.19 show the total quantity of clams, mussels, and farm raised seaweed sold from Maine aquaculture producers. Prices shown are at nominal levels. For the elasticity analysis, all prices for clams and mussels are converted into real prices in 2017 dollars using the CPE index. Income elasticity of demand is estimated using real disposable income indexed to 2017 dollars. Elasticity estimates for mussels and clams are for the period 1960-2022 (63 observations) and the demand equation is estimated including a linear trend. The estimated price elasticity for farm-raised seaweed is a point estimate based upon the period 2018 to 2020 using prices converted with the CPE into real prices. The estimated price and income elasticities are shown in Table 4.20.

Table 4.20: Estimated elasticities

	Own Price	Income
Soft-shell clams	-1.17	5.37
Mussels	-.93	3.23
Farm-raised seaweed*	-3.03	2.39

*Elasticity for seaweed is a point estimate for 2019-2020.

The demand for both soft-shell clams and farm-raised seaweed are elastic (>1 in absolute terms). In other words, consumers of these two products are sensitive to changes in price. A 1% increase in the price of cultivated seaweed products would result in a 3% decrease in quantity consumed, or conversely, a 1% decrease in price would result in a 3% increase in quantity consumed. The reported elasticity for mussels is inelastic (<1), or more succinctly, consumers are less sensitive to price changes. This estimate is for blue mussels which have an existing and robust market, but it is not possible to extend this result to ribbed mussels with limited market appeal. All three products are found to be normal goods. Given the paucity of data, it is difficult to draw too many conclusions about seaweed demand, but it is suggestive that aquaculture producers face some competitive pressures. For clams, the estimates are more robust.

6.b.2. Sensitivity Analysis

Tables 4.4-4.10 provide an overall picture of the costs that producers entering the industry in the next few years may face. Costs for individual farmers will vary based upon the location of their operations, capital outlays and seed capital needs, labor costs, and the costs of other inputs. Sensitivity analysis provides a means for us to evaluate and capture the impact from changes in some of these factors. Modeling these changes in break-even analysis involves analyzing the shifts in the point at which production and sales of the product become profitable. Deriving stylized cost and revenue functions from the initial cost analysis, we can represent the costs of production in terms of the following:

4. Total Cost = Fixed costs + Variable costs(Q)

and

5. Total Revenue = PQ

As discussed earlier, profit (or loss) is simply total revenue minus total cost. For the analysis, we assume that only one of the input variables changes at a time to assess how the break-even point will change and what that may mean for a representative firm. For macroalgae, producers' output is wet pounds produced and sold. In the case of mussels and clams, output is measured in terms of pounds of either species produced. Productivity, the output per unit of input is a critical component in the analysis as this will impact variable costs. As inputs become more productive, per unit costs of production will fall.

We have already noted that varying the area under cultivation (Table 4.6) can have a dramatic effect on profitability for macroalgae cultivation. Tables 4.4 through 4.10 also identify break-even prices, for both fixed acreage/production levels at which firms would be profitable. For a one-acre farm, the break-even price, the point at which the firm could begin to generate profits, occurs at $0.69 per pound if the firm can achieve productivity of 7.7 pounds per lineal foot. Productivity levels yielding 6.25 pounds per foot result in a break-even price of $0.85 per pound, and at the lower yield of 2.63 pounds, the break-even price rises to $2.03 per pound. Increased farm size does result in lower break-even prices at these lower yield levels as noted in Table 4.6.

Looking beyond the fixed cultivated acreage situation, and assuming aquaculture operators face a market price, we can estimate the break-even level of output. Using equations 4 and 5, the break-even level of output (linear model) for single harvest macroalgae with yields of 6.25 wet pounds per foot can be forecast:

6. Profit = TR-TC = PQ – (9765 + .29Q)

Break-even occurs where total revenue and total cost equal each other. Setting Equation 6 equal to "0" and varying the market price will yield a possible range of break-even output levels. Using the price range of $0.40 to $0.70 per wet pound (Piconi et al. 2020), break-even output levels will range from over 88,773 to 23,817 wet pounds for yields of 6.25 pounds per foot and 57,441 to 20,777 for 7.7 pounds (Table 4.21).

Table 4.21: Break-even level of output for macroalgae varying market price

Price ($)	FC	VC*	BE Q*	VC**	BE Q**	VC***	BE Q***
0.40	9,765	0.68	-34875	0.29	88773	0.23	57441
0.50	9,765	0.68	-54250	0.29	46500	0.23	36167
0.60	9,765	0.68	-122062.5	0.29	31500	0.23	26392
0.70	9,765	0.68	488250	0.29	23817	0.23	20777

* yield =2.63 wet lbs. **yield = 6.25 wet lbs. *** yield = 7.70 wet lbs.

As is evident from Table 4.21, changing other input prices or costs can have a dramatic impact on overall break-even yields that would result in macroalgae farmers being able to achieve profitability. The startup costs and fixed costs presented in the cost tables in Section 5 assume a required rate of return of 6 percent and do not include borrowing costs if operations use debt financing. In a meta-analysis, Campo and Zuniga-Jara (2018) suggested that aquaculture may need a rate of return as high as 10.6 percent.

Using a rate at this level or adding interest charged on borrowed funds for capital equipment into the analysis would increase fixed costs, which would result in an increase in the minimum break-even level of output for any given price level. Increases in other costs such as wage rates or other similar factors underlying variable costs (seed costs for example) would increase overall variable costs, thus reducing profit margins and driving up the break-even point.

Table 4.22: Break-even level of output soft-shell clams varying price (lbs)

Price ($)	FC	VC*	BE Q*
1.80	4,208	1.46	12376
2.33	4,208	1.46	4837
2.39	4,208	1.46	4525
3.36	4,208	1.46	2215
2.72	4,208	1.46	3340

*Prices used were for period 2018-2022. Assumes one acre farm with 83 netted areas.

The analysis is similar for soft-shell clams except that we hold acreage and netted areas fixed at one acre with 83 nets. Market price varied between $1.80 to as high $3.36 per pound for Maine clams between 2018 and 2022. Since these prices were well above the variable cost of production, the analysis presented in Table 4.22 indicates *Mya arenaria* aquaculture could be profitable in Long Island Sound waters. The analysis assumes that farmers can achieve the productivity levels for these yields. Yield levels are dependent on factors, including the survival rates of planted seed clams, water temperatures, and predation. Higher market prices allow farmers to begin to realize profits at lower levels of output. Like macroalgae culture, other factors such as borrowing costs, higher desired returns on investment, and higher levels of capital investment would lead to increasing fixed costs and result in higher required output levels for break-even. Increasing wage rates or the costs of juvenile seed clams would increase variable costs and thus increase required output levels to achieve break-even.

While it would be possible to undergo the same exercise with ribbed mussel, the market for this species is not well-developed. Though we used the structure of blue mussel aquaculture to model ribbed mussels, it is an open question as to whether farmers would be able to realize sales at blue mussel market prices. Table 4.10 identifies two different fixed cost situations, the first with higher annual costs (because of capital equipment needs at startup) and the second in which farmer already has equipment in place that can be used in the production of mussels. Fixed costs in the first case are estimated at $2250 per mussel raft, while for case two they are $750 per raft. Variable cost in both cases is estimated at $0.46 per pound of mussels. However, with the higher fixed cost, break-even price is estimated at $0.75 per pound, while for the lower fixed cost, break-even price is $0.56 per pound. Fifty-six cents per pound serves as the lower bound for ribbed mussel aquaculture. Again, as with the other species discussed, increases in labor costs, juvenile mussel seed costs, or other variable inputs would increase the variable costs of production, resulting in higher required output levels to achieve profitability. Changes in required expected rates of return, borrowing costs and other factors entering fixed costs holding market price constant would have the effect of moving the break-even level of output in the direction of change, e.g., increases in these costs would increase the quantity at which break-even takes place and vice versa.

7. DISCUSSION AND EVALUATION OF OVERALL ECONOMIC FEASIBILITY

Based upon the analysis presented above, macroalgae aquaculture has the potential to be profitable. However, in saying that, we must note that it will present a few challenges, especially for new entrants with limited aquaculture experience. Existing firms that are already engaged in some type of marine or aquaculture-based business (fishing, oysters, hardshell clams, etc.) and own much of the required capital equipment would be able to enter macroalgae cultivation at lower costs than new firms/entrants. Macroalgae aquaculture for these firms could also be viewed as potentially revenue enhancing, allowing them, for example, to spend the winter months on sugar kelp and the rest of year on their other endeavors. Some of the identified macroalgae species (*Porphyra*, *Gracilaria*, and *Chondrus*) can be harvested multiple times in the year, again enhancing revenue opportunities for these firms.

The break-even analysis (Section 6) establishes that there is a path towards profitability for macroalgae, especially species such as *Saccharina latissima* (sugar kelp). As reported from Maine data (Brayden and Coleman 2023; Engle et al. 2020), prices for these cultivated seaweeds ranged from \$0.40 to \$0.70 in 2020, and \$0.60 to \$2.20 per wet pound. At these price ranges, growers would be able to operate profitably. Reported international prices for some of these other species such as *Chondrus* and *Porphyra* (see Tables 4.12 and 4.14) were as low as \$0.065 per pound, which would be too low for a typical aquaculture farm in Long Island Sound to ever realize a profit. Data from Maine on all combined (wild harvest) seaweeds covering the period from 1964-2022, which includes species such as *Chondrus*, reports a price of \$0.11 per wet pound for both 2021 and 2022.

Price points though are only part of the issue. The long lead times involved in licensing and approvals from local, state, and federal regulators, for seaweed aquaculture may make it difficult for potential industry entrants to secure and maintain necessary capital for start-up and operations. Another concern is the question of securing acreage for lease and the location of those areas. Alongside issues of operating in "approved" versus "unapproved" areas of the Long Island Sound, it is also a busy maritime channel with significant commercial and recreational traffic with many possible commercial and recreational uses. Just as reported in the popular press, wind turbine operators have faced extreme scrutiny by the fishing community and local communities across Long Island over potential impacts on fishing grounds and navigational hazards, and the visibility by property owners of these offshore wind turbines. Several studies have noted that aquaculture operations close to some residential areas may have a significant and negative impact on some property/housing values (Sudhakaran et al. 2021). Soft-shell clam cultivation takes place in shallow tidal zones, which may potentially lead to conflicts between aquaculture operations and coastal homeowners and communities or limiting operational locations.

There are numerous market related issues that aquaculture of all species of macroalgae and bivalves will face. From the regulatory side, the need for bioextraction is greatest in "unapproved waters." It is not clear whether macroalgae or bivalves raised in these environments (assuming operations are permitted in these areas) will find a market. The various kelp, seaweed, and bivalves would have to be processed into various extracts or biomass for use in other products. Which products specifically, goes beyond the scope of the analysis presented here. The market analysis conducted in Chapter 3 has identified various potential uses for the biomass produced from aquaculture beyond human use.

Maps of Long Island Sound show that there are still significant areas of approved water that could be opened for macroalgae and bivalve aquaculture. In New York, there are still legal obstacles to allowing the cultivation of macroalgae in Long Island Sound, but it is legal in Connecticut waters. For bivalves, there are fewer legal constraints. The issue for shellfish though, is marketing their products. Soft-shell clams are primarily grown and harvested for food. They are a viable species for aquaculture, however given the costs associated with their production, it is not certain that farmers would be able to realize a high enough price per pound outside of their traditional human consumption use.

Ribbed mussels (*Geukensia demissa*) are perhaps the most problematic species for commercial production. Like *Mya arenaria* (soft-shell clams), blue mussels (*Mytilus edulis*) have traditionally been cultivated for food. *Geukensia demissa* though has no history of commercial exploitation. There have been scientific demonstration projects and studies using ribbed mussels for bioremediation in the New York metropolitan area. Some local Long Island communities have even been engaged in seeding ribbed mussels in their waters for bioremediation purposes. While we have modeled ribbed mussels using blue mussel culture methods, that was mainly for ascertaining production costs. It is not clear that ribbed mussel aquaculture would be able to command the same price as blue mussels, though ribbed mussels could be farmed for a variable cost as low as $0.46 per pound. A market price over that level could provide a possible pathway towards profitability.

Throughout much of this analysis, we have viewed these species essentially as commodity products. This is especially true if seaweed, ribbed mussels, or soft-shell clams are sold in their raw or unprocessed or minimally processed states. However, if aquaculture farmers engage in some level of processing, or have wider access to processing facilities in the region, they may be able to find alternative market outlets for their production. Processing facilities in the Long Island Sound region are very limited. Expansion of processing facilities, or at the very least, the capabilities of aquaculture operations to process and package their product for market would aid in enabling farmers to become profitable and successful.

8. CONCLUSIONS

Overall, it appears that commercial aquaculture of most all identified species could be implemented in Long Island Sound. Macroalgae, such as *Saccharina latissima*, are already cultivated in Connecticut and have been successfully cultivated in Maine. Bivalve aquaculture in Long Island Sound also has the potential to be profitable. Achieving profitability though is not necessarily going to occur in a linear path. The number of active aquaculture operations or marine based production as a percentage of the region's economy is quite small, representing less than 1 percent of the region's gross domestic product.

There are significant competing investment opportunities for entrepreneurs with aquaculture just one of the potential choices. It is more likely that existing marine-based companies and interests would enter the industry. Existing companies and individuals that are already engaged in some level of aquaculture or marine based production (oyster farming, fishing) may already have much of the necessary capital in place to enter production and just need to go through application and approval processes to lease acreage and startup cultivation activities. This process, from both the interviews we conducted and, in the literature, was described as a long and sometimes arduous process.

For macroalgae and bivalve aquaculture to flourish in Long Island Sound, new and even existing entrepreneurs and farmers will need access to capital resources, technical and educational assistance to develop the human capital and labor resources for aquaculture, and access to processing facilities that will enable output to be saleable beyond its raw state. Online resources such as the National Seaweed Hub (National Seaweed Hub, 2024) or GreenWave's "Ocean Farming Hub" or "Seaweed Source" (Seaweed Source — GreenWave, n.d.) provide a range of education and market access tools and materials to prepare and assist seaweed aquaculture. Similar resources exist online for shellfish, such as the East Coast Shellfish Growers Association (East Coast Shellfish Growers Association – Representing the Needs of Aquaculture and the Environment, n.d.). These resources will help potential entrants into these industries.

Ultimately though, for seaweed and bivalve aquaculture to fully develop and thrive, it will have to be both profitable and competitive with other potential investment opportunities. Profit-oriented bioremediation of Long Island Sound is a strong attraction for some social-minded and responsible entrepreneurs. However, like land-based agriculture, aquaculture is not necessarily an easy life or path that many Long Islanders or Connecticut residents to follow. Streamlining regulatory processes, the creation of more support structures such as expanding USDA crop insurance further into aquaculture (see for example

Bowen 2019), and the expansion of processing facilities and seed hatcheries in the region will help to support profit-oriented aquaculture bioextraction.

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CHAPTER 5: CONCLUDING FINDINGS ON THE FEASIBILITY OF COMMERCIAL NUTRIENT BIOEXTRACTION

There were three overarching goals for this project: (1) identifying macroalgae and bivalve species suitable for cultivation and use in bioextraction for Long Island Sound, (2) evaluating the regulatory and market environment that cultivators face, and (3) the economic feasibility to commercially and profitably exploit these species. The essential question distills down to, is bioremediation through the cultivation of species with demonstrable high nitrogen uptake rankings commercially feasible and profitable in Long Island Sound?

These questions were addressed by three separate teams working collaboratively on the project. As discussed in Chapter 2, a ranking model was created by the biology team to evaluate selected organisms at the species, genus, and division level to identify optimal algal types for possible cultivation in Long Island Sound. Their findings demonstrate that members of the green algae, *Ulva* spp. and *Cladophora* spp. primarily, are the top group for potential nitrogen bioextraction within LIS. The other group of top-ranking macroalgae were members of the red algae (*Porphyra* spp. and *Chondrus* spp. primarily). Of the top five genera, *Ulva*, *Cladophora*, and *Chondrus* were projected to be the have the greatest range of suitable habitat in Long Island Sound. Thus, *Ulva* spp. presents a top candidate for nutrient bioextraction, which is in-line with other sectors of aquaculture.

For bivalves, *Mya arenaria* (soft-shell clams) emerged as the top bivalve for potential bioextraction within Long Island Sound, with *Argopectin irradians* (bay scallops) and *Geukensia demissa* (ribbed mussels) following. These three species all have higher potential nitrogen uptake values than the highest ranking macroalgae species. Based on this one metric, these bivalve species may have a greater impact on nitrogen bioremediation than macroalgae. However, bivalves take several years to grow to harvestable size compared to most macroalgae, which take less than one-year for harvest, possibly reducing the overall bioextraction potential of these bivalves.

Some of the other macroalgae identified in the original request for proposals such as *Saccharina latissima* (sugar kelp), which has a commercial presence in the northeastern United States in states like Maine, ranked much lower in all three categories for ranking: potential nitrogen uptake, growth rate, and habitat suitability. The economic analysis though suggests that given its existing commercial viability in the region, it may represent a good gateway macroalgae for aquaculture in Long Island Sound.

Global climate change is likely to have a significant impact on the presented ranking over time by altering the amount of available suitable habitat available for growth. *Saccharina latissima* (sugar kelp), all three *Porphyra* (laver/nori) species, and *Palmaria palmata* (dulse) all had reported temperature tolerances below the monthly maximum sea surface temperature measured for Long Island Sound. On the other hand, increased ocean warming may create more suitable habitat for other macroalgae species such as *Porphyra purpurea* (laver/nori) or some other typically southern genera, such as *Hypnea* spp. (hook weed) and *Sargassum* spp. Thus, selection of species to target and invest in greater nutrient bioextraction will need to take ocean warming into close consideration, and where possible, efforts should be made to identify and cultivate more thermally resistant strains of species with high nitrogen uptake potential.

The marketing and regulatory analysis team (Chapter 3) approached the issue from the perspective of market viability. For macroalgae and bivalve cultivation and aquaculture in Long Island Sound to be commercially viable, growers will need to secure regulatory approval to operate, site licenses and leases for acreage to cultivate, and find promising product market sectors in which to sell their output. On the regulatory side, the team found that the aquaculture industry is heavily regulated at the federal, state (Connecticut and New York), and local level. Regulatory compliance addresses the interests of a wide range of stakeholders and environmental concerns, including growers, recreational users and the public, and the marine community. While both Connecticut and New York have guidance documents and actively work to support those looking to enter this industry, more could be done to create an efficient and business friendly point of entry to the aquaculture industry.

On the marketing side, the analysis found many promising product market sectors that growers may be able to tap into in the short run, including biostimulants, pet food, and cosmetics. Additional product markets offered potentially higher value addition in the long term, such as nutraceuticals and pharmaceuticals, but they are still in their formative phase and are not currently viable markets. The marketing team is not exceptionally bullish on the long-term outlook for macroalgae for food (restaurants and retail) given the highly competitive nature of this sector, both domestically and internationally. They conclude that further research on feasible market sectors would benefit with the addition of technical expertise focused on the conversion and processing of raw seaweed into downstream products.

The economic feasibility analysis (Chapter 4) found that commercial aquaculture of most all identified species could be implemented in Long Island Sound. While some commercial crops may not rank as high for nitrogen bioremediation as others, macroalgae species such as *Saccharina latissima* (sugar kelp) are already cultivated in Connecticut and have been successfully cultivated in Maine. Although the initial impetus for encouraging cultivation of these various species is for bioextraction, producers will ultimately have to concern themselves with profitability if they are to remain in business. Macroalgae and bivalve aquaculture in Long Island Sound can be profitable. Achieving profitability, though, will take time and will not necessarily occur in a linear path.

Commercial uses exist for almost all identified species. Although the marketing team had reservations about the competitiveness for macroalgae as a food item, it still represents a potential market for growers, especially if they can tap into the consumers' willingness to purchase locally produced products. The primary market for *Mya arenaria* (soft-shell clams) is as food whether through retail or wholesale trade. One bivalve, *Geukensia demissa* (ribbed mussel) presents its own marketing challenges and it is an open question as to whether this can be grown profitably.

There are significant competing investment opportunities for entrepreneurs, with aquaculture just one of the potential choices. For existing companies already engaged in some aspect of aquaculture or marine based production (oyster farming and fishing), moving into macroalgae aquaculture may be a logical step in diversifying their product line and increasing profit potential. For macroalgae and bivalve aquaculture to thrive in Long Island Sound, new and even existing entrepreneurs/farmers will need access to capital resources, technical and educational assistance to develop the human capital and labor resources for aquaculture, and access to downstream processing facilities enabling growers to realize potentially higher revenues from sales.

In the long-term, seaweed and bivalve aquaculture will have to prove itself to be profitable and competitive with other potential investment opportunities. Profit-oriented bioremediation of Long Island Sound is a strong attraction for some social-minded and responsible entrepreneurs. However, like land-based agriculture, aquaculture is not necessarily an easy life or path that many Long Islanders or Connecticut residents follow.