Shelling Out for Shellfish: an Analysis of the Economic and Environmental Impacts of Increasing Oyster Aquaculture in Rhode Island

by

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Abstract

Though oysters have long been sought after for their meat, it is less well known that they also provide several important ecosystem services. Oysters and other bivalve mollusks clean water by filtering nutrients and clearing sediment, provide a reef habitat for several species important to recreational and commercial fishing, and act as stormwater surge protection, among other benefits. In this paper, I analyze environmental and economic effects of increasing the amount of oyster aquaculture in Rhode Island under five different scenarios, ranging from no aquaculture to the carrying capacity of oyster aquaculture in Narragansett Bay. Using the Ecopath with Ecosim (EwE) modelling software, I find that oysters, when increased significantly, have a small but positive effect on the recreational fishing industry in Rhode Island and a small but negative effect on the commercial fishing industry. The results of this model demonstrate that increasing the amount of aquaculture in Narragansett Bay in the scenarios which were less than the carrying capacity would have minimal ecological impacts on other species in the bay. I also find that the current amount of aquacultured oysters in the bay remove approximately $52,879.42 of nutrients annually from Narragansett Bay via sequestration into soft tissue alone, using prices of nutrient credits from the Maryland Water Quality Market as a proxy for the value of that nutrient removal. As the amount of oyster aquaculture increases under the different scenarios, the value of nutrient removal increases as well. I conclude that increasing the amount of oyster aquaculture in the state will have minimal to no negative impacts on the economy or environment; rather, it would likely be beneficial to the economy due to the effects of increased quality of the water around the state and the increased amount of oysters being sold.

Introduction

Seafood is a major industry in Rhode Island, and though aquaculture is currently a small part of the industry, sustainably farmed seafood, including mollusks and kelp, are becoming increasingly important in the fight to feed a growing population in a sustainable manner. As aquaculture grows in popularity around the world, it is important to understand what consequences that trend will have on both the environment and the economy.

The analyses found in this paper are the result of research conducted on behalf of the Rhode Island Food Policy Council (RIFPC) in their effort to understand how supporting policy surrounding increased aquaculture in Rhode Island would affect the environment and economy of the state. To that end, I developed a research question and methodology to investigate some of the potential effects of increasing aquaculture in Rhode Island. I chose to focus on oyster aquaculture due in part to the fact that oysters make up 99% of aquaculture in Rhode Island and because of the relatively large amount of information surrounding the topic compared to information regarding aquaculture of other bivalve mollusks, including clams and scallops.

Throughout the course of this report, I attempt to estimate the value that aquacultured oysters have in Rhode Island. Though oysters provide many ecosystem services, I focus this paper on analyzing two ecological effects of oysters and their consequences on the state economy. Specifically, I first approximate how the biomass of species in the same ecosystem will respond to an increase or decrease in the amount of aquacultured oysters using data from a recently constructed ecosystem model of Narragansett Bay. With the results from the ecosystem model analysis, I estimate the value of that change in biomass in the context of the fishing industry in Rhode Island. Second, I analyze the nutrient removal services that oysters provide. By determining how much nitrogen and phosphorus oysters in Rhode Island remove from the water annually, and by using prices of nutrient credits from water quality markets in the Chesapeake Bay area, I estimate the value of this important ecosystem service that oysters provide.

Though the numbers in this report are by no means a perfect representation of the impact that increasing aquaculture in Rhode Island might have, they provide an understanding of the broad trends the state might see. This report also intends to draw attention to the wide array of ecosystem services that oysters and other bivalve mollusks provide and supports the understanding that advocating for aquaculture businesses, with policy or otherwise, may have more of an economic impact than what meets the eye.

Chapter 1: Oyster aquaculture in Rhode Island and nutrient trading markets

A history of oysters in Rhode Island

The history of the consumption and use of the eastern oyster, *Crassostrea virginica*, in Rhode Island is well documented. Upon his arrival in Rhode Island, Roger Williams noted the Narragansett tribe's affinity for oysters, describing how they would dive for the shellfish during the summer.[1] Historically, oyster reefs in Narragansett Bay and the coastal salt ponds of Rhode Island were extensive. Once colonial Rhode Islanders arrived in the state, however, the colonists' population began to grow, and they needed building material. They began to harvest the oysters in vast quantities not for meat, but rather to use the shells as building material. Oyster shells are a source of calcium carbonate, which these colonists used as a substitute for limestone in masonry mortar.[2]

As early as 1766, Rhode Islanders recognized that they were overfishing the historically abundant wild oyster beds. Starting then, the newly formed Colonial Assembly and the Rhode Island General Assembly began passing a series of laws to protect the marine resource. Eventually, they enforced a seasonal closure of the beds from May 1 to September 20.[3] These laws sparked the beginning of oyster aquaculture in Rhode Island, with individuals beginning to lease land for the purpose of growing oysters starting in 1884.[4] In the same year, the Rhode Island Shellfisheries Commission was created by the General Assembly to support the future growth of aquaculture in the state. However, aquaculture did not sit well with the local fishermen, who disagreed with the state being allowed to grant exclusive oyster cultivation and

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[1] Williams 1643

[2] Rice 2006

[3] Ibid.

[4] Rhode Island 1890

harvesting rights to individuals in what was previously public land. These fishermen began openly stealing oysters from the leased areas, until the General Assembly reorganized the laws around aquaculture and restructured the Shellfisheries Commission. With a succession of effective leaders of the Commission, oyster aquaculture in Rhode Island grew during the 1890s and 1900s. Narragansett Bay alone contained over 21,000 acres of private oyster beds.[5] This growth culminated in peak oyster harvest in 1911, with a harvest worth approximately $135 million in today's oyster prices.[6] For comparison, there were 339.08 acres of aquaculture under cultivation in all of Rhode Island in 2019, with a combined value of $6.07 million.[7]

Around the same time, the Rhode Island Shellfisheries Commissioners and scientists at the newly established Rhode Island Universities began taking note of the apparent link between water pollution and oysters, conducting experiments on and doing research regarding the oyster populations in the state. Studies were performed on the water quality and its effects on local oysters in Rhode Island as early as the 1890s.[8]

A sharp decline in the oyster industry occurred in the early 1920s, due largely to "large quantities of oil floating on the waters of our rivers, bay, and tributaries," instantly killing oyster larvae in RI waters.[9] The oil, combined with runoff from farms, heavy metal ion effluents from industries along the river, and the sewage spilling into the waters, had disastrous effects on the oyster population, and the industry suffered. In addition to these environmental factors, the country was going through the Great Depression, leaving the industry with no demand for any luxuries, including raw seafood. Then in 1938, Rhode Island experienced the Great Hurricane, which destroyed oyster infrastructure including shucking houses, shipping wharves, and the

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[5] Griffin 2016

[6] Ibid.

[7] http://www.crmc.ri.gov/aquaculture/aquareport19.pdf

[8] University of Rhode Island Agricultural Experiment 1896

[9] RI Shellfisheries Commissioners 1922

oyster vessels. What few oyster companies survived both the Great Depression and the Great Hurricane fought another battle with the onset of World War II in 1941, which left them without able-bodied workers, harming the industry even further.[10]

By the 1950s, there were only two remaining oyster companies in business in Rhode Island. The industry remained stagnant for decades, until demand for aquaculture in Rhode Island emerged once again in the late 1980s and early 1990s. That heightened demand led to the creation of the Legislative Commission on Aquaculture, which passed legislation that created a coordinated application process and appropriated funds to create an "Aquaculture Coordinator" position.[11] Since the 1996 legislation, the aquaculture industry in Rhode Island, of which 99% is oysters,[12] has seen steady growth, going from 15 farms in 1999, to 33 in 2009, to 81 in 2019.[13]

Oyster restoration initiatives in Rhode Island

Since 2000, there have been four oyster restoration programs in Rhode Island: 1) the North Cape restoration program, run by Rhode Island Department of Environmental Management (RI DEM) and the National Oceanic Atmospheric Administration (NOAA) to address an oil spill in the Block Island Sound in 1966; 2) the Oyster Gardening for Restoration and Enhancement (OGRE) program, run by Roger Williams University to increase spawning stock of oysters via community involvement; 3) the Environmental Quality Incentives Program (EQIP), run by National Resources Conservation Service (NRCS), which is a voluntary conservation program that provides financial assistance to oyster growers to create oyster habitats primarily in coastal ponds; and 4) a program run by The Nature Conservancy and RI

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[10] Rice 2006

[11] Ibid.

[12] Byron 2011

[13] http://www.crmc.ri.gov/aquaculture.html (1999, 2009, 2019)

DEM that focuses on increasing suitable settlement substrate for oysters.[14] As of 2016, these four programs together had seeded over 26 million oysters in Rhode Island.[15]

In 2016, Matthew Griffin, a graduate student at University of Rhode Island (URI), conducted a performance evaluation of the North Cape and OGRE programs. There was not sufficient data to conduct a similar evaluation of the EQIP program or the program run by The Nature Conservancy. However, Griffin (2016) assumed that the relative performance of oysters within all four project sites was similar due to the similarity in practices used in each of the programs. Griffin assessed the effectiveness of oyster restoration programs in Rhode Island over the last 15 years. He estimated the total benefit in dollars from water quality improvement, fish production, and submerged aquatic vegetation (SAV) enhancement per acre of oyster reef and compared that to the total costs of running the two restoration programs, including the cost of labor and local hatchery operation budgets. Importantly, this model does not take into account the value of the oyster harvest itself, as it assumes that these reefs, which are protected from harvest, are not for consumption.[16]

The performance analysis determined that the two oyster reef restoration projects studied were not cost effective. This poor productivity is primarily because of the non-self-sustaining nature (i.e., poor recruitment and high mortality) of oyster restoration in Rhode Island, likely due to improper site selection. The potential inaccuracies in site selection might be due in part to a Rhode Island Department of Health rule that prohibits restoration from occurring in water where shellfishing is not allowed. This rule blocks restoration in sites with better conditions, specifically sites with lower salinity regimes, such as Narrow River, Green Hill Pond, Quicksand Pond, and the Seekonk River. Though historically, native oysters were abundant in Rhode Island

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[14] Griffin 2016

[15] Ibid.

[16] Ibid.

salt ponds, they have higher survival in areas of lower salinity due to lower predation in such regions.[17] An additional limiting factor for reefs restored by the EQIP program is the illegal harvest of restored reefs.[18] In a situation where the reefs were self-sustaining, restoration investments would be recouped via the ecosystem services provided by oysters in 17 years, with a capital gain for $4,200 annually afterwards.[19]

Of the four programs, all are still ongoing except for the North Cape restoration project, which concluded in 2011. In addition to those four projects, Roger Williams University now runs the Center for Economic and Environmental Development (CEED). CEED annually produces approximately 50,000 oysters to suspend from rafts in the Blount Oyster Pond on Prudence Island in Narragansett Bay, and they have planted over one million young oysters into Jenny's Creek in Jamestown.[20] DEM continues to annually announce shellfish seasonal area closures to any shellfish harvesting due to potential water quality impacts within local marinas and mooring fields.

The NRCS EQIP oyster restoration project in Rhode Island began its first phase in 2008 with its first cohort of eight aquaculturists. The program was started at the time as a collaboration between NRCS, DEM, The Nature Conservancy, Save the Bay, and the approximately 20 oyster aquaculturists that existed at the time in Rhode Island. The goal of the program was, and still is, to increase essential oyster habitat restoration to simultaneously improve water quality and provide habitat for other organisms within the oyster reef itself.[21] The program is administered by DEM in partnership with NRCS and local oyster aquaculturists. Essentially, the growers in the program place cultch, the material on which a reef is grown, in subtidal sanctuary waters and

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[17] Griffin 2016
[18] Personal communication with Eric Schneider, DEM
[19] Griffin 2016
[20] https://www.rwu.edu/academics/schools-and-colleges/fssns/ceed/shellfish-hatchery/oysters
[21] NRCS 2008

then seed the cultch with juvenile oysters. Afterwards, they conduct post-enhancement monitoring to keep track of reef health and success. NRCS and DEM have implemented the program in phases, with Phase I lasting from 2008-2011 and creating 117 reefs, and Phase II beginning in 2015 and creating 100 seeded reefs and 10 unseeded reefs.[22] In all, both phases combined have employed approximately 50 growers, and Phase II specifically has employed over 30 aquaculturists and is likely to continue for the foreseeable future.[23] For their 2020 cohort, NRCS will award $903,000 to the eight oyster growers in the program. Rhode Island was the first state to begin EQIP oyster restoration work, and others have since followed suit, including Virginia, Maryland, New Jersey, and Washington. In Massachusetts, there is an EQIP aquaculture program that focuses on recycling of biofouled gear rather than oyster restoration.

Most recently, NRCS is awarding an additional $809,000 to nineteen local Rhode Island oyster growers to purchase the surplus restaurant-quality oysters that such businesses could not sell due to COVID-19 as of September 2020.[24] NRCS will release the purchased oysters into the wild in a further effort to clean and support a strong ecosystem in Narragansett Bay in addition to supporting local aquaculture.

Oyster benefits for the environment

Though oysters have long been prized for their meat, their true value also takes into account the extent to which they interact with and improve the environment. Grabowski and Peterson (2007) have highlighted seven categories of ecosystem services provided by oysters: 1) production of oysters, 2) water filtration and concentration of pseudofeces, 3) provision of habitat for epibenthic inverts, 4) carbon sequestration, 5) augmented fish production, 6)

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[22] http://www.dem.ri.gov/programs/marine-fisheries/surveys-pubs/habitat.php

[23] Personal communication with Eric Schneider, DEM

[24] Personal communication with Joseph Bachand, NRCS

stabilization of adjacent habitats and shoreline, and 7) diversification of the landscape and ecosystem.[25] For the purposes of this paper, I will focus on the production of oysters, water filtration, provision of habitat, carbon sequestration, and augmented fish production, with a particular emphasis on oyster production and water filtration.

Oysters and other bivalve mollusks have long been studied for their feeding and filtration habits. Before the 1870s, oysters in the Chesapeake Bay could filter the entire water column in three to six days.[26] Over time, oyster populations were so depleted in the area that, as of 2007, an identical quantity of water filtration would have taken 325 days.[27]

In order to feed, oysters take in suspended particulate matter from the water column, ingest the edible particles, and bind the rejected particles with mucus, depositing them on the sediment surface as pseudofeces.[28] This filtration improves water clarity by reducing the amount of phytoplankton and suspended sediment that would otherwise have clouded the water, drawing them down to the benthos, the bottom sediment of a body of water. Filtering and clearing the water in such a way allows light penetration in shallow water, which facilitates the growth of important submerged aquatic vegetation (SAV), such as seagrass beds, that further improve water clarity and serve as a nursery ground for many coastal species.[29] On average, oysters reduce the amount of suspended particles in the water column, enabling them to promote the growth of SAV, at an estimated rate of 0.064 hectares of SAV per one hectare of oyster reef.[30] This is nearly an order of magnitude filtration rate higher than hard clams (*Mercenaria mercenaria*), another bivalve mollusk.

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[25] Grabowski and Peterson 2007
[26] Newell 1988
[27] Grabowski and Peterson 2007
[28] Ermgassen 2012
[29] Newell and Koch 2004
[30] Ibid.

In addition to reducing turbidity and increasing water clarity, oysters' filter feeding leads to denitrification and nutrient sequestration, removing nitrogen, carbon, and phosphorus from the water column. As they filter the particulate matter to feed, oysters and other bivalve mollusks sequester some nitrogen into both the shell and tissue and expel the rest as ammonia. If and when the oyster is harvested, the nitrogen is removed from the system.[31] This nutrient reduction quality of suspension feeders, including oysters, makes them particularly interesting as a potential nitrogen sink for nonpoint sources to mitigate the harmful effects of anthropogenic activities such as excessive fertilizer use in agriculture. There is a disagreement within the literature regarding whether or not oyster aquaculture and restored oyster reefs remove nitrogen at comparable rates.[32;33] However, work done specifically in Rhode Island by Humphries (2016) has shown that farmed oysters and restored oyster reefs do indeed conduct a similar level of denitrification compared to restored reefs.[34]

Oysters also reduce carbon and phosphorus levels in the water column. While oysters sequester some phosphorus in their shells via remineralization, they primarily move the nutrient to the sediment, where it gets buried, as a form of waste.[35] Oysters sequester carbon specifically in the form of calcium carbonate in their shells as they grow. Rates of uptake of particulate organic carbon (POC) and phosphorus vary seasonally, with the maximum rate occurring in the spring, summer, and fall.[36] These seasons are both when particulate concentrations are typically highest and when the metabolisms of oysters are highest as well. In addition to their direct

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[31] Officer 1982, Bricker et al 2019
[32] Humphries 2016
[33] Parker and Bricker 2020
[34] Humphries 2016
[35] Dame and Libes 1993
[36] Dame et al. 1989

carbon sequestration, oysters have been documented to facilitate expansion of salt marsh, kelp, seagrass, and other blue carbon habitats, which sequester more carbon than terrestrial forests.[37]

Oysters and their reefs also provide habitats for several species of epibenthic fish and decapods, functioning essentially as the temperate analog to coral reefs. The shell itself is a home for sessile fauna such as barnacles, sponges, hydrozoans, bryozoans, and tunicates. The reef that oysters form provides a habitat for species including blue crab (*Callinectes sapidus*), grass shrimp (*Palaemonetes pugio*), and several fish species. Because the reefs concentrate so many small fish and shrimp, they serve as an important foraging site for fin fishes and other consumers.[38] In Rhode Island specifically, artificial oyster reefs, or grow-out cages used in aquaculture, provide habitat in Narragansett Bay for black sea bass (*Centropristis striata*), cunner (*Tautogolabrus adspersus*), scup (*Stenotomus chrysops*), and tautog (*Tautoga onitis*).[39] An estimated 10 m^2 of restored oyster reef creates an extra 2.6 kilograms of fish and crustacean annually.[40] There is currently ongoing research conducted by DEM to analyze how restored oyster reefs impact local fish populations in Rhode Island, with a specific focus on species that are commonly fished recreationally.[41]

Oyster benefits for the economy

The fisheries and seafood sector in Rhode Island contributed $538.3 million in annual gross sales and employed 4,381 people in the state in 2016.[42] Within the seafood industry, oysters make up a large proportion of aquaculture in the state. Other aquaculture crops in Rhode Island include soft shell clams, surf clams, bay scallops, mussels, and sugar kelp. The combined farm

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[37] Fodrie et al. 2017

[38] Posey et al 1999

[39] Tallman 2007

[40] Peterson et al. 2003

[41] Personal communication with Eric Schneider, DEM

[42] Sproul and Michaud 2016

gate value, meaning the value of a product minus the selling costs, of Rhode Island's 80 aquaculture farms in 2019 was $6.07 million,[43] a slight decrease from $6.09 million in 2018.[44] In the same year, aquaculture farms supported over 200 jobs.

In addition to harvest, the ecosystem services that oysters provide lead to positive net benefits in the economy. From an economic perspective, oysters and other bivalve mollusks are special because of the positive externalities they provide. An externality is an action of one agent that affects other individuals or parties without that effect being reflected in the cost of the action. Common examples of positive externalities include vaccines, where one person getting a vaccine benefits the entire community by helping in preventing the spread of a disease. Another is bees: by keeping honey bees to sell honey, those bees help pollinate the nearby plants. By growing oysters, aquaculturists provide positive externalities to anyone else who accesses the body of water in which they are growing. For someone who lives near the water, the water filtration that oysters provide keeps the water clean and enjoyable to be near. For commercial or recreational fishermen, the habitat that oysters provide to several species of fish and crustaceans, in addition to the water filtration they achieve, is an important part of keeping fish stocks high.

There is a growing body of research that attempts to estimate the monetary value of these positive externalities in order to conduct accurate cost-benefit analyses of conservation projects. These studies can help form policy and guide restoration programs by determining if the upfront costs of restoration are offset by the value of the positive externalities that arise from the ecosystem services that oysters provide.

For example, the value of denitrification and nutrient sequestration that oyster reefs provide has been a subject of much research and conversation. Nutrient levels—primarily

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[43] http://www.crmc.ri.gov/aquaculture/aquareport19.pdf

[44] http://www.crmc.ri.gov/aquaculture/aquareport18.pdf

nitrogen and phosphorus—in Rhode Island waters, including in Narragansett Bay, have been a cause for concern for several decades. Excess nutrients in the water cause harmful algae blooms, depleting the oxygen levels in the water and blocking sunlight from reaching fish and plants below the surface. These algal blooms have the potential to be harmful from a public health standpoint, as well. In September 2016, routine monitoring of the Bay detected elevated levels of the toxic algae *Pseudo-nitzschia*, which, when consumed by humans in the form of shellfish, can cause serious health effects, such as nausea, vomiting, and amnesia. Between 2011 and 2016, DEM reported that twenty-six reservoir lakes, ponds, and two rivers experienced toxic or potentially toxic blooms. Of those twenty-six, nine of the bodies of water were drinking water reservoirs.[45]

These nutrients flow into the water from both point and nonpoint source polluters. Point sources are so named because it is easy to find the direct source of pollution and include, for example, industrial and sewage treatment plants or confined animal feeding operations. Nonpoint sources are those that cannot be traced to one specific pipe or discharge point, and in Rhode Island include overland stormwater runoff, compromised septic systems, salt and sand from winter road maintenance, and sediment from improperly managed construction sites and affect every watershed in the State.[46] In the past year, Rhode Island DEM awarded $569,500 in matching grants for three projects to mitigate water pollution from nonpoint sources with funding from the Environmental Protection Agency.

In the Chesapeake Bay, as in the Narragansett Bay, nitrogen and phosphorus are the two major nutrient pollutants of concern. States around the Chesapeake have adopted a nutrient credit trading program as one way to lower nitrogen and phosphorus levels in the water. Two of the six

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[45] https://www.rimonitoring.org/harmful-algal-blooms/recent-trends/
[46] http://www.dem.ri.gov/programs/water/quality/non-point/

most active markets of this kind in the world are the Pennsylvania and Virginia nutrient credit markets, both of which were developed under the Total Maximum Daily Load (TMDL) for the Chesapeake Bay Watershed.[47] I further discuss the details of the nutrient credit trading program in the following section. Although such programs are largely restricted to an exchange of credits between point sources and agriculture mitigation techniques, DePiper et al. (2017) has used the prices from such programs as a proxy for estimating the value of nutrient removal from the water column, which they apply to the quantity of nutrients that oysters filter from the Chesapeake Bay.[48] DePiper et al. conclude that making money from both harvesting oysters and selling nutrient credits provides significantly higher values than just harvesting, allowing oyster growers to more comfortably cover their operating costs and expand their operations.[49]

In addition to harvest values and nutrient removal values, the habitat that oysters create provides additional economic value to recreational and commercial fisheries. While commercial fisheries are clearly an important aspect of Rhode Island's economy, recreational fishing is a similarly large contributor of income to the state. The most recent NOAA Fisheries Economics report from 2016 attributed $412,000,000 in sales, $176,000,000 in income, and $270,000,000 in value added to Rhode Island's GDP from recreational fishing, as well as 4,173 jobs.[50]

Several studies have attempted to quantify the impact of oysters on commercial and recreational fisheries. Generally, there is more literature regarding the economic impact of oysters on commercial fisheries and less on recreational fishing, and more literature on wild and restored oyster reefs and less on aquaculture. That said, as mentioned previously, oyster aquaculture in Rhode Island provides a habitat for several species of fish common in recreational

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[47] Fisher-Vanden and Olmstead 2013
[48] DePiper et al. 2017
[49] Ibid.
[50] National Marine Fisheries Service 2018

catch. In the Chesapeake Bay, Hicks (2004) found higher recreational catch amounts to be linked to increased quantity of oyster reefs, indicating that recreational fishermen were likely to be strong supporters of oyster restoration programs.[51] With commercial and recreational fishing, the hypothesis that increasing the amount of oyster reefs in an area will positively affect fishery value relies on the assumption that either quality or quantity of other habitat is a limiting factor for commercial fish species and nekton (actively swimming aquatic organism). Most studies relating to oyster reef restoration assume this is the case (i.e., that reef or structured habitat is indeed limiting) because of the associations of so many species of fish with reef-dependent prey and the drastic depletion of functioning reef habitats along the east coast.[52]

Humphries and La Peyre (2015), in their Louisiana study, found that the presence of oyster reefs more than doubled the provision of increased nekton biomass and supported augmented commercial fisheries value when compared to control sites. Specifically, the authors found that oyster reefs augmented nekton biomass by 0.12 kg m^{-2} and fisheries value by \$0.09 m^{-2}, more than double the value given a mud-bottom habitat without oyster reefs, showing a clear benefit to commercial fishermen due to oyster reef restoration.[53] Although the added value to commercial fisheries does not cover the cost of oyster restoration projects alone, these results likely underestimate the value of the reef by not factoring in other ecosystem services or harvest potential. Grawbowski et al. (2012) reported an increase in value by \$0.41 m^{-2} for commercial fisheries, and a total added value, excluding harvesting and recreational fishing, of between \$5,500 and \$99,000 depending on location.[54]

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[51] Hicks 2004
[52] Peterson et al. 2003
[53] Humphries and La Peyre 2015
[54] Grabowski et al. 2012

Little work has been done specifically in Rhode Island to quantify the value that oysters add to recreational or commercial fishing. However, DEM and The Nature Conservancy, with support from the US Fish and Wildlife Service Sport Fish Restoration Program, have begun developing nine experimental reefs composed of recycled surf clams and oyster shells that they then seed with live oysters in Quonochontaug Pond. They are testing the hypothesis that the construction of oyster reefs in shallow coastal waters can increase the amount of fish that are important in recreational catches, such as black sea bass, tautog, striped bass, tautog, scup, and winter and summer flounder.[55] In 2015, DEM and TNC built eight reefs in Ninigret Pond to track species of crabs, shrimp, and fish that are attracted to them. No results have been published, but this study will provide additional useful insight into how oysters impact the fishing industry and their ecosystems in Rhode Island.

Nutrient Pollution Trading Market in the Chesapeake Bay

______Because a portion of Chapter 3 relies on information from the Chesapeake Bay area nutrient credit trading markets, here I provide some context and background on these markets to inform the discussion later in this report.

In December 2010, the EPA established the Chesapeake Bay Total Maximum Daily Load (TMDL), setting limits on the amount of nutrients (specifically nitrogen and phosphorus) and sediment that can enter the bay annually. The legislation requires the states in the Chesapeake Bay Watershed (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and Washington, DC) to develop and implement Watershed Implementation Plans (WIPs) that detail how each state will achieve its TMDL allocation. Even before the implementation of the TMDL, Chesapeake Bay states noticed the extent of pollution in the bay and had developed Tributary

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[55] Monti 2017

Strategies, which were voluntary plans for reducing each sector's nutrient loads. The costs of meeting these allocations led several of the states, specifically Maryland, Pennsylvania, and Virginia, to introduce nutrient trading programs as a more cost-effective way of achieving the same levels of abatement.[56] Such programs have since adopted the TMDL as a legally-enforceable cap.

Nutrient markets work by taking advantage of the fact that different sources face different costs when abating a certain amount of pollution. For example, it may be cheaper for a farmer to offset their pollution by, say, planting cover crops, than it would for a sewage plant to research and install a new form of technology that lessens the amount that they are polluting. In such a case, trading allows sources that can abate relatively cheaply to generate nutrient credits by reducing their own load by more than is required. They can then sell any excess abatement to a source for which it is more expensive to abate themselves than to pay someone else to abate. In this way, nutrient markets allow for two options: either 1) reduce the amount of pollution to the required level on site or 2) pay for credits, where another source is reducing their pollution by more than enough to reach their own required amount. Both options result in the same amount of pollution reduction, but nutrient markets allow for the possibility of reaching that amount at a lower cost by utilizing the power of the market.

A Chesapeake Bay Commission report on nutrient credit trading calculated the estimated savings of reducing nutrient pollution in several trading scenarios and compared them to the baseline of no market for trading pollution credits. They found that if significant point source polluters were only allowed to trade with themselves in the same geographic area (i.e., the same basin and state), the total annual cost of achieving the same load reduction targets would be 20% lower than in a no trading scenario, including a transaction cost of 38%. In a situation where

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[56] Branosky et al. 2011

significant point source polluters could purchase credits from agricultural nonpoint sources in addition to other point source polluters, the savings could reach 36% lower than the no trading scenario.[57] When the geographic range from which to buy credits expands to anywhere within the basin of the significant point source polluter, regardless of state lines, the estimated cost savings increase to 44% lower than no trading, and expanding further to the boundaries of the watershed attains a 49% lower cost of reaching TMDL goals than if each polluter had to abate on their own with no trading pollution credits.[58] Several such reports, indicating the cost effectiveness of a nutrient trading program under different scenarios, suggest expanding the number of eligible practices and allowing interstate trading to achieve maximum impact.[59]

As it currently stands, the majority of buyers and sellers of nutrient pollution credits in the Chesapeake Bay area are point source polluters and agricultural nonpoint sources. However, various government agencies, nonprofit organizations, and academic institutions have been working to understand the potential costs and benefits of including oyster aquaculture in the trading scheme. In December 2016, a panel of experts recommended that the Chesapeake Bay watershed award nitrogen and phosphorus removal credits to aquaculture operations as a Best Management Practice (BMP). The panel was comprised of oyster scientists and practitioners from the East Coast, including people from academia, nonprofit organizations, and county, state, and federal agencies, such as NOAA and the Talbot County Department of Public Works, with expertise in aquaculture, ecology, water quality, or fishery management. In addition, the panel held public stakeholder meetings to gather feedback on their primary recommendations and received additional feedback on their report from various nonprofit organizations such as the Chesapeake Bay Commission, Southern Environmental Law Center, Norfolk Public Works, and

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[57] Van Houtven et al. 2012
[58] Ibid.
[59] Ibid.

the Chesapeake Bay Foundation. Ultimately, after a year of research, the panel decided on a decision framework that would allow for "the incremental determination, approval, and implementation of nitrogen, phosphorus, and suspended sediment effectiveness estimates" of oysters in the Chesapeake Bay for use in determining the amount of credits to award an oyster aquaculturist.[60]

Indeed, as of 2017, jurisdictions within the Chesapeake Bay watershed can now include harvested oyster tissue in their WIPs. Though oysters sequester nutrients into their shell as well, the value of the credits generated by oyster aquaculture is limited to only the nutrients sequestered in oyster tissue. This is because the shells are often put back in the Bay to grow new oysters and are thus not removed from the system.[61] Thus far, Maryland is the only state with currently listed oyster aquaculture credits on their water quality trading board. As of 2020, 10 aquaculturists had posted their credits on the board.

In the Chesapeake Bay, to participate in nutrient credit trading markets, oyster aquaculturists generate nutrient credits to then sell to point source polluters, which they can either do independently or through an aggregator. A single credit is equal to one pound of nitrogen or phosphorus. As of May 2020, for the first time, a municipal building in Maryland bought nutrient credits from an oyster farm, Orchard Point Oyster Co., to offset its nitrogen use. The deal was brokered by Blue Oyster Environmental, an aggregator and broker of credits produced from aquaculture oysters, and the $1,600 (four credits, or pounds, of nitrogen removal) that Orchard Point made from the trade will allow them to buy more oyster seed to continue expanding their business and putting more oysters into the water.[62]

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[60] Cornwell et al. 2016
[61] Weber et al. 2018
[62] Parker and Bricker 2020

While the convention center deal was voluntary, most nutrient credit trades are to satisfy a TMDL requirement. There are beginnings of deals with oyster aquaculturists to meet these requirements, as well. For example, Anne Arundel County in Maryland is in the process of solidifying a deal with a local oyster farm on the West River to meet mandates for treating stormwater runoff. The county will pay $4,950 for 107 pounds of nitrogen and 12 pounds of phosphorus removed from the river by Witt Seafood.[63]

Because the inclusion of aquacultured oysters in the nutrient credit trading markets is recent, and because determining how to process and price the credits coming from oysters is complex, there have been very few instances of successful trades between oyster growers and point source polluters. Weber et al. (2018) notes that, ultimately, these markets were not designed to be an economic incentive for aquaculture. Additionality, the idea that credit payments should result in a net nutrient decrease that would not have otherwise happened, has been a barrier to including more aquaculture in the nutrient credit markets; the concern is that oyster aquaculture would filter water regardless of the payment, leading some to believe that including aquaculture in these trading schemes is not cost effective and prevents that money from generating additional reductions elsewhere.[64] However, providing oyster growers with an additional revenue stream allows them to expand their operations, as previously mentioned, thus providing additional nutrient reduction capacity as well as seafood provision. Currently, Maryland oyster growers do not have to prove an increase in harvests to qualify to generate credits.

Scale has been another concern with credit generation from oyster aquaculture. When Anne Arundel agreed to purchase credits from Witt Seafood, they could only purchase the equivalent of three acres' worth of treatment of impervious surface due to Witt Seafood's limited

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[63] https://www.bayjournal.com/news/fisheries/oyster-growers-hope-polluters-will-shell-out-for-nutrient-credits/article_d5d4abac-8e1e-11ea-be85-8f3b710e121b.html

[64] Weber et al. 2018

supply (i.e., oysters simply do not generate as many nutrient credits as large municipal areas need). For reference, the county has over 5,000 acres of impervious surface. However, the county officials believe it is worth potentially catalyzing efforts on a larger scale and demonstrating that oyster aquaculture credits are a viable method of achieving abatement goals.

Chapter 2: Projected resulting change in biomass from change in aquaculture in Narragansett Bay

Introduction

Oysters provide several ecosystem services that have the potential to benefit Rhode Island's economy. They also play a role in the food web of their ecosystem in terms of the resources they consume and the food that they provide (i.e., what their predator-prey relationship is with the other species in the ecosystem). It is thus important to analyze how changing the amount of oysters in an ecosystem affects the food web; that is, what effect does changing the amount of oyster aquaculture have on an ecosystem through predator-prey relationships? How does that change affect the economy? To begin to answer these questions, I used an ecosystem model of Narragansett Bay to find the projected change in biomass of other species when oyster aquaculture biomass changes, based solely on predator-prey relationships in the bay. Using those projections and average ex-vessel prices of the species in the bay that are important to commercial and recreational fishing, I assigned an economic valuation to changes in oyster aquaculture in Narragansett Bay.

From the model, I conclude that the projected biomass of functional groups associated with recreational fishing (piscivorous fish and benthivorous fish) is expected to increase with a significant rise in cultured shellfish biomass, while biomass of groups associated with commercial fishing (planktivorous fish, carnivorous benthos, and suspension feeding benthos) is projected to decrease. There is very little change in biomass of other groups with small changes in cultured shellfish biomass. It is important to note, however, that the amount of recreational fishing in Narragansett Bay is increasing significantly, while commercial fishing is shifting to areas either outside of the bay or right at its mouth. Further, this model and economic valuation only takes predator-prey relationships into account when projecting biomass, and does not consider the ecosystem services that have generally positive impacts on each functional group. Therefore, the results of this model can be considered a baseline or minimum amount of economic change aquacultured oysters in Narragansett Bay can provide to the economy.

Methods

I. Ecopath with Ecosim ecosystem modeling in Narragansett Bay

To understand the impacts that aquacultured oysters have on the ecosystem where they are grown, I used an ecosystem model using Ecopath with Ecosim (EwE). Ecopath with Ecosim (EwE) is an ecological modeling software suite developed by a former NOAA employee composed of two different features: Ecopath and Ecosim. Ecopath is a static, mass-balanced view of the ecological system, while Ecosim is a dynamic simulation module. I focused on Ecosim for the purposes of this paper. Essentially, Ecosim takes in a time series of data for the functional groups in a system and can project how the biomass of those species will change over time given changes in a certain independent variable, called a forcing function in the model. In this case, cultured shellfish biomass is the forcing function. The specific model I used also included phytoplankton biomass and fishing pressure as additional forcing functions, though I only adjusted cultured shellfish biomass values for the purposes of this project. EwE is often used in policymaking to analyze the potential impact of fishery management policy options and marine protected areas, among other policy efforts.

Annie Innes-Gold and Maggie Heinichen, masters students at the University of Rhode Island (URI), along with their colleagues at URI, developed the ecosystem model as an up-to-date tool for ecosystem-based management, published in November 2020 using EwE. Prior to their model, there were two other ecosystem models of Narragansett Bay: Byron et al. (2011) created an EwE ecosystem model to calculate the ecological carrying capacity of shellfish aquaculture in the bay,[65] and Monaco and Ulanowicz (1997) defined an ecosystem model to compare trophic structure and sustainability of Narragansett Bay, Chesapeake Bay, and Delaware Bay.[66] However, Monaco and Ulanowicz did not include cultured shellfish or fisheries as functional groups in their model. Both Byron et al. and Innes-Gold et al. did include cultured shellfish as a functional group and included fisheries pressure as another element of their model. The model created by Byron et al. is not temporally dynamic, meaning that it cannot be used to predict how ecosystems will change over time. Innes-Gold et al.'s model therefore is the most up-to-date and applicable model for the purposes of this project.

Innes-Gold et al., in their updated model of the Bay, categorized the species that make up the ecosystem of Narragansett Bay into 15 functional groups. The species included in each group can be found in their Supplementary Table 1.[67]

Innes-Gold et al.'s model used an automated fitting procedure within the EwE software that estimated the vulnerabilities for the observed biomass time series from 1994 until 2018. I worked with them to optimize the parameters of the model, specifically the vulnerabilities, to best fit my question about oyster aquaculture. I primarily used the vulnerabilities that they found best fit their data set, but altered two values: the automatic vulnerability values where cultured shellfish was a predator for zooplankton and for phytoplankton, because oysters' diet is composed of those two groups. The original values were 0.8100 for oyster predation of phytoplankton and 0.1900 for zooplankton, and I increased both values to 1,000,000, effectively making the relationship between an oyster and its prey entirely top-down. The shellfish, in this

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[65] Byron et al. 2011
[66] Monaco and Ulanowicz 1997
[67] Innes-Gold et al. 2020

way, are not food-limited and can consume as much of their prey as they need to support the biomass that I input into the model. The use of 1,000,000 specifically was somewhat arbitrary but is representative of the highest value a vulnerability can be in a EwE to make the model as top-down as possible. This assumption is somewhat realistic; there is no indication that cultured shellfish in the bay are food limited or that they will become food limited until they reach their carrying capacity.[68]

II. Scenarios used in ecosystem modeling

I used Innes-Gold et al.'s model of Narragansett Bay to increase and decrease the amount of cultured shellfish, a group that is composed primarily of oyster aquaculture, under four scenarios: 1) a constant amount of oyster aquaculture in the bay (no change from the last year from which we have data, 2018, where cultured shellfish = 1.21162 g/m^2); 2) a minimum amount of cultured shellfish (a decrease in biomass to no oyster aquaculture in the bay, where cultured shellfish = 0 g/m^2); 3) a recent historical maximum amount of cultured shellfish (an increase to the highest biomass of oysters in the bay since the beginning year of the model, 1994, where cultured shellfish = 5.40344 g/m^2); 4) 10 times the current biomass of cultured shellfish (an increase where cultured shellfish = 12.11620 g/m^2), to reflect a similar oyster restoration goal set by the Chesapeake Bay in 2000; and 5) the maximum biomass of oysters in the bay (an increase to the carrying capacity of oysters, as described in Byron et al. 2011, where cultured shellfish = 297 g/m^2). It is important to note that the cultured shellfish biomass in Scenario 5 is a similar quantity to the historic maximum biomass of oyster aquaculture in Narragansett Bay (144,562

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[68] Byron et al. 2011

tons) and is a similar quantity to the current standing stock of other estuarine bays such as the Chesapeake Bay and the Delaware Bay.[69]

III. EwE limitations

As with all models, EwE has its shortcomings. Most notably for our purposes, this EwE model does not take environmental factors or the ecosystem services that oysters provide into account. Rather, it only reflects the predator-prey relationship between organisms in the Bay. Furthermore, as is the case with any model, while the results are useful in predicting what might happen to the biomass of functional groups in the ecosystem, they are not meant to be relied on as absolutely certain. The projected biomass of each functional group could have increased or decreased in magnitude depending on the strength of interactions between a predator and its prey. For example, carnivorous benthos could have increased due to the increase in deposit feeding benthos, which they consume, or could have decreased because their predators (benthivorous fish) increased. The outcome depends on if the functional group is more controlled by bottom-up or top-down forces, which is determined in EwE models by the vulnerabilities in the system. Vulnerabilities cannot be quantified by observation in real ecosystems, so it can be difficult to know the accuracy of the vulnerabilities and thus the accuracy of the resulting biomass predictions.

IV. Economic analysis and valuation

Once I calculated the projected change in biomass of each functional group, I began determining a valuation of each scenario. I collected data from the NOAA landings database[70]

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[69] Ibid.

[70] https://foss.nmfs.noaa.gov/apexfoss/f?p=215:200::::::

and the National Marine Fisheries Service Fisheries of the United States report[71] to find the average ex-vessel (i.e., paid to fishermen at the time of first sale) prices of each species within a functional group and then found the weighted average of those prices to compute the average price per m^2 of each functional group. I used observed biomass of each species within each functional group to weight the prices across the functional group. To ultimately determine the valuation per area for each functional group, I multiplied the group average weighted price by the different biomasses of each scenario for each functional group using results from the EwE model. Finally, I summed the per area valuation across all functional groups for each scenario (i.e., the sum of the per area valuations for Scenario 1, then Scenario 2, etc.). The results of these calculations can be found in Table 2. The calculations I made and the data I used to arrive at the results in Table 2 can be found in the appendix.

I will focus on six functional groups in the calculations of the per area valuations for each scenario: piscivorous fish, benthivorous fish, carnivorous benthos, suspension feeding benthos, planktivorous fish, and cultured shellfish. The species in these six groups are those that best represent the commercial and recreational fishing catch in Rhode Island and for which catch data exists. With the total per area estimated valuations for each scenario, I determined the percent change from the baseline scenario (Scenario 1) in order to get a sense of the difference between each scenario from an economic perspective.

It is important to note that the ex-vessel price for each species is applicable when those species, and their corresponding functional group, are sold commercially. While these values can serve as a proxy for the economic value of the projected changes in biomass for all of the functional groups, they are not highly accurate representations of the value each group brings to

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[71] Liddel and Yencho 2020

the state. These values are most likely an underestimate of true value. For commercial fisheries, the money the fishermen make selling the fish gets multiplied as they in turn buy homes, purchase food for their families, and expand their businesses. With respect to recreational fishing, while the ex-vessel price of the fish itself can serve as a representation of what fishing is worth to the fisherman, this value does not take into account the money the recreational fishermen pay to Rhode Island businesses to rent or buy a boat and equipment, stay in a hotel, purchase food for their trip, or any other transactions they may make on their trip. The true value of recreational fishing comes from the enjoyment that the fisherman experiences as well as what they pay local businesses to enjoy fishing recreationally.

Results

Scenario 1 acted as a control group against which to compare results, as it is the scenario that maintains current levels of shellfish aquaculture in the bay. Increasing the amount of cultured shellfish in Narragansett Bay by 346%, as in Scenario 3, and by 900%, as in Scenario 4, had minimal impact on the biomass of other functional groups. Decreasing the cultured shellfish biomass by 100% to zero, as in Scenario 2, had similarly little impact. That said, increasing the amount of cultured shellfish to the carrying capacity in Scenario 5, an increase of 24,413%, had a noticeable effect on biomass of other functional groups. Exact results can be found in Table 1 and Figure 1, with numbers sourced from the projected biomass results of each group in 2030. By 2030, every group reached a stable plateau.

I. Scenario 1

Scenario 1 served as a projection for the biomasses of each functional group holding the current biomass of Cultured Shellfish constant at its last measured level in this model, 1.21162 g/m^2 measured in 2018. Under this constant level of aquaculture in the bay, the functional groups are projected to maintain approximately consistent biomass from the last year of observed data until 2030. When this constant amount of cultured shellfish is assumed, the projected valuation is \$0.86 per m^2. Without the value of the cultured shellfish, the valuation for Scenario 1 is \$0.79 per m^2.

II. Scenario 2

Scenario 2 represented a scenario in which the amount of oyster aquaculture in the bay decreases to zero. The most notable differences between the projections under Scenario 2 compared to Scenario 1 include changes to zooplankton, gelatinous zooplankton, and small squid. All three groups increased, by 0.61%, 0.54%, and 0.58%, respectively. In this scenario with no cultured shellfish, only benthic algae, deposit feeding benthos, and benthivorous fish saw a projected decrease in biomass, albeit a small one, of 0.0024%, 0.04%, and 0.08%, respectively. Despite the positive trends in primary production, the per area valuation of Scenario 2 decreased 7.86% from the valuation from Scenario 1, to a value of \$0.79 per m^2. As seen in the change in biomass, the only value to decrease other than cultured shellfish was benthivorous fish. The other four groups saw slight increases in value per area. Without the increase in value from cultured shellfish, Scenario 2 would increase in value approximately 0.298% from Scenario 1.

III. Scenario 3

The time series that this model used as an input has data extending back to 1994. From 1994 until 2018, which was the last year the model has recorded data, the maximum biomass of cultured shellfish was 5.40344 g/m^2. While this amount is nowhere near the historic maximum of cultured shellfish in the bay, it served as a more recent maximum and represented an increase in cultured shellfish of 345.97% from current values. This increase in cultured shellfish led to the absolute largest projected change in zooplankton, which decreased 2.08% from Scenario 1. Generally, most functional groups experienced slight decreases with the associated increase in cultured shellfish. The only groups with a positive change in biomass were benthic algae, deposit feeding benthos, and benthivorous fish.

In terms of per area valuation, Scenario 3 increased 27.2% from the value of Scenario 1 to a total of \$1.09 per m^2. Once again, benthivorous fish and cultured shellfish were the main drivers of positive change in this scenario. Without the value of cultured shellfish, Scenario 3 would decrease 1.009% in per area valuation to \$0.78 per m^2.

IV. Scenario 4

One of the first goals that the Chesapeake 2000 Agreement set was an oyster restoration project that would increase the amount of oysters by ten times what was in the bay at the time, or an increase of 900%.[72] Scenario 4 analyzes how a similar tenfold increase would affect biomass and per area valuation in Narragansett Bay. As in Scenario 3, the highest absolute change came from zooplankton with a percent decrease of 5.27%. Suspension feeding benthos, carnivorous benthos, and planktivorous fish all decreased, by 2.87%, 1.32%, and 1.99%, respectively. Again,

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[72] Cerco and Noel 2005

similar to Scenario 3, the only functional groups to experience a positive change in biomass, other than benthic algae, were deposit feeding benthos and benthivorous fish, which increased by 0.35% and 0.69%, respectively.

With cultured shellfish in the valuation, the per area value of Scenario 4 increased from Scenario 1 by 70.861%, from $0.86 to $1.47 per m^2, primarily due to the cultured shellfish and benthivorous fish, as in Scenario 3. Without cultured shellfish, the per area valuation decreased to $0.77 per m^2, a decrease of 2.5%.

V. Scenario 5

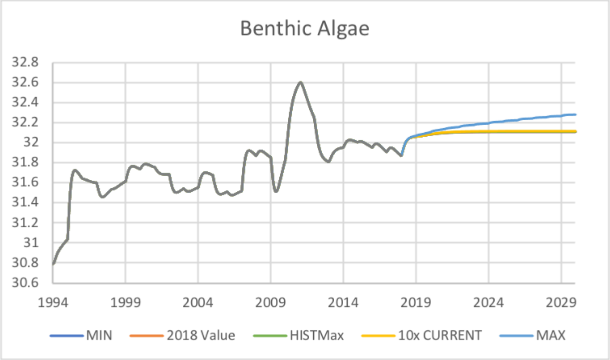
In Byron et al. 2011, the authors used their own EwE model to determine the carrying capacity of cultured oysters in Narragansett Bay. They determined that the carrying capacity biomass is 297 g/m^2, a 24,412.64% increase from the current biomass of oyster aquaculture in the bay. This dramatic increase led to the most notable projected decreases in biomass of zooplankton, large squid, and suspension feeding benthos, with decreases of 59.83%, 28.97%, and 29.33%, respectively. Benthivorous fish and planktivorous fish both increased, by 11.88% and 20.45%, respectively. Detritus increased by 6.77%.

The per area valuation of Scenario 5 follows a similar pattern to the scenarios before it. With the value of the cultured shellfish, which increased dramatically in this scenario, the per area valuation of Scenario 5 increases 1962.8% from Scenario 1 to $17.75 per m^2. However, in this instance, the value of piscivorous fish increases in addition to benthivorous fish and cultured shellfish. Without the value of cultured shellfish, the per area valuation decreases significantly to $0.598, a 24.28% decrease from Scenario 1.

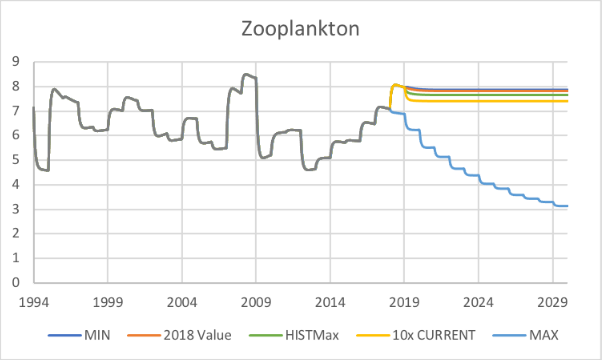
Functional Group	Scenarios				
	Scenario 1 (CS = 1.2116 g/m^2)	Scenario 2 (CS = 0 g/m^2)	Scenario 3 (CS = 5.4034 g/m^2)	Scenario 4 (CS = 12.12 g/m^2)	Scenario 5 (CS = 297 g/m^2)
Phytoplankton	34.25918 (0)	34.25918 (0)	34.25918 (0)	34.25918 (0)	34.25918 (0)
Benthic Algae	32.11032 (0)	32.10955 (-0.0024%)	32.11299 (0.0083%)	32.11719 (0.0214%)	32.28151 (0.5331%)
Zooplankton	7.809371 (0)	7.856992 (0.6098%)	7.646867 (-2.0809%)	7.398018 (-5.2674%)	3.137005 (-59.8302%)
Gelatinous Zooplankton	98.28867 (0)	98.81834 (0.5389%)	96.51266 (-1.8069%)	93.88985 (-4.4754%)	74.36465 (-24.3406%)
Deposit Feeding Benthos	104.0829 (0)	104.0416 (-0.0397%)	104.2255 (0.1370%)	104.44789 (0.3507%)	109.6035 (5.3040%)
Susp. Feeding Benthos	38.50106 (0)	38.63096 (0.3374%)	38.06109 (-1.1427%)	37.39705 (-2.8675%)	27.2077 (-29.3326%)
Cultured Shellfish	1.21162 (0)	0 (-100%)	5.40344 (345.9682%)	12.11620 (900%)	297 (24412.636%)
Carnivorous Benthos	12.71852 (0)	12.73848 (0.1569%)	12.65117 (-0.5295%)	12.55040 (-1.3219%)	11.33356 (-10.8893%)
Small Squid	0.953606 (0)	0.959158 (0.5822%)	0.946682 (-0.7261%)	0.93232 (-2.2322%)	0.752818 (-21.0557%)
Large Squid	1.144514 (0)	1.14864 (0.3605%)	1.130548 (-1.2203%)	1.10952 (-3.0575%)	0.823183 (-28.0758%)
Planktivorous Fish	20.09338 (0)	20.13995 (0.2318%)	19.93502 (-0.7881%)	19.69362 (-1.9895%)	15.80718 (-21.3314%)
Benthivorous Fish	14.14606 (0)	14.13516 (-0.0771%)	14.18374 (0.2664%)	14.24276 (0.6839%)	15.82621 (11.8772%)
Piscivorous Fish	9.906386 (0)	9.908813 (0.0245%)	9.899473 (-0.0698%)	9.89300 (-0.1351%)	11.93223 (20.4499%)
Seabirds	0.056769 (0)	0.056779 (0.0176%)	0.056734 (-0.0617%)	0.05668 (-0.1568%)	0.056638 (-0.2308%)
Detritus	8.578691 (0)	8.584654 (0.0695%)	8.558969 (-0.2299%)	8.53075 (-0.5588%)	9.159151 (6.7663%)

Table 1: Projected biomass (in g/m^2) in 2030 of each functional group across Scenarios 1-5 with associated changes in Cultured Shellfish. Percent change from the baseline projection (Scenario 1) is reported in parentheses.

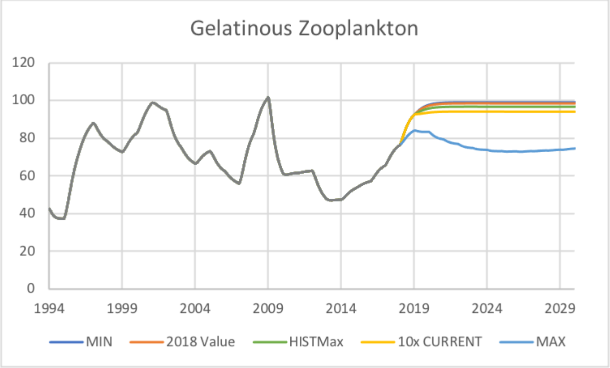
(a)


Benthic Algae
32.8
32.6
32.4
32.2
32
31.8
31.6
31.4
31.2
31
30.8
30.6
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX

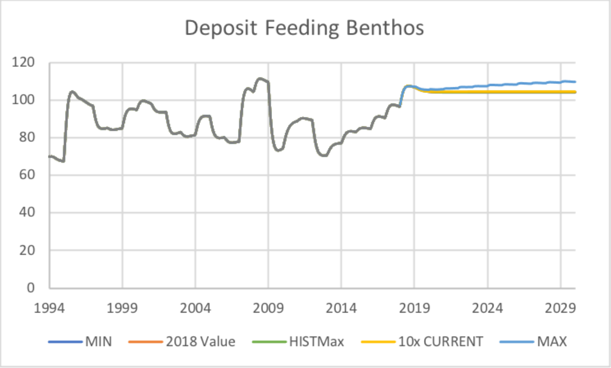
(b)


Zooplankton
9
8
7
6
5
4
3
2
1
0
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX

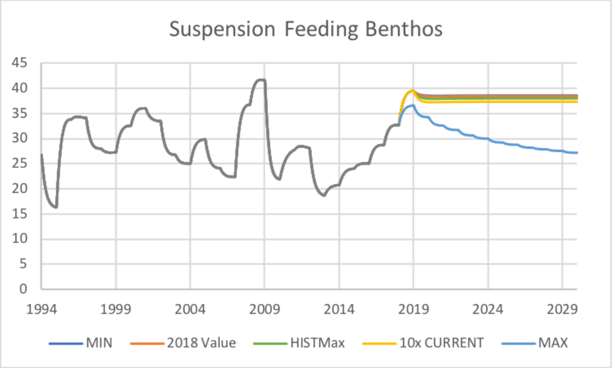
(c)


Gelatinous Zooplankton
120
100
80
60
40
20
0
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX

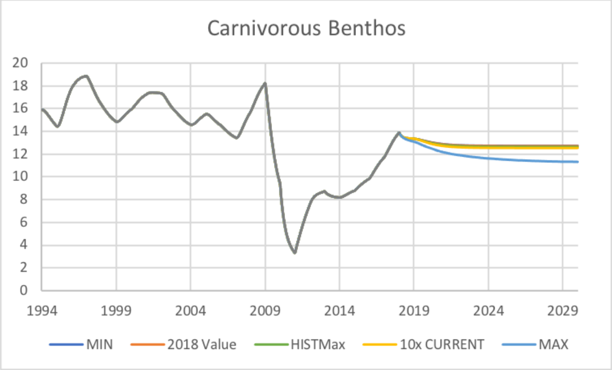
(d)

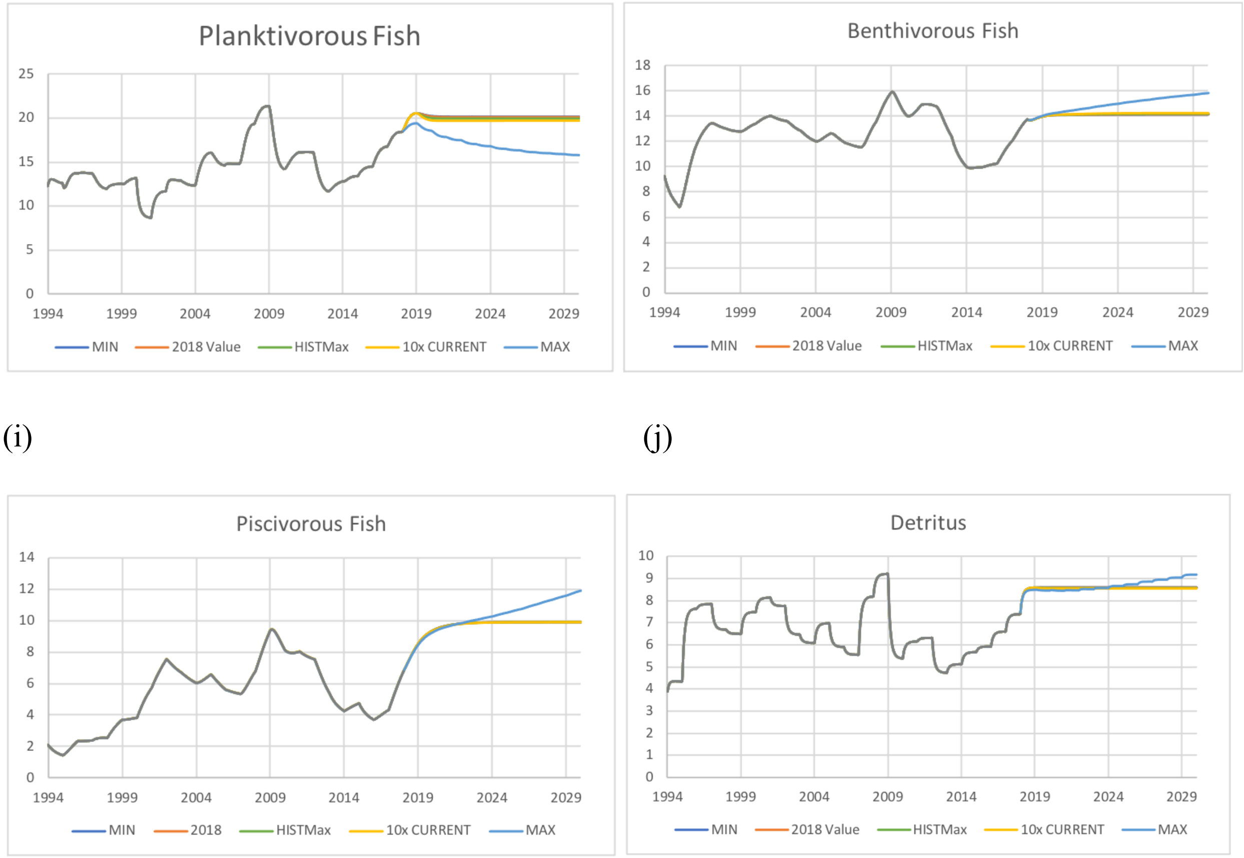

Deposit Feeding Benthos
120
100
80
60
40
20
0
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX

(e)


Suspension Feeding Benthos
45
40
35
30
25
20
15
10
5
0
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX

(f)


Carnivorous Benthos
20
18
16
14
12
10
8
6
4
2
0
1994
1999
2004
2009
2014
2019
2024
2029
MIN
2018 Value
HISTMax
10x CURRENT
MAX


(g)

(h)

(i)

(j)

Figure 1 (a-j): observed (1994-2018) and projected (2019-2030) biomass in each functional group, with biomass in g/m^2 on the y-axis and years on the x-axis.

Functional Group	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Piscivorous Fish	0.048707	0.048719	0.048673	0.048641	0.058667
Benthivorous Fish	0.008053	0.008047	0.008074	0.008108	0.009010
Carnivorous Benthos	0.061247	0.061343	0.060922	0.060437	0.054577
Planktivorous Fish	0.013033	0.013064	0.012931	0.012774	0.010253
Cultured Shellfish	0.069960	0	0.312001	0.699604	17.149136
Suspension Feeding Benthos	0.659358	0.661583	0.651823	0.640451	0.465951
TOTAL	*0.86* *(0)*	*0.79* *(-7.858%)*	*1.09* *(27.206%)*	*1.47* *(70.861%)*	*17.75* *(1962.813%)*

Table 2: Per area valuations (in \$/m^2) of functional groups that contribute to recreational (piscivorous fish and benthivorous fish) and commercial (planktivorous fish, carnivorous benthos, and suspension feeding benthos) fishing. Cultured shellfish is included as well, as it contributes to the fishing economy of Narragansett Bay. Percent change from the baseline projection (Scenario 1) given in parentheses in the total row.

Discussion

Within the 15 functional groups, certain groups contain species which are relevant to the commercial fishing industry and others which are more important to the recreational fishing industry. For commercial landings, planktivorous fish (including menhaden and herring), carnivorous benthos (lobster, crab, and whelk), and suspension feeding benthos (quahogs, mussels, and wild oysters) are the relevant groups. Groups relevant to recreational landings are piscivorous fish (striped bass, bluefish, and summer flounder) and benthivorous fish (scup). Plankton and detritus groups are useful in assessing changes in overall system productivity potential, since they are at the base of the food web and significant changes to those groups can be representative of productivity of the system as a whole.

As a whole, zooplankton and gelatinous zooplankton biomass saw the highest negative association with an increase in cultured shellfish. This indicates a potential drop in system productivity potential due to the significantly increased amount of cultured shellfish, which consume zooplankton. They also consume benthic algae, which saw a small but positive projected increase in biomass as oyster biomass increased, likely due to the corresponding decrease in carnivorous benthos, another predator of benthic algae. Detritus biomass, the other indicator of productivity potential, is projected to increase with a significant increase in oyster biomass, as in Scenario 5. In the scenarios with a smaller and more realistic increase in cultured shellfish, namely Scenarios 3 and 4, zooplankton and gelatinous zooplankton decreased, but by significantly less than in Scenario 5. This indicates that, even if oyster aquaculture were to boom to 10 times its current size, system productivity would remain at comparable levels to the current state.

Among the functional groups that are relevant to commercial fishing, there was an overall projected negative trend associated with an increase in cultured shellfish biomass. By the year 2030, suspension feeding benthos had a projected nearly 30% decrease, carnivorous benthos are projected to decrease by 10.9%, and planktivorous fish by 21.3%. The recreational fish groups fared better with an increase in cultured shellfish biomass. The benthivorous fish and piscivorous fish groups both are projected to experience an increase in biomass by 11.9% and 20.5%, respectively. While it is challenging to determine exactly why those changes would occur under a maximum amount of cultured shellfish, understanding the predator-prey relationships within this ecosystem model provides a potential explanation. Likely, deposit feeding benthos (DFB) increased due to the increase in detritus, one of their food sources. DFB is 77% of benthivorous fish diet, which likely led to the increase in benthivorous fish. Similarly, benthivorous fish makes up 25% of piscivorous fish diet, leading to an increase in piscivorous fish. The decrease in zooplankton because of predation from cultured shellfish likely caused the projected decrease in planktivorous fish and suspension feeding benthos. The decrease in carnivorous benthos can likely be attributed to the increase in its predator, benthic fish.

As was the case with zooplankton and gelatinous zooplankton, while the changes in the functional groups above were very pronounced when cultured shellfish was at its carrying capacity, changes to the functional groups mentioned in the previous paragraph were minimal in the scenarios with more feasible increases in cultured shellfish. It is highly unlikely that the amount of cultured shellfish in the bay will increase to its carrying capacity in the near future, so it is important to pay attention to Scenarios 3 and 4 as well as Scenario 5. In Scenarios 3 and 4, there was no absolute change in the functional groups relevant to recreational and commercial fishing higher than 2%. Essentially, this indicates that even if aquaculture in the bay were to increase by 10 times as much as it currently is, there would be very little effect, positive or negative, on recreational or commercial fishing.

Excluding cultured shellfish, the changes in per area valuation were largely driven by two groups: suspension feeding benthos and piscivorous fish, which had the two highest weighted average prices of $0.017 per gram and $0.0049 per gram, respectively. Cultured shellfish had an average weighted price of $0.058 per gram. Although piscivorous fish increased in Scenario 5, the significant decrease in suspension feeding benthos in the same scenario outweighed that positive change and contributed to the net decrease in per area valuation in Scenario 5, not including cultured shellfish. The same is true of Scenarios 3 and 4, to a lesser extent.

These findings are not surprising on their own. As mentioned in the beginning of this chapter, the projected biomasses from the ecosystem model are derived solely from the predator-prey relationship between the different functional groups. Because cultured shellfish have no predators in the model, an increased amount of them has only indirect benefits to other species and can have direct consequences as the cultured shellfish compete for resources with other species. However, cultured oysters do have significant benefits to the other species in the bay. They perform several ecosystem services that promote a healthier ecosystem, including providing habitat for benthivorous fish species such as black sea bass, as well as keeping excess nutrients from creating algal blooms that limit the amount of dissolved oxygen in the water. These ecosystem services are simply not reflected in this model.

All of that said, it is important to note that Narragansett Bay specifically has become increasingly popular for recreational fishing compared to commercial fishing. Commercial fishing in Rhode Island takes place primarily in Northwest Atlantic Fisheries Organization (NAFO) areas 539 and 537, with 25,845 and 2,146 trips made in each area respectively according to an industry profile conducted in 2010 by the Cornell University Cooperative Extension Marine Program.[73] Areas 539 and 537 are south of Narragansett Bay, just beyond the three mile limit off the coast of Rhode Island. In comparison, 384 commercial fishing trips were made in the same year in the NAFO area that contains Narragansett Bay. While commercial fishing is undoubtedly important to Narragansett Bay, the majority of it occurs elsewhere around the state.

Recreational fishing, on the other hand, is prevalent in the bay. Between 1994 and 2018, the beginning and end of the observed data for the EwE model used in this paper, commercial fishing landings biomass in the bay decreased from 21.097 g/m^2 to 9.913 g/m^2, while recreational fishing landings biomass increased from 3.134 g/m^2 to 5.177 g/m^2.[74] Notably, of the commercial fishing biomass data, 4.455 g/m^2 of the 9.913 g/m^2 total comes from high volume species in the planktivorous fish group, such as herring and menhaden, which are fished at the mouth of the bay. While the commercial catch biomass is still higher, recreational fishing has boomed as commercial fishing has decreased significantly. Given this context, the predicted increase in biomass of those functional groups which are associated with recreational fishing is an indicator that increased oyster aquaculture in the bay can have economically significant impacts in the state.

These projected biomasses and per area valuations may serve as a baseline for the environmental and economic impact that aquacultured oysters can provide to the bay. These results reflect just the predator-prey relationship between oysters and the other species in the ecosystem, without taking into account the ecosystem services that make oysters so beneficial to the environment. Taking into account the habitat creation and water filtration would almost

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[73] Hasbrouck et al. 2011

[74] Innes-Gold et al. 2020

certainly be beneficial to other species in the bay, likely increasing biomass for several functional groups and creating a healthier ecosystem as a whole.

Chapter 3: Approximating the value of nutrient sequestration by aquacultured oysters

Introduction

Oysters have long been known to effectively clean water via filter feeding practices. As they consume organic material such as algae and phytoplankton, oysters themselves remove nutrients from the water in three ways: 1) the assimilation of some of the nutrients and carbon into oysters' soft tissue and shell;[75] 2) the removal of nutrients via biogeochemical processes in which the oysters convert some organic nitrogen into nitrogen gas, a form of nitrogen inaccessible to phytoplankton for use in growth; and 3) the release of some nutrients in biodeposits, meaning the nutrients in oyster waste get deposited on the sediment surface and are often buried under the surface.[76] The bivalves stimulate sediment denitrification in the sediment below their reefs, as well. In addition to removal of nutrients, oysters also filter inorganic matter, such as suspended sediment, which increases water clarity in their ecosystems.

We know that we derive value from these practices. For example, the filtration of sediment allows the growth of eelgrass, which in turn provides habitat for many species of fish and further filters the water to keep it clear, aesthetically pleasing, and able to support a diverse body of organisms.[77] Filtering the nitrogen and phosphorus from bodies of water allows for healthy aquatic habitats and lowered public health threats from poor water quality.

Removing nutrients from the water column has become increasingly important as the amount of nitrogen and phosphorus from wastewater treatment plants, stormwater runoff from

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[75] Kellogg e al. 2013
[76] Newell et al. 2005
[77] Newell and Koch 2004

urban areas, and excess fertilizer runoff from farms increases and accumulates in the water. In Rhode Island alone, there are 96 bodies of water with documented quality impairments.[78] Some potential dangers of such a buildup of nutrients in Rhode Island waters were seen dramatically in August 2003, when a million dead fish washed up on the shores of Narragansett Bay because of a sharp drop in dissolved oxygen levels caused by eutrophication. At that time, nutrient levels in the bay were approximately four or five times higher than when colonists arrived in Rhode Island.[79] In the years since the fish kill, the state has spent time and money developing restoration plans for impaired bodies of water, primarily focusing on reducing nutrient loads from wastewater treatment facilities by using "advanced systems." These systems have decreased nitrogen and phosphorus levels in the bay by approximately 55%, surpassing the original goal of 50% reduction, but current levels are still three times higher than they were before such elevated levels of human activity.[80]

While it is outside the scope of this paper to determine the value of all benefits of water filtration by oysters, in this section I will approximate the value of removing nitrogen and phosphorus from the water column. To measure the benefit of this externality, I will use prices of nutrient pollution credits from nutrient trading markets in the US, specifically in the Maryland Water Quality Trading Program, as a proxy. By determining how much nitrogen and phosphorus oysters in Rhode Island remove from the water, I can approximate the value of nutrient removal and determine how that value may grow with an increasing amount of oysters in the state.

Methods

I. Determining quantity of nitrogen and phosphorus removed per oyster

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[78] http://www.dem.ri.gov/programs/water/quality/
[79] https://seagrant.gso.uri.edu/narragansett-bay-changes/
[80] Ibid.

As mentioned previously, there are three mechanisms by which oysters filter water. However, I will be primarily focusing on the assimilation of nutrients into the growing oyster body for the purposes of this valuation. There are two reasons for this decision: 1) the Chesapeake Bay's Expert Panel Report on including oyster aquaculture as a Best Management Practice (BMP) in nutrient trading markets, on which I am basing a significant amount of my process, similarly only considers credits generated from nutrient assimilation into the soft tissue of the bivalves;[81] and 2) there is extremely limited information regarding the amount of nutrients removed via biodeposits, and very conflicting studies regarding the amount of denitrification oysters stimulate.[82] That said, I will do my best to include information on the nutrient reduction caused by the other two mechanisms where possible in order to contextualize the results of this chapter.

The first question I sought to answer, then, was how much nitrogen and phosphorus can an oyster remove from the water column in a year through sequestration, or during its lifetime before harvest? Though there are many studies from around the country that explore such values, filtration and assimilation is specific to location (for example, rates may change due to changes in water temperature or the rate at which water flows over the oysters). Age and size of the oysters also factor into these rates. Within Rhode Island specifically, there are a few studies that measure denitrification or assimilation rates that I will discuss. However, when finding nutrient quantity assimilated into an oyster, typically a percentage of dry weight is used as an average amount of nitrogen and phosphorus removed from the system.

For example, in Ray et al. (2019), the authors studied two-year-old oysters (approximately 2.93g dry weight tissue, nearly market size) grown in Ninigret Pond in Rhode

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[81] Cornwell et al. 2016

[82] Kellogg 2013

Island and raised in a tank designed to mimic the conditions of the same pond. Though they were primarily studying the denitrification rate, the authors used the assumption that the quantity of nitrogen sequestered in the dry weight of the oysters' tissue was 7.86%; since the oysters were 2.93 g each, this gives an estimated 0.224 g of nitrogen per oyster when harvested after two years.[83] There is a significant amount of nitrogen and phosphorus stored in the shell as well, but shells are often returned to the body of water after the soft tissue is consumed, meaning they are only a temporary store of nutrients and do not permanently remove them from the system.[84] Furthermore, the Chesapeake Bay Expert Panel BMP Report includes only nutrients stored in soft tissue as a generator of credits, so I focus on the soft tissue in this paper as well.

In the same report on including oyster aquaculture as a Best Management Practice (BMP) in nutrient trading markets, the expert panel created a default estimate of the amount of nitrogen and phosphorus, in grams, in different sized oysters. This amount represents the grams of nutrients that are removed from the water column when the oyster is harvested. For the Chesapeake Bay specifically, the panel determined that 8.2% of the dry tissue weight of each oyster was the average nitrogen content and 0.9% was the phosphorus content.

These values were based both on site-specific studies of nutrient content in oysters within the Chesapeake Bay and some studies from the Atlantic coast more broadly. However, I found no such site-specific studies for cultured oysters specifically in Narragansett Bay or in Rhode Island. Ray et al., although they used oysters from Rhode Island in their study, used a nitrogen content of 7.86% of dry weight tissue from Higgins et al. (2011), which studied oysters from the Chesapeake Bay. Higgins et al. was one of the seven studies used to determine the average nitrogen content and one of the four to determine phosphorus content for the Chesapeake Bay

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[83] Ray et al. 2019

[84] Weber et al. 2018

BMP report. Both average values in the report utilized studies with a range of culture methods (i.e., off bottom vs on bottom) and environmental conditions.[85] Furthermore, Narragansett Bay is similar in many respects to the Chesapeake Bay; they are both shallow water estuaries with tidal influence at one end of the bay and a riverine-input at the other end, and both open to the Atlantic Ocean.[86] Because of the lack of data specific to nitrogen and phosphorus content in oysters in Rhode Island and the robustness of studies used in the Chesapeake Bay Expert Panel Report, I will use 8.2% and 0.9% for average amount of nitrogen and phosphorus, respectively, in my calculations of nutrient assimilation in this chapter.

II. Total amount of nutrients sequestered in Narragansett Bay

After determining the amount of nutrient removal per oyster, the next question is the amount of nutrients that are removed from the system as a whole. To calculate that figure, I turned my attention to the amount of oysters, specifically aquacultured oysters, that are living in the system. As in the previous chapter regarding biomass changes given different scenarios of oyster aquaculture, I will once again focus on Narragansett Bay. As of 2018, the live weight of cultured oyster biomass in the bay was 1.21 t/km^2 per year. Under the assumption that dry weight is 0.02% of live weight,[87] this is equivalent to 0.0242 g/m^2 in dry weight, which is the unit used in the expert panel report from the Chesapeake Bay. With an area of Narragansett Bay of 379,951,000 m^2, there are approximately 9,206,972.63 g of cultured oyster tissue in dry weight in the bay. From that weight of oyster tissue in the bay and the percent of nitrogen and phosphorus determined above (8.2% and 0.9%, respectively), it follows that there are approximately 754,971.76 g of nitrogen and 82,862.75 g of phosphorus, or 1,664.43 pounds of

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[85] Cornwell et al. 2016
[86] Byron et al. 2011
[87] Ibid.

nitrogen and 182.68 pounds of phosphorus, to be consistent with the units in which credits are sold, which could be removed from Narragansett Bay if all the cultured oysters were harvested.

For a more accurate representation of the amount of nutrients that are removed from the system via oyster harvest, I used Byron et al.'s finding that approximately 37% of the total biomass of cultured oysters in the bay is harvested on average annually.[88] 37% of the dry weight of cultured oysters in the bay is 3,406,579.87 g, which yields 279,339.55 g of nitrogen and 30,659.22 g of phosphorus removed from the bay annually via aquaculture harvest. That is equivalent to 615.84 pounds of nitrogen and 67.59 pounds of phosphorus. While this is by no means an exact measurement, it is a useful approximation for the purposes of this paper.

After determining the current amount of nutrients being sequestered by aquaculture currently in the bay, I decided to calculate the total amount of nutrients that would be removed from the water by means of sequestration into the soft tissue of the oyster in the scenarios from the previous chapter. Using an identical process as in the instance with the current amount of oysters in the bay, I converted the live weight biomass from Scenarios 3, 4, and 5 (Scenario 1 being current amount, which I already calculated, and Scenario 2 being no oysters, which would similarly entail no nutrients being sequestered) using the assumption that dry weight is 2% of live weight, found how many grams of dry oyster tissue would be in the bay in those scenarios, and determined how many pounds of nutrients would be sequestered in their tissue in those instances.

III. *Market price of nutrient pollution trading credits*

As the credits are part of an active market, there is no one set price to purchase an offset. The price paid in Maryland, so far the only state to have a credit transaction with an oyster farm,

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[88] Byron et al. 2011

for a nutrient removal credit generated by oyster farmers can range from $75 per pound to a few thousand dollars. Per the Maryland Department of the Environment (MDE) Water Quality Trading board, "the value of credits will be determined by market forces of supply and demand, and their value will be determined through negotiations between the buyer and seller."[89] A single credit is equal to one pound of nitrogen or phosphorus.

As mentioned previously, there have been two transactions to purchase nutrient removal credits from oyster growers in Maryland following the release of the expert panel report in 2017. In May 2020, a municipal building purchased four nitrogen credits from Blue Oyster Environmental, an aggregator of aquaculture-generated credits, for $1,600. This gives a value of $400 per nitrogen credit, which a representative of Blue Oyster Environmental says is likely the maximum an oyster-generated nitrogen credit would sell for in Maryland.[90] Anne Arundel county, also in Maryland, is purchasing 107 pounds of nitrogen and 12 pounds of phosphorus credits from Witt Seafood for $4,950. Unfortunately, it is not evident what amount of that total payment will be for phosphorus credits and how much will be for nitrogen. As an approximation, that total amount might equate to $41.60 per credit.

Though the representative from Blue Oyster Environmental once sold nitrogen credits at $400 each, he described the range of prices for a nitrogen credit as typically between $75 and $150. He also mentioned that the emphasis thus far with oyster-generated credit transactions has been solely on nitrogen, which is reflected in the minimal information available on the prices of a phosphorus credit from aquaculture.[91]

As of 2018, the Maryland Department of the Environment (MDE) provides annual payments to purchase nutrient reduction credits from various sources that are not from the

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[89] https://mde.maryland.gov/programs/Water/WQT/Pages/WQT_Purchasing_Credits.aspx

[90] Personal communication with Jordan Shockley 2/1/21

[91] Personal communication with Jordan Shockley 2/1/21

agriculture sector, based on agreed upon prices. MDE accepts proposals from various credit generators annually, with different prices and quantities of credits for nutrients removed from specific systems, and selects one in each region from which to purchase. Though none of these chosen proposals are credits generated by oyster aquaculture, these prices generally reflect at what price MDE values the reduction of nitrogen and phosphorus.

Though prices vary slightly depending on the credit generator and location, MDE in most instances has agreed to pay $75 per pound of nitrogen per year and $99 per pound of phosphorus per year.[92] These values, at least for nitrogen, are largely consistent with the prices that Blue Oyster Environmental charges for credits generated by aquaculturists in the area. In addition to the consistency in pricing with nitrogen, because of the small amount of aquaculture-generated credit transactions thus far and the general lack of information regarding pricing with the transactions that have occurred, I opted to use these approved prices as a proxy in this report.

Results

In this chapter, I sought to answer two main questions: what is the total amount of nutrients being sequestered by oysters in Rhode Island, and what is the estimated value of that sequestration?

I found that there are two metrics to answer the first question and measure the amount of total nutrients being sequestered in Narragansett Bay: either the total amount of nutrients being stored in the tissue of the aquacultured oysters including oysters still in the water, or the approximate amount of nutrients being removed from the system annually via the sequestered nutrients in harvested aquacultured oysters. I do not believe one is superior to the other, but rather that they are both useful in their own respects. I found that, in all of Narragansett Bay, the

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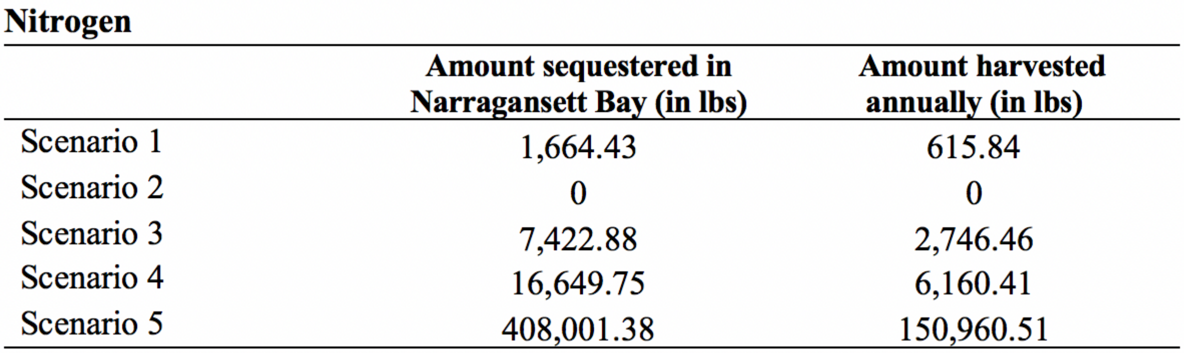
[92] Bay Restoration Fund Advisory Committee 2021

current amount of aquaculture oysters have sequestered approximately 1,664.43 pounds of nitrogen and 182.68 pounds of phosphorus. Annually, approximately 615.84 pounds of nitrogen and 67.59 pounds of phosphorus are removed from the bay with the harvest of the oysters.

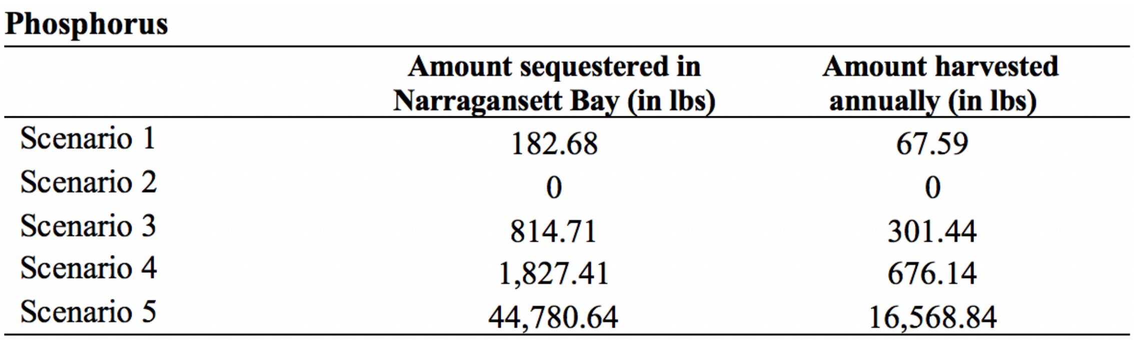
It is worth noting that the amount of aquaculture, and thus the amount of nutrients sequestered, in the bay is very small compared to historic levels, as mentioned earlier. Increasing the amount of aquaculture in the bay, which, as I showed in the previous chapter, is highly plausible, would have a linear effect on the amount of nutrients the oysters would remove from the Bay and other bodies of water around Rhode Island. To illustrate the amount of nitrogen and phosphorus that could be removed from the system with increasing levels of oysters in the bay, I used the different scenarios from the previous chapter and applied the same methodology as to the current amount of oysters. The results of this analysis can be found in Tables 3 and 4.



Nitrogen

	Amount sequestered in Narragansett Bay (in lbs)	Amount harvested annually (in lbs)
Scenario 1	1,664.43	615.84
Scenario 2	0	0
Scenario 3	7,422.88	2,746.46
Scenario 4	16,649.75	6,160.41
Scenario 5	408,001.38	150,960.51

Table 3: quantities of nitrogen sequestered in aquacultured oysters in Narragansett Bay in various scenarios, measured in pounds. The first column represents the amount of nitrogen that is stored in the soft tissue of all oysters in the bay, while the second is the amount of nitrogen that is removed from the bay via the oysters that are harvested annually.

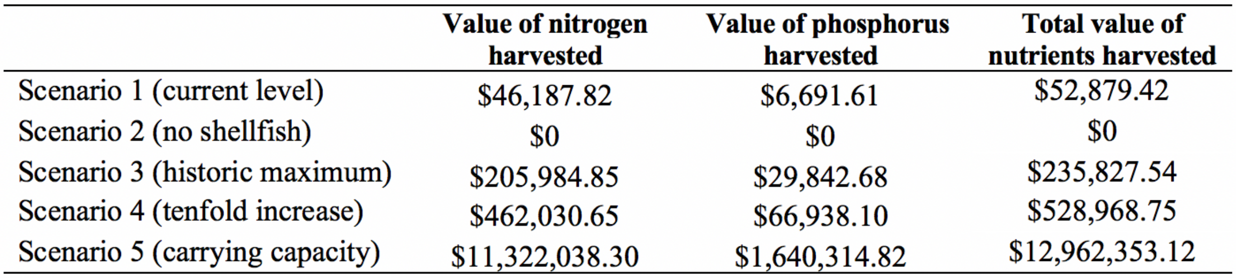


Phosphorus

	Amount sequestered in Narragansett Bay (in lbs)	Amount harvested annually (in lbs)
Scenario 1	182.68	67.59
Scenario 2	0	0
Scenario 3	814.71	301.44
Scenario 4	1,827.41	676.14
Scenario 5	44,780.64	16,568.84

Table 4: quantities of phosphorus sequestered in aquacultured oysters in Narragansett Bay in various scenarios, measured in pounds.

When I applied the approximate value of removing nitrogen and phosphorus from the system to the approximate amount of nutrients that harvesting oysters from aquaculture operations entails, I found that the current level of oyster aquaculture in the bay (Scenario 1) removes $46,187.82 worth of nitrogen and $6,691.61 worth of phosphorus from Narragansett Bay annually. However, it is important to remember that these values only represent the amount of nutrients physically removed from the system when the oysters are harvested, and so is only approximately 37% of the nutrients being sequestered in the soft tissue of the oyster at any given time.



	Value of nitrogen harvested	Value of phosphorus harvested	Total value of nutrients harvested
Scenario 1 (current level)	$46,187.82	$6,691.61	$52,879.42
Scenario 2 (no shellfish)	$0	$0	$0
Scenario 3 (historic maximum)	$205,984.85	$29,842.68	$235,827.54
Scenario 4 (tenfold increase)	$462,030.65	$66,938.10	$528,968.75
Scenario 5 (carrying capacity)	$11,322,038.30	$1,640,314.82	$12,962,353.12

Table 5: the approximate value of nutrients being harvested along with oysters from Narragansett Bay annually, based on the quantities of nutrients sequestered in the soft tissue of harvested aquacultured oysters in various scenarios

Discussion

These results represent a baseline, or minimum, amount of value that is derived from the nutrient reduction services provided by aquaculture in the bay. As I mentioned previously, the amount of nitrogen and phosphorus removed from the system that are taken into account with those dollar values is only part of the story. Most notably, oysters stimulate denitrification of the sediment below where they are grown in addition to removing nitrogen in the many ways mentioned earlier. Though there is not general consensus among the literature regarding to what extent the denitrification is stimulated in the sediment, one study conducted in Rhode Island found that the denitrification rate under off-bottom aquaculture was 346 (±168.6) μmol $m^{-2} h^{-1}$.[93] This rate is similar to the assimilation of nutrients oysters conduct; taking it into account which would increase this valuation significantly.

As I mentioned at the beginning of this chapter, oysters also remove nutrients via buried biodeposits, which this valuation does not account for. Though I found no information on the rates of biodeposit burial for oysters in Rhode Island, a study conducted in the Chesapeake Bay found that oysters annually buried 251.15 mg of nitrogen per year per gram of dry weight and 272.34 mg of phosphorus per year per gram of dry weight.[94] Accounting for this burial of nutrients, as Newell et al. (2014) did in their study, would increase the valuation yet again.

As a further indication that this valuation serves as a minimum, the dollar value only represents the soft tissue of the oyster and not the shell. This decision was based on the practices laid out in the Chesapeake Bay BMP report: while the soft tissue is consumed by people and thus permanently removed from the system, the shell is often reused and put back into the body of water, meaning that it is only a temporary removal of nutrients. That said, there is a significant amount of nutrients sequestered in the shell that oysters are removing, even if temporarily, from the system.

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[93] https://www.frontiersin.org/articles/10.3389/fmars.2016.00074/full

[94] Newell et al. 2004

In terms of the efficacy of nutrient removal of aquacultured oysters compared to restored reefs, Rhode Island studies have shown that they remove nitrogen at comparable high rates.[95] There is research that suggests that harvesting the oysters may even be more effective in nitrogen uptake than restored reefs. Though in Dalrymple and Carmichael (2015) the percentage of nitrogen in soft tissue remained the same throughout age classes, the rate of assimilation into the tissue in juvenile oysters was faster than in adult oysters, which were even found to return nitrogen to the system at a certain point in their adult life cycle.[96] Constantly harvesting oysters and replanting them before they begin leaking nitrogen back into the water is likely a good method of removing more excess nitrogen than letting oysters grow indefinitely in restored reefs. Little is known about the same comparison for phosphorus.

I would like to note that it is not always productive to think of nitrogen as entirely negative; it is necessary for production both on land and in water. Though I have been using Narragansett Bay as a model in this section, there is reason to believe that the levels of nitrogen in the bay are not in need of dramatic reduction. The efforts made by the state after the fish kill in 2003 were largely successful. That said, there are other bodies of water in Rhode Island that do certainly have excess nutrients, as evident by the high number of impaired bodies of water in the state, and generally less is known about phosphorus.

There is no doubt that the nutrient removal that oysters provide is of value to anyone who benefits from bodies of water in which oysters grow, from those who fish in these waters to those who play in or around them. Though there is no certain way of measuring what that value truly is, in this chapter I have determined a minimum valuation of this ecosystem service. It is important to remember that the valuation presented in this chapter is a dramatic

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[95] Humphries et al. 2016
[96] Dalrymple and Carmichael 2015

underrepresentation of the true value of nutrient removal; it only considers one of the many ways oysters remove nitrogen and phosphorus from the system.

However, such an estimation may be useful in determining if, or how much, funding should be allocated to oyster aquaculturists to expand their operations, should such a policy or grant ever be considered. It is also useful in simply recognizing that oysters naturally improve the bodies of water in which they grow, often without anyone knowing that they are doing it. Placing any kind of value on these services, albeit an underestimate, encourages many to have a deeper appreciation for oysters and other bivalve mollusks.

Conclusion

Oysters have a long history as an industry in Rhode Island. At the start of the twentieth century, $135 million of oysters were harvested from around the state, with 21,000 acres of private oyster beds in Narragansett Bay alone. Due to a combination of heavy water pollution, natural disasters, and several economic recessions and depressions, the industry shrank substantially over the last century. However, the amount of acres leased for aquaculture farms and the number of those farms in Rhode Island is beginning to grow again, and I sought to answer what the environmental and economic consequences of that trend might look like.

By analyzing two ecosystem services that oysters provide and their effect on the state economy, I found that, based on these two parameters, aquacultured oysters have a small but measurable positive impact on both the environment and economy of Rhode Island. Increasing the amount of these oysters will likely have positive impacts economically and minimal consequences environmentally in the state. Figures 2 and 3 below show the combined change in value from chapters two and three (i.e., both the value of nutrient reduction and the per area valuation given changes in biomass in Narragansett Bay) across the five scenarios used throughout this paper. From these figures, it is clear that the majority of the value oysters provide is from their nutrient removal capacity.

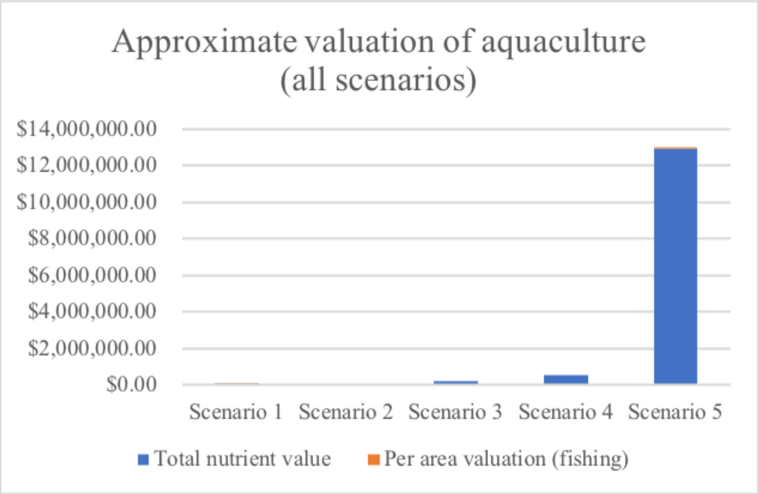

Figure 2: the approximate values (in $) across all five scenarios, combining both the value of nutrient removal conducted by the aquacultured oysters and the per area fishing valuation in Narragansett Bay given a certain amount of aquacultured oysters.

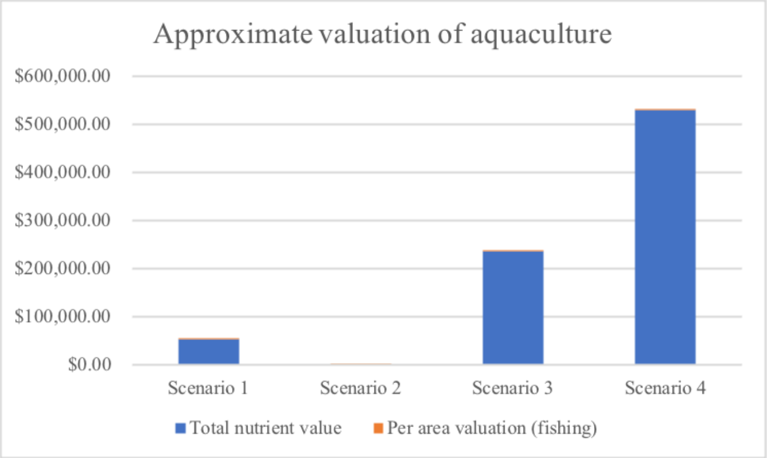

Figure 3: the approximate value (in $) across scenarios 1-4, combining the value of nutrient removal and per area fishing valuation in Narragansett Bay given a certain amount of aquacultured oysters.

From my analysis using the ecosystem model of Narragansett Bay, I found that oysters have minimal impact on other species in the bay (meaning no major increases or decreases in biomass), even when increased exponentially. In fact, the only significant impacts on the biomass of other species occurred when the biomass of oysters was increased to the carrying capacity. While technically this amount of aquaculture is feasible in the bay, as it is comparable to peak historic levels, it is not likely to reach these levels any time in the next several decades, if ever.

This conclusion is helpful in understanding that increasing the levels of aquacultured oysters will likely not harm other species in the ecosystem, at least in terms of direct competition for resources. When considering policy to support these aquaculture farms, this will be useful in rebutting claims that the oysters may compete with or harm other species.

Although overall the effects on the biomass of other species in the bay was very small with current levels of oyster aquaculture, at significantly larger quantities, the results from the ecosystem model showed that increasing the amount of aquacultured oysters would contribute positively slightly to recreational fishing species and negatively slightly to commercial fishing species, but only in terms of direct competition for resources. It is probable that they actually boost the population of other species by providing habitat and cleaning the water, but these were not parameters of the model used and so were not factored into the analysis. Future research, perhaps using a different modeling tools such as Impact Analysis for Planning (IMPLAN) or Farm Aquaculture Resource Management (FARM), might be helpful in understanding all of the dynamics involved in planting more oysters in the state, including taking into account the other ecosystem services that oysters provide. Several studies using both IMPLAN and FARM modeling in the Chesapeake Bay have been published to analyze or project the effect of certain behaviors and policies on the bay.

Other future research could include conducting a similar analysis to the one presented here using data from the salt ponds of Rhode Island in order to more accurately represent the effects of increasing the amount of aquaculture on the whole state instead of solely relying on data from Narragansett Bay. While the bay is a useful representation for the purposes of this report, it only accounts for approximately half of all aquaculture in the state. Specifically, the valuations in this paper only represent the amount of aquaculture in Narragansett Bay, which is home to only 140 acres of aquaculture of the 275 acres in the state, as of 2016.[97] A large percentage of aquaculture in the state takes place outside of the bay; taking the additional aquaculture farms into account would likely increase the total valuation of the impacts of shellfish on the state's economy. It would be interesting to understand how the aquaculture is different in different ecosystems throughout the state, and how those differences may factor into an analysis similar to this one.

The analysis conducted in the third chapter of this report showed that aquacultured oysters remove hundreds of thousands of dollars' worth of nutrients from RI waters annually, even at their current levels, by means of sequestration into soft tissue. As mentioned previously, this number is representative of just a fraction of the total amount of nutrient removal that oysters conduct as part of their natural filter feeding. Research in the future that focuses more precisely on how much nitrogen and phosphorus oysters and other bivalve mollusks remove from their ecosystems would be instrumental in determining a more in-depth estimate of the value of this ecosystem service, which can be useful to policymakers in the future when passing legislation regarding topics ranging from water quality or support for oyster growers.

Additionally, it would be an interesting endeavor to conduct an analysis of the feasibility of a nutrient credit or water quality trading market in Rhode Island or New England more broadly. From my own research, I would expect such a program only in Rhode Island to likely be more trouble than it is worth; the program requires extensive infrastructure and planning, and, on the whole, Rhode Island's nutrient pollution is not at the same severe levels as the Chesapeake Bay. Rhode Island has shown success in the past reducing large quantities of pollution when necessary, including after the fish kill in 2003, so setting up a program such as this one might ultimately not be worth it.

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[97] Uchida 2019

However, on a smaller scale, a policy proposal might include DEM or another Rhode Island government entity to consider paying oyster aquaculturists to expand their business and remove more nutrients from the water in cases with particularly nutrient-polluted small bodies of water around the state. Maryland Department of the Environment (MDE) conducts a similar program, which I described in the third chapter of this report, which would not require the same levels of infrastructure and planning that a water quality trading market would. Instead, MDE accepted proposals from several different sources of pollution reduction and funded the most cost effective option. Such a program in Rhode Island or New England might be feasible and lead to considerable pointed nutrient reduction in historically polluted waters.

A last question to consider moving forward is, while the findings of this paper indicate that increasing oyster aquaculture in Rhode Island has several quantifiable benefits, is there the demand to support this hypothetical increase in supply? Aquacultured oysters, once planted, typically must be harvested within two to four years before they exceed market size. Expanding the number and scale of oyster farms in the state would need to be accompanied by a simultaneous increase in demand in order for these businesses to remain viable in the future. Exploration into markets for flash frozen oysters, value added products involving oysters, or similar ventures would be an important piece of supporting more aquaculture in the state.

There are certainly other ways of supporting aquaculture in Rhode Island that do not include directly contributing to these businesses or paying for services. Specifically, increasing awareness more broadly of the environmental benefits that oysters provide might be helpful, and can be done in several ways. Some examples include local schools organizing class field trips to one of the many oyster farms around the state, or perhaps highlighting oysters and other bivalve mollusks for their environmental benefits at the next Rhode Island Seafood Festival.

Increasing the amount of oyster aquaculture in Rhode Island would likely have several effects on both the environment and the economy of the state. In terms of competition for resources, an increase in oysters would have a small but positive impact on the species that are important to the recreational fishing industry in Narragansett Bay, and a small negative impact on the commercial fishing industry in the area. Beyond their effect on the food web, oysters provide a number of positive externalities, including filtering bodies of water and reducing excess nutrients. Between these ecosystem services and the minimal impact on other species, oysters have the potential to benefit the environment while simultaneously providing a boost to Rhode Island's seafood industry.

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Appendix

These tables show price data for each of the species in the functional groups used in the EwE model in Chapter 2.

(a) Piscivorous Fish

Species	**Biomass (g/m^2)**	**Price ($/g)**	**Weighted Avg. Price ($/g)**
Summer Flounder	0.5532188853	0.00745457	
Atlantic Striped Bass	0.02408363619	0.00998504	
Bluefish	0.1232428197	0.00206130	
Weakfish	0.09769570757	0.00409965	
Spiny dogfish	0.2424184759	0.00040263	
Group weighted average			*0.00491674*

(b) Benthivorous Fish

Species	**Biomass (g/m^2)**	**Price ($/g)**	**Weighted Avg. Price ($/g)**
Winter Flounder	0.8140808757	0.00125623	
Tautog	0.09661657346	0.00795665	
Little Skate	6.087678188	0.00029713	
Scup	0.5535772481	0.00123645	
Striped Sea Robin	0.124489886	(No data)	
Black Sea Bass	0.01096511116	0.00835975	
Group weighted average			*0.00056929*

(c) Carnivorous Benthos

Species	**Biomass (g/m^2)**	**Price ($/g)**	**Weighted Avg. Price ($/g)**
Atlantic Rock Crab	9.811584559	0.00172030	
Spider Crab	0.88296821	(No data)	
Lobster	3.311503384	0.01355859	
Channeled Whelk	0.3635790005	0.02334910	
Green Crab	0.29	0.00112676	
Group weighted average			*0.00481555*

(d) Suspension Feeding Benthos

Species	Biomass (g/m^2)	Price ($/g)	Weighted Avg. Price ($/g)
Eastern Oyster	0.04423395737	0.05818088	
Quahog	0.04423395737	0.02282355	
Blue Mussel	0.71	0.01421293	
Group weighted average			*0.01712571*

(e) Planktivorous Fish

Species	Biomass (g/m^2)	Price ($/g)	Weighted Avg. Price ($/g)
Atlantic Menhaden	0.7333976874	(No data)	
Atlantic Moonfish	0.01892965067	(No data)	
Alewife	0.1753200021	(No data)	
Bay Anchovy	1.278500448	(No data)	
Atlantic Silverside	0.7433854747	(No data)	
Atlantic Herring	7.393006389	0.00079818	
Butterfish	0.9619163151	0.00161924	
Blueback Herring	0.1942112016	(No data)	
Group weighted average			*0.00064865*

(f) Cultured Shellfish[1]

Species	Biomass (g/m^2)	Price ($/g)	Weighted Avg. Price ($/g)
Cultured Oyster	0.0134442	0.05818088	
Cultured Mussel	0.0001358	0.01421293	
Group weighted average			*0.05774119*

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[1] https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2018-report