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Vulnerability Assessment of the Gulf of Maine Eastern Oyster Aquaculture Industry to the Projected Impacts of Ocean and Coastal Acidification

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This Master's Project

Vulnerability assessment of the Gulf of Maine Eastern oyster aquaculture industry to projected ocean and coastal acidification

by

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OA	Ocean acidification
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ion
$CaCO_3$	Calcium carbonate
H^+	Hydrogen ion
OH^-	Hydroxide ion
GOM	Gulf of Maine
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathway
DRE	Damariscotta River estuary
SST	Sea surface temperature
H_2CO_3	Carbonic acid
HCO_3^-	Bicarbonate ion
MHW	Marine heatwave
HAB	Harmful algal bloom
Ω_{ar}	Aragonite saturation state
DMR	Department of Marine Resources
DOL	Department of Labor
IHV	Immediate harvest value
MHI	Median household income
MOCA	Maine Ocean and Coastal Acidification Partnership
SAV	Submerged aquatic vegetation

Abstract

Ocean acidification is an emerging global environmental issue with known impacts on calcifying marine and estuarine organisms, including oysters. Anthropogenic climate change increases ocean uptake of atmospheric carbon dioxide, which decreases seawater pH and the availability of crucial calcium carbonate minerals, namely calcite and aragonite. Acidification poses a major threat to the Eastern oyster aquaculture industry in the Gulf of Maine (GOM), which is highly susceptible to acidification and highly economically dependent on the industry's economic contributions. In this report, I evaluated overall vulnerability of the GOM Eastern oyster aquaculture industry by assessing ecological exposure, social sensitivity, and adaptive capacity to the impacts of acidification. Projections of aragonite saturation, sea-surface temperature, and precipitation under IPCC carbon emissions scenarios demonstrate the region's high ecological exposure to acidification. Sales revenue, employment, and labor income represent the region's high economic dependency and thus social sensitivity to changes in the industry. Combined, these make the region highly vulnerable to the impacts of ocean acidification. The issue has already garnered significant attention from agencies and institutions with the capacity to implement initiatives that bolster the industry's ability to mitigate and adapt to changes, thereby lowering overall vulnerability of the industry to medium-high. To further augment the adaptive capacity of the GOM Eastern oyster aquaculture industry, I recommend implementing community education programs, bolstering the role of oyster hatcheries, incentivizing multi-trophic aquaculture, and conducting site-suitability analyses for future aquaculture locations.

1. Introduction

Anthropogenic climate change is arguably the greatest modern-day environmental issue. One of the most severe consequences of climate change is global warming of terrestrial ecosystems, caused by rising concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases. Marine ecosystems, however, face a different but equally dire problem. Ocean acidification (OA), known by many environmentalists as “the other carbon dioxide problem” (NOAA PMEL Carbon Program n.d.), is caused by increased ocean uptake of atmospheric CO_2. Ocean carbon uptake catalyzes a series of chemical reactions that produce carbonic acid and hydrogen ions in surface seawater, causing seawater pH to decrease (Feely et al. 2009). This is not an unnatural process, but the amount of CO_2 entering the oceans and the rate at which carbonic acid (H_2CO_3) is being produced has increased to unsustainable levels for aquatic organisms and ecosystem health (Gruber et al. 2019). For this reason, OA has emerged onto global platforms as a major consequence of climate change that must be urgently addressed.

Because of its relatively emerging status, there are large gaps in the scientific community’s understanding of exactly how OA impacts marine ecosystems (Salisbury and Jönsson 2018). One aspect that is relatively well understood, however, is how OA affects marine calcifers, or organisms that require calcium carbonate minerals to develop their shells and skeletons (Waldbusser et al. 2011; Talmage and Gobler 2009; Cooley et al. 2015; Waldbusser et al. 2013; Sui et al. 2022). As seawater becomes more acidic, the availability of aqueous alkaline calcium ions decreases, and thus becomes less and less accessible for use by calcifers (Waldbusser et al. 2011). The impacts of this on various species of oyster have been researched over the past decade and include stunted larval development, heightened larval mortality, adult shell dissolution, and impacts on adult reproduction (Sui et al. 2022; Doney et al. 2009; Dove and Sammut 2007). This creates serious cause for concern that the abundance and distribution of oysters will be dramatically compromised as CO_2 concentrations continue to increase in the atmosphere and in surface seawater.

The potential reduction in oyster abundance and distribution caused by acidification would have detrimental socioeconomic impacts on communities and regions that support oyster aquaculture industries. In the United States, oyster aquaculture is most prominent in the Pacific Northwest, Gulf of Mexico, Mid-Atlantic, and Northeast regions (NMFS 2019). The state of Maine has a strong history of commercial Eastern oyster production, and a large portion of the state’s annual revenue is dependent on the commercial fishing and aquaculture sectors (Hanes 2018; Maine Department of Marine Resources [DMR] 2022). The Gulf of Maine (GOM) Eastern oyster aquaculture industry has grown rapidly since the beginning of the 21st century and increasingly contributes to Maine revenue and employment, particularly in the communities where oyster aquaculture businesses are located. However, intensifying OA and its impacts on oyster biological and physical health may render the GOM nonviable for Eastern oyster cultivation.

In this report, I aim to address the following questions: How is the GOM likely to be exposed to ocean and coastal acidification throughout the 21st century? What are the likely ecological and socioeconomic impacts of projected acidification on the Gulf of Maine Eastern oyster aquaculture industry? What management efforts can be made to mitigate, remediate, and adapt to the impacts of acidification on Maine coastal ecosystems and communities? I employ a modified vulnerability assessment framework in my approach to answering these questions and providing recommendations for GOM environmental managers and oyster aquaculture stakeholders.

2. Background

2.1 Ocean acidification

Ocean acidification (OA) refers to changes in ocean chemistry due to the uptake of atmospheric CO_2 through thermodynamics and gas transfer processes that occur at the air-sea interface (Doney et al. 2009). These changes include reductions in seawater pH, carbonate ion (CO_3^{2-} concentrations), and the saturation states of calcium carbonate ($CaCO_3$) minerals calcite and aragonite (Feely et al. 2009). OA is not an unnatural process; however, the dramatic increase in anthropogenically-derived atmospheric CO_2 since the Industrial Revolution has correspondingly increased the rate at which OA is occurring. Between 1994 and 2007, the ocean absorbed roughly 2.6 billion metric tons of atmospheric CO_2 per year, a fourfold increase from the entire period between 1800 and 1994 (Gruber et al. 2019). Already, the total CO_2 emissions from the past two centuries have caused a 0.1-unit drop in average seawater pH (Kong et al. 2022). The Intergovernmental Panel on Climate Change (IPCC) reports projected atmospheric CO_2 concentrations exceeding 800 ppm by 2100, which would further lower seawater pH by 0.2-0.3 units to approximately 7.8 (Feely et al. 2009). Other CO_2 emission scenarios predict changes in ocean pH up to 0.5 units lower than current levels by 2100 and between 0.8 and 1.4 units lower by 2300 (Boulais et al. 2017).

The basic chemistry of OA has been understood since the 1970s, when oceanographers such as Wally Broecker first described the interrelatedness of ocean chemistry, atmospheric CO_2 levels, and anthropogenic climate change (Broecker et al. 1970; Broecker and Simpson 1973; Broecker 1975). The potential for OA to become an urgent environmental issue was described in these early publications; however, as anthropogenic CO_2 emissions and climate change progressed into the 21st century, there became little doubt that the potential was now a likely reality. In less than a decade, OA rose to the forefront of critical issues faced by ocean researchers and coastal and marine resource managers (Doney et al. 2009). Despite this, there continue to be significant gaps in the scientific community's preliminary understanding of OA, including its effects on individual species and community ecology outside of controlled laboratory research (Salisbury and Jönsson 2018).

2.2 Coastal acidification

The effects of ocean acidification are likely to be amplified in coastal water bodies such as estuaries. Estuaries are bodies of brackish water formed at the confluence of riverine systems and marine systems. While rising CO_2 levels are projected to acidify open ocean in the near future, some estuaries are already being subjected to unsustainable CO_2 concentrations (Talmage and Gobler 2009). Because of their geography, estuaries are subjected to both marine and freshwater sources of acid and carbon input (Waldbusser et al. 2011). Coastal upwelling of deep seawater naturally heightens CO_2 concentrations in surface water due to the decomposition of organic matter. Coupled with greater atmospheric CO_2 uptake at the air-sea interface, surface waters are experiencing increased intensity, magnitude, and duration of acidification, leading to more acidic seawater flowing into estuaries (Barton et al. 2015).

Estuaries also face multiple freshwater sources of acid and carbon input that the open ocean does not, making them more susceptible to acidification and other environmental stressors (Farr et al. 2021; Waldbusser et al. 2011). Nutrient loading, heavy precipitation events and consequent runoff, upstream hydrologic modifications, and other anthropogenic impacts significantly contribute to high-CO_2 low-pH conditions in estuaries (Salisbury and Jönsson 2018; Gledhill et al. 2015; Kyzar et al. 2021). Additionally, because of large volumes of low-alkaline freshwater input, estuaries and other coastal water bodies have a reduced buffering capacity (Gledhill et al. 2015; Waldbusser et al. 2011), meaning that fewer moles of hydrogen ions (H^+) or hydroxide ions (OH^-) are required to decrease or increase the pH of a solution by 1 (Hagens et al. 2015). The combination of marine and freshwater acid and CO_2 sources and reduced buffering capacity means that estuaries will experience acidification and its environmental impacts sooner than other water bodies (Waldbusser et al. 2011).

Numerous economically and ecologically significant aquatic species reside in estuarine habitats, including calcifying organisms such as oysters, clams, mussels, and scallops (Cooley et al. 2015). Calcifying organisms are particularly vulnerable to acidification, which raises concern for the growth and survival of these species as their habitats become more acidic. In 2006, global marine harvests supplied 110 million metric tons of food and were valued at $160 billion (Cooley et al. 2015). Loss of calcifying organisms like shellfish would not only remove a large contributor to global food resources and revenue but would also have severe ecological impacts on marine ecosystems and food webs (Cooley et al. 2015), leading to the decline of other economically and ecologically significant species.

2.3 Acidification impacts on oysters

Although gaps in present knowledge exist, one major known concern is how ocean and coastal acidification impact marine and estuarine calcifers, organisms that build their shells and skeletons through biocalcification (Waldbusser et al. 2011; Talmage and Gobler 2009; Cooley et al. 2015; Waldbusser et al. 2013; Sui et al. 2022). Biocalcification is the accumulation of $CaCO_3$ to form hard tissue and is critical for larval growth and development. Oyster larvae accumulate approximately 90% of their body weight through biocalcification within 48 hours of fertilization (Waldbusser et al. 2013), making it a crucial physiological process for early oyster development. Acidification affects the process of biocalcification in two ways, disruption of new shell formation and dissolution of existing shell. Acidification lowers the availability of CO_3^{2-} and biologically important calcium minerals calcite and aragonite (Waldbusser et al. 2011). Without sufficient $CaCO_3$ for biocalcification, larval shell development is impaired and there is an increased morphological deformation rate that may have lasting effects into adulthood (Sui et al. 2022).

In addition to harmful effects on oyster larval development, adult oyster growth and survival are also negatively impacted by increased acidification. A 2007 study on the growth and survival rates of Sydney rock oysters (*Saccostrea glomerata*) in acidic conditions found that exposure to low pH waters resulted in significantly reduced growth ($P < 0.001$) and significantly higher mortality rate ($P < 0.001$) (Dove and Sammut 2007). This was attributed to acid-induced dissolution of the oysters' shells, which was found to occur more in smaller sized oysters (Dove and Sammut 2007). This suggests that young oysters with stunted development and deformities caused by impediments to biocalcification may be more vulnerable to increased acidification as adults as well.

Another physiological response that is negatively impacted by exposure to increased acidification is oyster reproduction. Combined data from experimental manipulation studies on the reproductive rate of four different shellfish species exposed to increased CO_2 concentrations show a linear negative response from each species (Doney et al. 2009). The degree of CO_2 concentration and subsequent acidification is significant when analyzing their impacts on shellfish reproduction. The reproductive rate of the Eastern oyster (*Crassostrea virginica*) was relatively unaffected by moderate acidification that may reflect next-century conditions (pH 7.5); however, severe acidification (pH 6.7-7.1) compromised the production of egg cells in female oysters and sperm cells in male oysters (Boulais et al. 2017). If anthropogenic CO_2 emission surpass plausible projections and lean further into higher-end projections, the rate of shellfish reproduction will decline and cause population bottlenecks across multiple species, including the Eastern oyster.

The combined effects of impaired larval development, adult shell dissolution, and disrupted reproduction caused by acidification will likely have profound impacts on the distribution and abundance of oyster populations in coastal regions of the United States and around the globe. The loss of oyster populations would have concomitant socioeconomic effects on local commercial shellfish and aquaculture industries. In some areas, local oyster fisheries and hatcheries have already begun to face consequences of acidification. In the US Pacific Northwest, a large coastal upwelling event caused seawater pH in some areas to drop to 7.6, resulting in high levels of larval mortality at the Whiskey Creek Shellfish Hatchery. Larvae production in 2008, during the second major mortality event, only reached approximately 25% of a normal production. After ruling out biological pathogens as the cause of the mortality events, hatchery personnel ultimately attributed the loss of larvae to acidified seawater (Barton et al. 2015). This example demonstrates the profound effect that acidified seawater can have on oyster larvae, and subsequently the commercial shellfish industry. In 2009, once the acidification had been adequately addressed, production of oysters, clams, mussels, geoduck, and all shellfish larvae and seed in Washington, Oregon, California, and Alaska generated USD 128 million in sales (Barton et al. 2015), solidifying the importance of the industry to the region and demonstrating the massive economic risk of leaving acidification unaddressed.

2.4 Acidification in the Gulf of Maine

Another region that is both highly susceptible to ocean and coastal acidification and socioeconomically driven by commercial shellfisheries is the GOM. Physical processes in the GOM are characterized by strong tides, wind-driven mixing, and coastal currents (Salisbury and Jönsson 2018). Because of these processes, water parameters, including temperature, salinity, and nutrient availability, are naturally highly variable in the GOM (Salisbury and Jönsson 2018;

Siedlecki et al. 2021). This variability generates diurnal and annual thermodynamic variability in the GOM carbonate system that can be related to projected long-term trends driven by acidification (Salisbury and Jönsson 2018; Siedlecki et al. 2021).

Analyses of the relationship between GOM water chemistry and acidification have found that the natural variability of GOM temperature, salinity, and nutrient availability can either exacerbate or mitigate the effects of acidification (Salisbury and Jönsson 2018; Siedlecki et al. 2021). Salisbury and Jönsson (2018) compiled a time series of GOM salinity and surface water temperature data spanning 34 years between 1981 and 2014. They found that the variability of these parameters created 5–10-year disruptions in the GOM carbonate system that were greater than the expected impact of acidification alone.

More recently, in the decade spanning 2005 to 2014, a dramatic warming event has caused the highest recorded surface water temperatures in the GOM in the last 150 years (Salisbury and Jönsson 2018), resulting in a greater uptake of atmospheric CO_2 at the air-sea interface (Servio and Englezos 2001). The greater CO_2 uptake combined with increased salinity, another result of warmer temperatures, was found to partially mitigate the effects of acidification on pH and increase the saturation state of aragonite throughout GOM surface waters by an average of 0.14 U (Salisbury and Jönsson 2018). Although the recent warming event is an extreme example of GOM variability — and has, in part, been linked in anthropogenic climate change (Chen et al. 2020) — the 34-year analysis found that, in general, the natural variability of GOM water chemistry can obscure the direct effects of acidification on the region (Salisbury and Jönsson 2018). In conclusion, Salisbury and Jönsson (2018) estimated that a 30-year period of consistent observations is required to discern whether changes in pH in the GOM are a result of natural variability or a direct impact of OA, and up to a century of observations to discern the same for aragonite saturation.

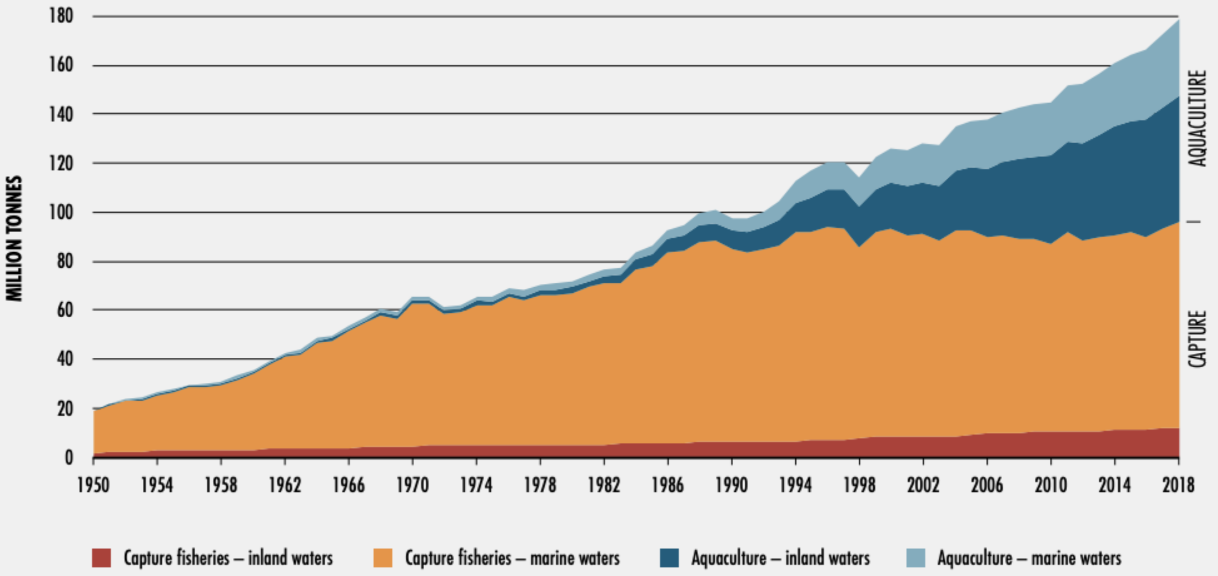
Coastal regions of the GOM are currently experiencing suboptimal aragonite conditions for biocalcification that can be exacerbated as acidification in those areas intensifies (Siedlecki et al. 2021). Aragonite saturation below 3 causes stress on calcifying organisms and saturation below 1 catalyzes dissolution of shells and skeletons produced through biocalcification (NOAA 2022). An aragonite saturation state of 1.5 has been deemed a critical threshold for the health of calcifying organisms (Siedlecki et al. 2021). Currently, nearshore GOM experiences aragonite saturation below the critical threshold 9-41% of the year depending on location (Siedlecki et al.

2021). Under the most severe IPCC future scenario, the entire GOM will experience aragonite conditions below the critical threshold for most of the year by 2050, with the most severe declines measured along the coast (Siedlecki et al. 2021). This is an extreme threat to commercial aquaculture species that contribute massively to the economy and cultural identity of Maine, including the Eastern oyster (Figure 1), one of the major species farmed in Maine estuaries for over five decades.

Figure 1: Eastern oysters (NOAA Fisheries 2022).

2.5 Aquaculture in the Gulf of Maine

Aquaculture is the cultivation of aquatic organisms in a controlled or selected water environment. It differs from capture, or wild caught, fisheries, which exist in natural environments with little to no artificial or manmade controls. Aquaculture may also be referred to as fish or shellfish farming. World capture fisheries production has largely plateaued since the mid-1990s, and in some regions there has been a noticeable decline in wild caught fisheries production (Figure 1) (FAO 2020). In response, the global aquaculture sector has rapidly expanded and is the fastest-growing food production sector (Cole et al. 2016). Between 2000 and 2012, the global aquaculture sector expanded at an annual rate of 6.2% (FAO 2014).



NOTE: Excludes aquatic mammals, crocodiles, alligators and caimans, seaweeds and other aquatic plants.
SOURCE: FAO.

Figure 2: Global capture fisheries and aquaculture harvest. Capture fisheries harvest appears to plateau while aquaculture harvest sharply increases (FAO 2020).

The three main types of organism that are farmed using aquaculture are finfish, shellfish, and plants (FAO 2020). In 2018, 46% or about 126 million US tons of total global fish (including finfish and shellfish) production was generated using aquaculture and accounted for 52% of human fish consumption (FAO 2020). China had the largest aquaculture production and contributed roughly 58% of the global total (FAO 2020). The United States produced only 975,000 US tons of fish by aquaculture, a small amount compared to the 4.75 million US tons produced by capture fisheries (OECD 2021). In 2018, finfish accounted for 66% of global aquatic animal production, followed by mollusks (predominantly bivalve mollusks) (22%) and crustaceans (11%). Marine invertebrates, aquatic turtles, and frogs made up the last 1% of production (FAO 2020). Total sale value of global aquaculture production in 2018 reached a record USD 263.6 billion (FAO 2020). The industry is projected to continue its rapid growth over the next several decades, and it is estimated that 62% of fish produced for human consumption will be farmed using aquaculture practices by 2030 (AES 2013). To reach this level of production and meet rising global demand, global aquaculture production would have to increase by an additional 70% (NIFA 2016).

In terms of aquaculture production, the US ranks seventeenth worldwide, but is the third largest market for seafood and annually imports 75-80% of fish and other seafood products (NMFS 2019). The Gulf of Mexico region produces the largest amount (51%) of marine aquaculture products by volume, followed by the Atlantic (28%) and the Pacific (21%). In terms of value, however, the Atlantic region leads at 41%, followed by the Pacific (36%) and the Gulf (23%) (NMFS 2019). In terms of shellfish aquaculture, the Gulf leads in volume (51%), but the Atlantic leads in value by approximately USD 14 million (NMFS 2019). Within the Atlantic region, Maine, Massachusetts, and the Chesapeake Bay area are the most productive regions for shellfish aquaculture, primarily of Atlantic sea scallops (*Placopecten magellanicus*), blue mussels (*Mytilus edulis*), and Eastern oysters. The focus of this paper going forward will be the Maine aquaculture industry, which primarily takes place in the marine and estuarine waters of the Gulf of Maine.

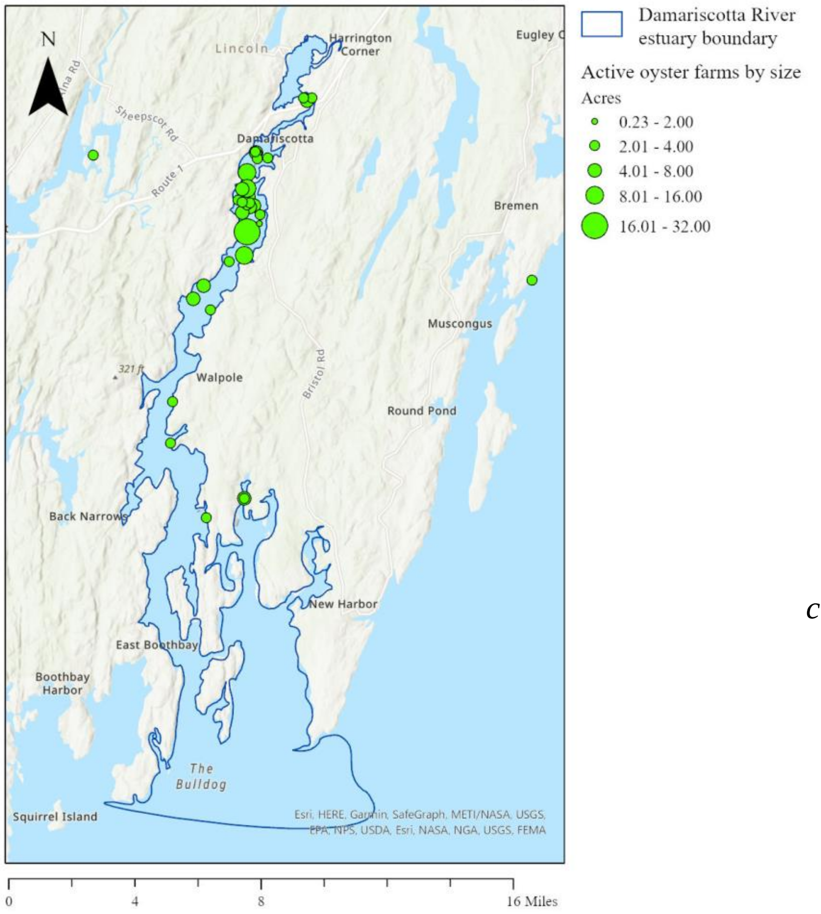
Aquaculture is a major contributor to the economy and cultural identity of Maine. The first aquaculture farms in the state were established in 1975 by the University of Maine's marine biology research center, the Darling Marine Center, in the town of Damariscotta (Hanes 2018). The farms were constructed in the upper Damariscotta River estuary (DRE), one of Maine's three main aquaculture regions, and grew only oysters and mussels (Hanes 2018). The two primary types of aquaculture farms in Maine are shellfish farms and finfish farms. Shellfish farms mainly produce Eastern oysters (Figure 2, 3) and blue mussels whereas finfish farms mainly produce Atlantic salmon (*Salmo salar*) (Hanes 2018). Although the first farms appeared in the 1970s, the industry grew slowly until the 21st century, when aquaculture began to rapidly expand. This expansion can be attributed to several factors, including the collapse of Maine's

Atlantic cod industry in the early 1990s, which drew local ex-fisherman into farming, and the boom of amenity migration and coastal landownership, which increased tourism and seasonal residency in aquaculture regions (Hanes 2018).

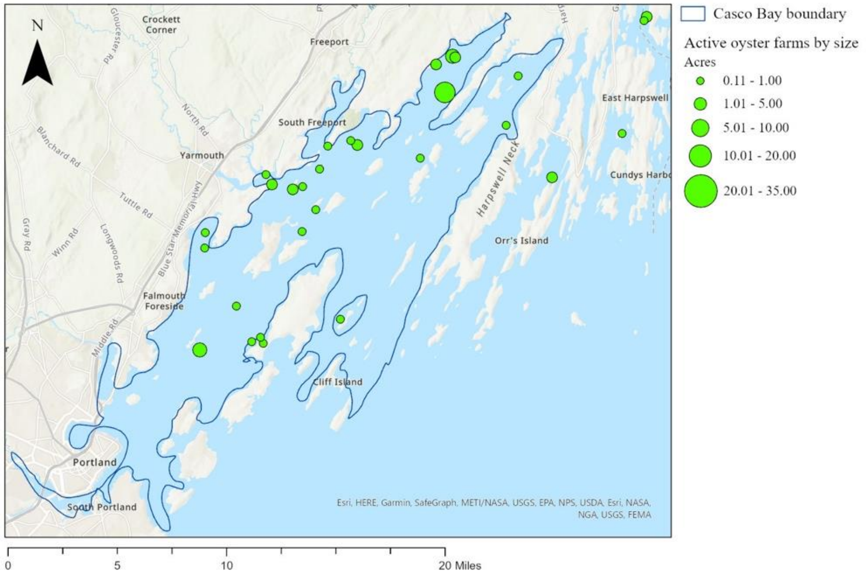
Eastern oyster aquaculture (Figure 3) in Maine has expanded significantly since the early 2000s. Total oyster aquaculture yields rose from roughly 2 million pieces (oyster count) in 2005 to just under 14 million pieces in 2019, with a corresponding increase in annual value from about USD 850,000 to USD 9.7 million (Maine DMR 2022). The most recent data from 2020 shows a total harvest of 10 million pieces with a total value of USD 7 million (Maine DMR 2022). Of all waterbodies in Maine that house active oyster farms, the three waterbodies with the highest number of farms are the DRE (Figure 4a), Casco Bay (Figure 4b), and Taunton Bay (Figure 4c) (Maine DMR 2021).

Figure 3: Eastern oyster aquaculture (Maine Aquaculture Innovation Center 2021).

a. Active Eastern oyster aquaculture farms in the Damariscotta River estuary, Maine



b. Active Eastern oyster aquaculture farms in Casco Bay, Maine



c. Active Eastern oyster aquaculture farms in Taunton Bay, Maine

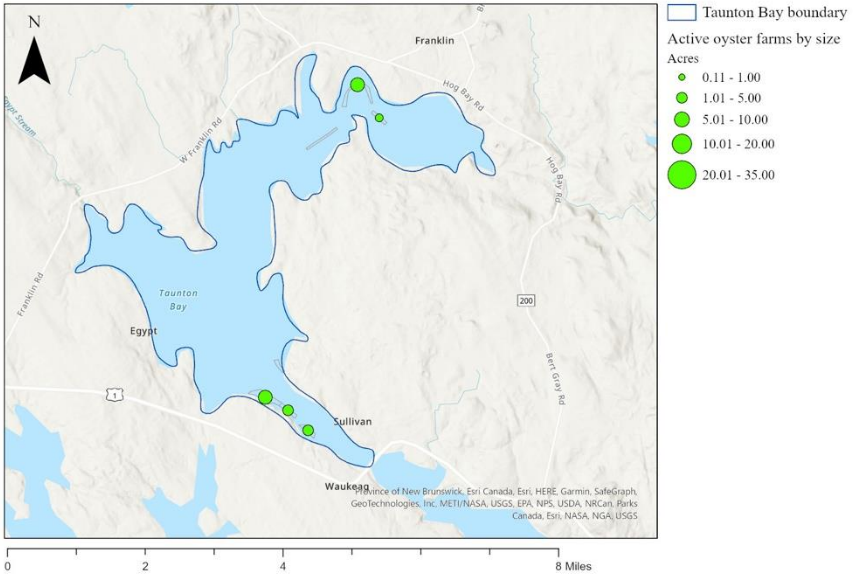
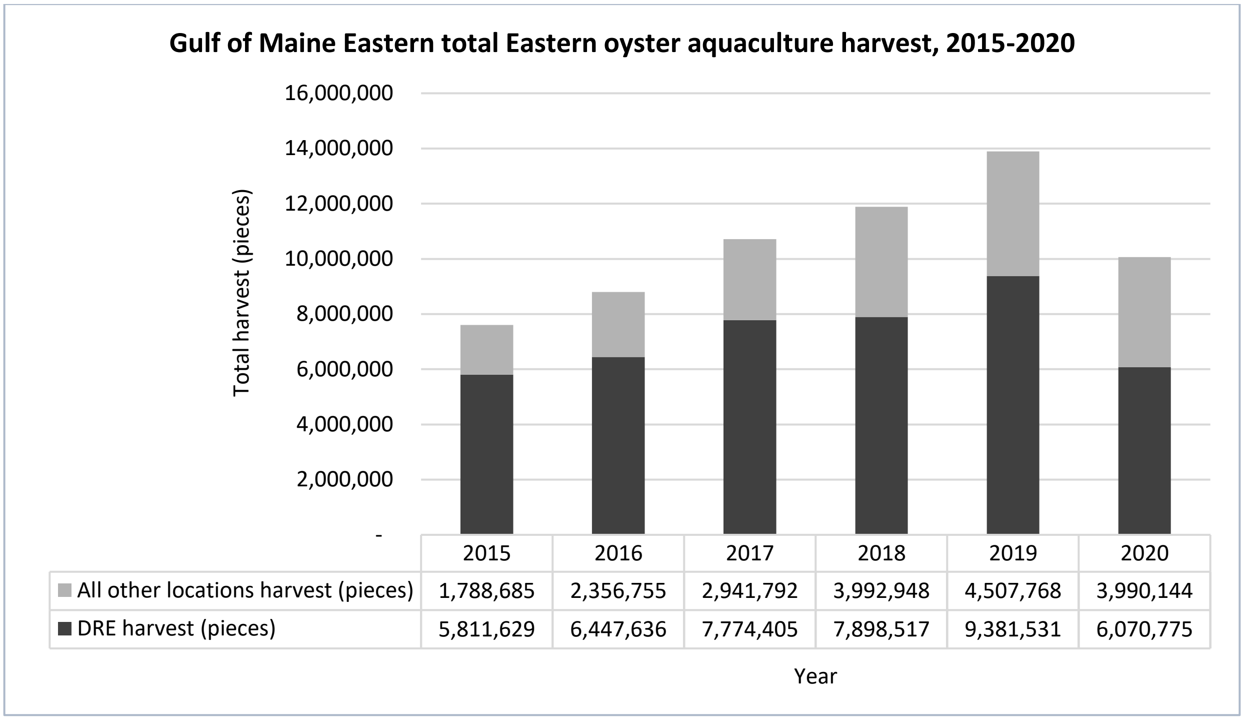


Figure 4: Active Eastern oyster aquaculture businesses located in a) the DRE, b) Casco Bay, and c) Taunton Bay, Maine. Oyster farms are symbolized using graduated points categorized by size in acres. Polygons with 1 pt. width dark blue outlines represent the waterbody boundary.

On average, approximately two-thirds of the total annual Eastern oyster harvest in Maine is comprised of oysters from DRE farms (Figure 5) (Maine DMR 2022). This is due to the geography and hydrology of the estuary, which is characterized by its narrow channel and high number of constrictions and channel bends (Lieberthal et al. 2019). These characteristics influence tidal asymmetry and material transport and create favorable conditions for oyster farming, particularly in the upper estuary, which is highly effective at retaining warm water and nutrients (Lieberthal et al. 2019).



	2015	2016	2017	2018	2019	2020
■ All other locations harvest (pieces)	1,788,685	2,356,755	2,941,792	3,992,948	4,507,768	3,990,144
■ DRE harvest (pieces)	5,811,629	6,447,636	7,774,405	7,898,517	9,381,531	6,070,775

Figure 5: Proportion of GOM total Eastern oyster aquaculture harvest (pieces) sourced from the DRE each year from 2015 to 2020. Total harvest represented by columns split between DRE harvest and all other locations harvest. DRE harvest is symbolized using blue and all other locations harvest is symbolized using orange (data sourced from Maine DMR, accessed April 26, 2022).

3. Methods

3.1 Vulnerability framework

The purpose of this report is to assess the overall vulnerability of the GOM Eastern oyster aquaculture industry to projected levels of ocean and coastal acidification. Vulnerability is measured by combining the exposure of a system to an environmental harm, people's dependence on the proper functioning of that system, and the capacity of a system to prepare for, mitigate, and adapt to the impact of exposure. The conceptual framework (Figure 6) for the assessment of shellfish aquaculture to acidification used in this report was derived from "Vulnerability and adaptation of U.S. shellfisheries to ocean acidification" (Ekstrom et al. 2015). Ekstrom et al. (2015) evaluate the ecological exposure, social sensitivity, and adaptive capacity of shellfish aquaculture industries in several regions of the U.S., including the West Coast, Northeast, Mid-Atlantic, Gulf of Mexico, Hawaiian Islands, and Alaska, to acidification, and they apply that framework to the Gulf of Maine aquaculture industry with a single-species focus on the Eastern oyster.

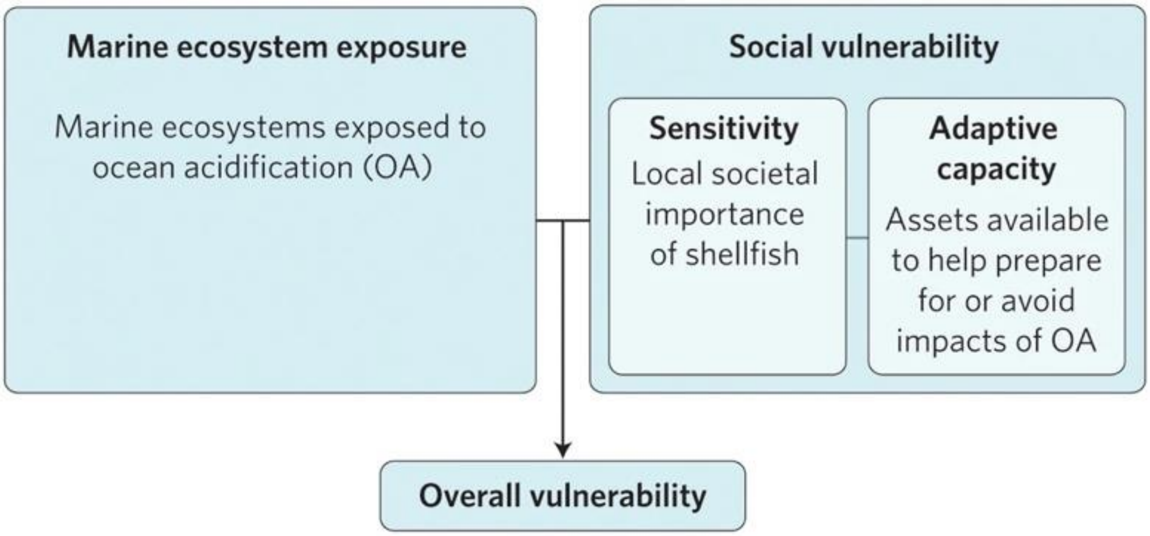


Figure 6: Vulnerability assessment framework, including ecological exposure, social sensitivity, and adaptive capacity (Ekstrom et al. 2015).

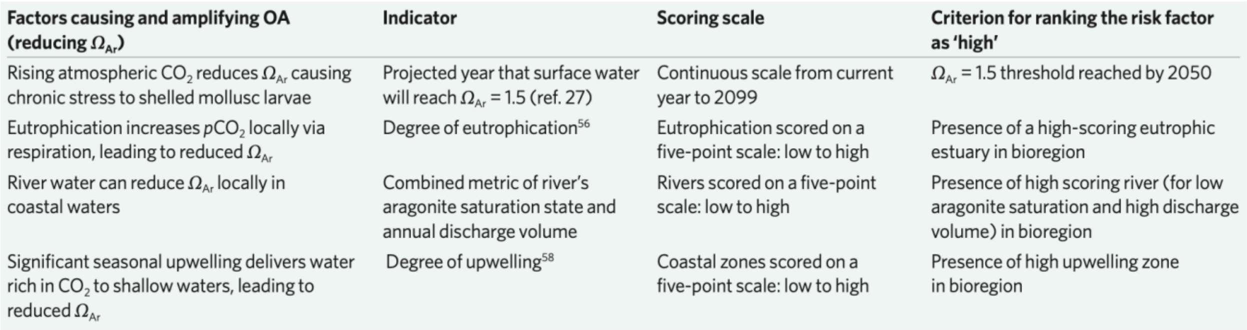
Ecological exposure of the GOM to projected ocean and coastal acidification was evaluated through a comparative analysis of existing literature on topics including ocean and coastal acidification, oyster growth and development under stressed conditions, and GOM water chemistry. Three environmental indicators were used in this report to identify likely future exposure to acidification: seawater pH (and associated aragonite saturation), SST, and annual precipitation to provide insight on the first guiding research question of this project. All global projections relevant to these indicators were sourced from the IPCC Fifth and Sixth Assessment Reports (IPCC 2014; 2021) and the 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC 2019). Only those projections based on the IPCC Representative Concentration Pathways (RCP) 2.6 and 8.5 carbon emissions scenarios were used for the purposes of this paper. Highly relevant sources of GOM-specific projections included the article "Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine" (Bricknell et al. 2021) and "Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations" (Siedlecki et al. 2021).

The social sensitivity aspect of the Ekstrom et al. (2015) framework is used to address the second guiding research question of this project. For the purposes of this report, social sensitivity was assessed based on economically measurable impacts of the GOM Eastern oyster aquaculture industry and the regional dependence of oyster aquaculture communities on the industry. Data on the harvest value, sales revenue, employment, and labor income were sourced from the State of Maine DMR webpage, the Maine Department of Labor (DOL) webpage, and the report "Maine Aquaculture Economic Impact Report" (Cole et al. 2016) compiled and published by the University of Maine Aquaculture Research Institute. All demographic data were accessed via the United States Census Bureau webpage and originated from the 2020 American Community Survey 5-Year Estimates nationwide program (United States Census Bureau 2020).

To address the third guiding research question and identify appropriate management recommendations, adaptive capacity as described by Ekstrom et al. (2015) is assessed. In this report, the adaptive capacity of the GOM Eastern oyster aquaculture industry to the potential impacts of acidification was measured by analyzing the goals and recommendations put forth in the 2015 Report of the [Maine State Legislature] Commission to Study the Effects of Ocean and Coastal Acidification and its Existing and Potential Impacts on Species that are Commercially Harvested and Grown Along the Maine Coast (Maine State Legislature 2015). Of the six goals and 25 recommendations put forth, those relevant to oyster aquaculture are compiled in a summary table. Adaptive capacity is also measured by the current capacity of local, state, and federal organizations to monitor the status of ocean and coastal acidification in the GOM is assessed, as well as the implementation of additional initiatives outside of monitoring.

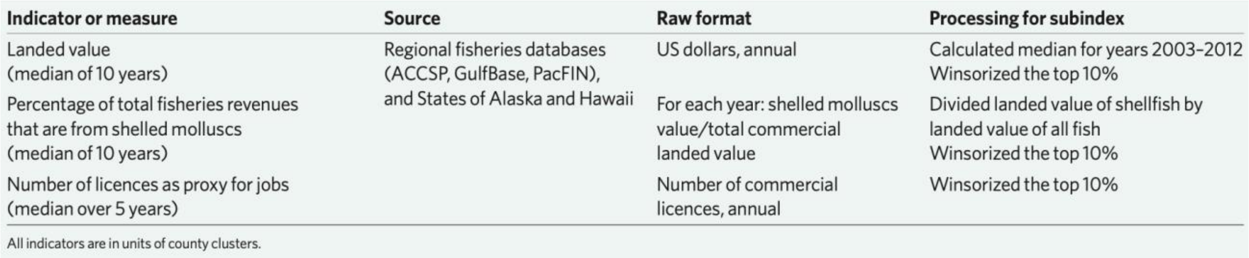
To assess the overall vulnerability of the GOM Eastern oyster aquaculture industry, exposure, sensitivity, and adaptive capacity must each be quantified in some way and then summed together. This is because, while each analysis represents a crucial aspect of the problem on its own, the major point of this project is to identify and evaluate the relationships between aspects and their effects on each other — i.e., how the level of ecological exposure and the degree of social sensitivity *combined* may impact the functioning of the oyster aquaculture industry, and how existing adaptive efforts could dilute these effects or reduce harm done. In Ekstrom et al. (2015), quantitative criteria were measured to assess exposure, sensitivity, and adaptive capacity. For ecological exposure, the projected year of $\Omega_{ar} < 1.5$ and degree of eutrophication, low-aragonite riverine discharge, and coastal upwelling were evaluated and scored on a low-to-high five point scale for each relevant bioregion (Table 1). For sensitivity of social systems, 10-year medians of landed (harvest) value and percentage of total fisheries revenue derived from shellfish production, as well as the 5-year median number of fisheries licenses representing employment were compiled (Table 2). Finally, for adaptive capacity, the availability of scientific knowledge and research and of employment alternatives, as well as relevant existing political action, were identified and processed (Table 3). By weighting and combining these quantitative measures of exposure, sensitivity, and adaptive capacity, Ekstrom et al. (2015) were able to assign scores that represented a bioregion's degree of vulnerability to acidification compared to other regions.

Table 1: Ekstrom et al. (2015) indicators of ocean acidification and criterion for determining ecological risk level in each bioregion.



Factors causing and amplifying OA (reducing Ω_{Ar})	**Indicator**	**Scoring scale**	**Criterion for ranking the risk factor as 'high'**
Rising atmospheric CO_2 reduces Ω_{Ar} causing chronic stress to shelled mollusc larvae	Projected year that surface water will reach $\Omega_{Ar} = 1.5$ (ref. 27)	Continuous scale from current year to 2099	$\Omega_{Ar} = 1.5$ threshold reached by 2050
Eutrophication increases pCO_2 locally via respiration, leading to reduced Ω_{Ar}	Degree of eutrophication[56]	Eutrophication scored on a five-point scale: low to high	Presence of a high-scoring eutrophic estuary in bioregion
River water can reduce Ω_{Ar} locally in coastal waters	Combined metric of river's aragonite saturation state and annual discharge volume	Rivers scored on a five-point scale: low to high	Presence of high scoring river (for low aragonite saturation and high discharge volume) in bioregion
Significant seasonal upwelling delivers water rich in CO_2 to shallow waters, leading to reduced Ω_{Ar}	Degree of upwelling[58]	Coastal zones scored on a five-point scale: low to high	Presence of high upwelling zone in bioregion

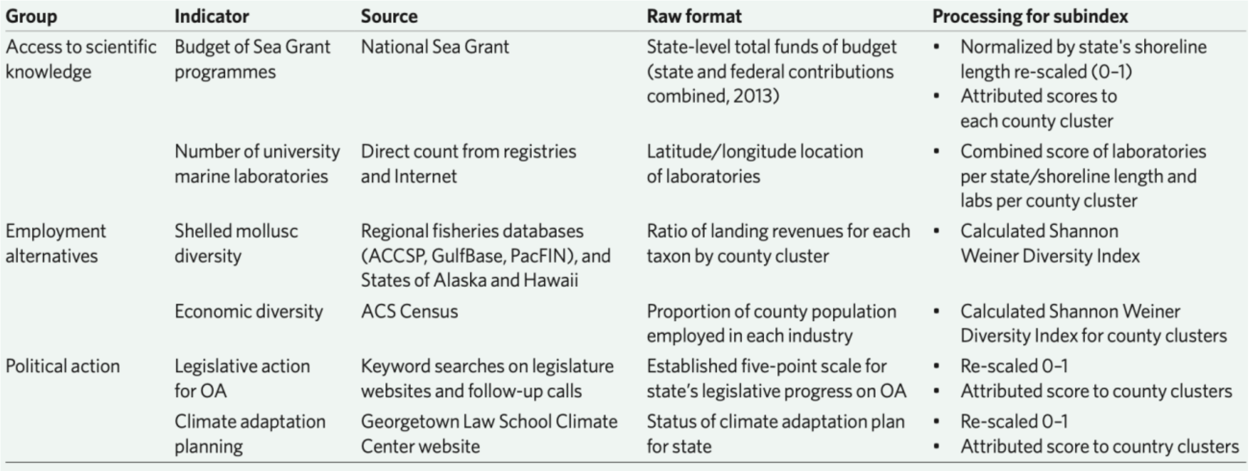
Table 2: Ekstrom et al. (2015) measures of economic contributions of the shellfish sector in each bioregion, used to represent socioeconomic dependency on the sector.



Indicator or measure	Source	Raw format	Processing for subindex
Landed value (median of 10 years)	Regional fisheries databases (ACCSP, GulfBase, PacFIN), and States of Alaska and Hawaii	US dollars, annual	Calculated median for years 2003–2012 Winsorized the top 10%
Percentage of total fisheries revenues that are from shelled molluscs (median of 10 years)		For each year: shelled molluscs value/total commercial landed value	Divided landed value of shellfish by landed value of all fish Winsorized the top 10%
Number of licences as proxy for jobs (median over 5 years)		Number of commercial licences, annual	Winsorized the top 10%

All indicators are in units of county clusters.

Table 3: Ekstrom et al. (2015) measures of the adaptive capacity within each bioregion.



Group	Indicator	Source	Raw format	Processing for subindex
Access to scientific knowledge	Budget of Sea Grant programmes	National Sea Grant	State-level total funds of budget (state and federal contributions combined, 2013)	• Normalized by state's shoreline length re-scaled (0–1) • Attributed scores to each county cluster
	Number of university marine laboratories	Direct count from registries and Internet	Latitude/longitude location of laboratories	• Combined score of laboratories per state/shoreline length and labs per county cluster
Employment alternatives	Shelled mollusc diversity	Regional fisheries databases (ACCSP, GulfBase, PacFIN), and States of Alaska and Hawaii	Ratio of landing revenues for each taxon by county cluster	• Calculated Shannon Weiner Diversity Index
	Economic diversity	ACS Census	Proportion of county population employed in each industry	• Calculated Shannon Weiner Diversity Index for county clusters
Political action	Legislative action for OA	Keyword searches on legislature websites and follow-up calls	Established five-point scale for state's legislative progress on OA	• Re-scaled 0–1 • Attributed score to county clusters
	Climate adaptation planning	Georgetown Law School Climate Center website	Status of climate adaptation plan for state	• Re-scaled 0–1 • Attributed score to country clusters

Similar to Ekstrom et al. (2015), this project requires a way of quantifying the risk level of acidification to the GOM Eastern oyster aquaculture industry based on the exposure, sensitivity, and adaptive capacity of the system. To achieve this, I designed my own non-definitive method of scoring the overall vulnerability of the industry to acidification (Table 4). Although I focused solely on the GOM in my research, I created a more general method of scoring that could be applied to other systems as well. I wrote parameters for varying degrees of exposure, sensitivity, and adaptive capacity based on the information I compiled about the threat that acidification poses to more large-scale (i.e., global) aquatic systems and then applied these parameters to my more specific knowledge of acidification in the GOM. Exposure is measured using current status and future projections of three indicators of acidification (pH/Ω_{ar}, SST, and annual precipitation). Sensitivity (i.e., economic dependency) is measured based on oyster aquaculture sales revenue (harvest value), employment, and labor income. Adaptive capacity is measured based on the number of adaptive initiatives (including relevant legislation, current monitoring capacity, and community education and outreach programs) either current in place or planned. The scores for each category can then be combined and used to determine overall vulnerability (i.e., risk level) (Table 5).

Table 4: Method of scoring ecological exposure, social sensitivity, and adaptive capacity of oyster aquaculture industries to ocean and coastal acidification.

Ecological Exposure	Social Sensitivity	Adaptive Capacity	Score
Current high exposure and projected to intensify	High economic dependency	No adaptive initiatives in place and none planned	3
No current high exposure, but likely in the future	Medium economic dependency	No adaptive initiatives in place, but some planned	2
No current high exposure and unlikely in the future	Low economic dependency	Adaptive initiatives in place and more planned (or no need for adaptive initiatives)	1

Table 5: Scoring overall vulnerability (i.e., risk level) of oyster aquaculture to acidification.

Risk Level	Total Score
High risk	9
Med-high risk	7, 8
Medium risk	6
Med-low risk	4, 5
Low risk	3

3.2 Geospatial Analysis Methods

Geospatial analysis was used to create layouts of active oyster aquaculture businesses in the DRE, Casco Bay, and Taunton Bay. To acquire data on aquaculture leases, I submitted a request form to the Maine DMR and received a Microsoft Excel spreadsheet that included data on the name, address, town, waterbody, acreage, lease start and end year, and primary species of all aquaculture businesses across the state for the years 2019, 2020, and 2021. The addresses provided in the dataset correspond to the point on each map. I was able to filter the data to include only those businesses that primarily farmed Eastern oysters and whose lease was still active (i.e., continued beyond 2022). From there, I symbolized the data using graduated symbols categorized by size (acreage) so that larger points indicated larger farms. I narrowed down the three waterbodies with the most oyster aquaculture businesses by creating a histogram of the waterbody data included in the spreadsheet and saw that the Damariscotta River, Casco Bay, and Taunton Bay had the highest counts. This is how I chose to focus on these three regions throughout my analysis of GOM oyster aquaculture.

To create site maps centered around the DRE (Figure 6a), Casco Bay (Figure 6b), and Taunton Bay (Figure 6c), I focused in on each waterbody and created three new feature classes titled “DRE_boundary,” “Casco_boundary,” and “Taunton_boundary.” I then created a polygon within each new feature class that approximately outlined the waterbody by using the Create function and Freehand tool, which formed a polygon that followed my cursor as I traced the waterbody boundary. I created three layouts focused on each waterbody that displayed the waterbody boundary and active Eastern oyster aquaculture businesses, symbolized by size, as well as a north arrow and scale bar for reference.

4. Results

4.1 Projected changes to indicators of acidification on a global scale

There are numerous climatic parameters that directly influence ocean and coastal acidification, including surface water pH, sea surface temperature (SST) and precipitation. These parameters are also referred to as natural or environmental indicators of acidification (Ekstrom et al. 2015). Each is directly affected by rising atmospheric CO_2 levels and consequent anthropogenic climate change. In 2020, the global average concentration of atmospheric CO_2 reached a record high of 412.5 parts per million (ppm) (NOAA 2021). This record average signifies that anthropogenically-derived CO_2 emissions have dramatically increased since the Industrial Revolution and are projected to continue rising barring stringent intervention. In the last two decades alone, atmospheric CO_2 has increased at a rate of 12% (NOAA 2021). At this rate, the concentration of atmospheric CO_2 would reach 486.75 ppm by 2050 and 610.5 ppm by 2100. Climate change projections put forth by the IPCC, however, indicate that, without the implementation of stringent mitigation, atmospheric CO_2 is likely to increase exponentially and reach concentrations much higher than 610.5 ppm (Figure 7). The IPCC and other researchers can apply these projections to environmental conditions such as seawater pH and temperature

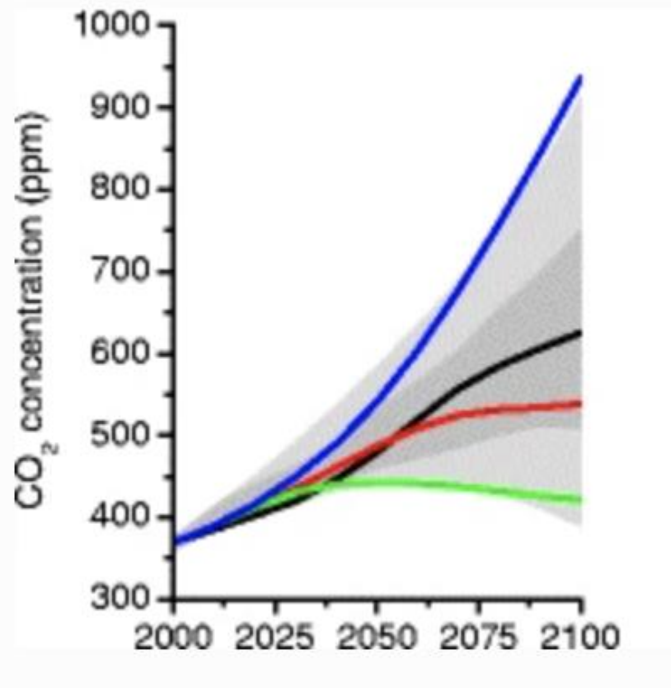


Figure 7: Atmospheric CO_2 concentration projections through 2100 based on IPCC RCP 2.6 (green), RCP 4.5 (red), RCP 6.0 (black), and RCP 8.5 (blue) (van Vuuren et al. 2011).

and precipitation and assess how these conditions, on global, regional, and local scales, will likely be affected by different degrees of atmospheric CO_2 concentration. In this section, recent IPCC climate scenarios will be described, including how they are used for the purposes of this report. Then, the likely changes to global seawater pH, water temperature, and precipitation caused by rising levels of atmospheric CO_2 and their relationship to ocean and coastal acidification are evaluated.

4.1.1 IPCC Representative Concentration Pathways

In 2014, the IPCC completed its Fifth Assessment Report (AR5) on the state of climate change and introduced a new set of future climate scenarios called the Representative Concentration Pathways that are used to evaluate future climatic conditions based on different levels of radiative forcing. The four RCPs put forth in AR5 are RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. The numeric values represent projected radiative forcing values of 2.6 watts per square meter (W/m2), 4.5 W/m2, 6.0 W/m2, and 8.5 W/m2 respectively for each pathway (Figure 8) (IPCC 2014; van Vuuren et al. 2011). These values are calculated based on the assumption that radiative forcing levels were 0 W/m2 in the year 1750 and that radiative forcing prior to the

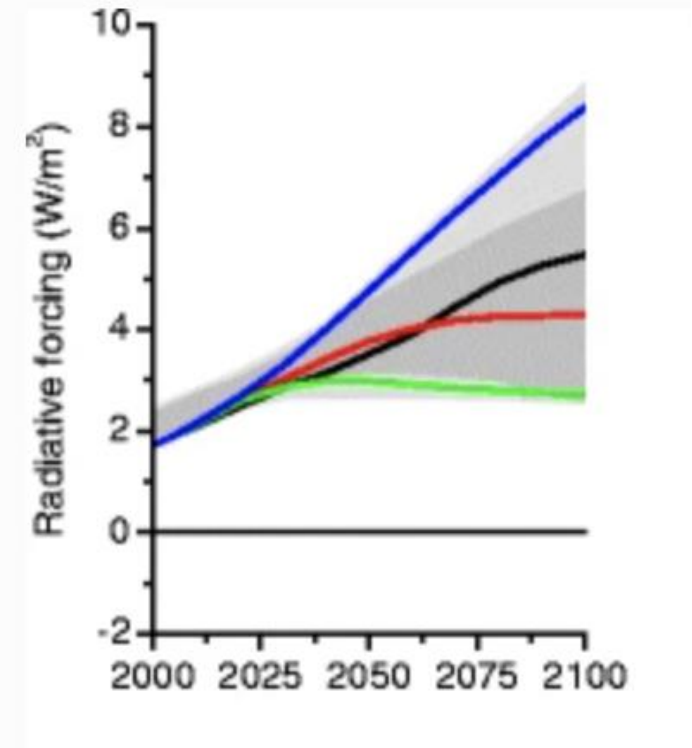


Figure 8: Radiative forcing (W/m2) projections through 2100 based on IPCC RCP 2.6 (green), RCP 4.5 (red), RCP 6.0 (black), and RCP 8.5 (blue) (van Vuuren et al. 2011).

Industrial Revolution was stable (IPCC 2014). Radiative forcing increases when there is more energy in the form of sunlight radiating towards Earth (incoming energy) than energy radiating back towards space (outgoing energy) (NOAA n.d.[a]; Chandler 2010). It is driven by climatic factors such as changes in the Earth's orbit, the amount of energy radiating from the sun, and large-scale volcanic eruptions that increase the number of light-reflecting particles in the atmosphere (NOAA n.d.[a]). It is also driven by anthropogenic factors such as increased atmospheric GHG concentrations and land use changes that cause the Earth's surface to reflect sunlight (NOAA n.d.[a]). As of 2011, total anthropogenic radiative forcing was approximately 2.3 W/m2, less than each RCP scenario projects levels will reach by 2100 (IPCC 2014).

For the purposes of this paper, data pertaining to RCP 2.6 and RCP 8.5 will be analyzed, as they represent the two most contrasting climate change scenarios and reflect the available literature published by the IPCC (IPCC 2014; 2019; 2021). RCP 2.6 is described as a mitigation scenario, or a "peak and decline" scenario, that rises to a radiative forcing level of 3.1 W/m2 by 2050 and then lowers to 2.6 W/m2 by 2100 (van Vuuren et al. 2011). A radiative forcing level of 3.1 W/m2 is equivalent to an atmospheric CO_2 concentration of approximately 490 ppm, which would return to approximately 475 ppm by the end of the century (van Vuuren et al. 2011). The decline in radiative forcing projected by RCP 2.6 is dependent on the implementation of highly stringent mitigation actions and policies that curb greenhouse gas (GHG) emissions in the latter half of the century (van Vuuren et al. 2007). It is the only climate scenario that incorporates climate policy. In contrast, RCP 8.5 has the highest end-of-century radiative forcing level and is the most drastic of the non-climate policy scenarios. It is often described as the "business as usual" scenario, although literature suggests that this is an inaccurate description, and that RCP 8.5 represents an extreme scenario contingent on continued reliance on fossil fuels (Ho et al. 2019; Ritchie and Dowlatabadi 2017). In this scenario, GHG emissions rise exponentially and result in a radiative forcing level of 8.5 W/m2 by the end of the century. This radiative forcing level is equivalent to an atmospheric CO_2 concentration of approximately 1,370 ppm, more than twice the record high concentration to date (van Vuuren et al. 2011). Both scenarios, although vastly different from each other, indicate that the concentration of atmospheric CO_2 and other GHGs will continue to rise throughout this century.

4.1.2 Ocean carbon uptake and surface water pH

When CO_2 is released into the atmosphere, it does not all remain there. From the beginning of the industrial era to the 21st century, cumulative anthropogenic CO_2 emissions total approximately 560 peta (10^{15}) grams (Pg) or 560 billion tons (Doney et al. 2009). Of this amount, just short of 50% remains in the atmosphere, and the remainder is absorbed by the ocean and by land vegetation (Doney et al. 2009). As of 2010, total ocean carbon uptake reached approximately 160 ± 20 Pg, indicating an average uptake rate of 2.6 ± 0.3 Pg per year (Gruber et al. 2019). There is a direct relationship between the concentration of CO_2 in the atmosphere and the rate at which the ocean removes CO_2 from the atmosphere; as atmospheric CO_2, so does the rate of ocean carbon uptake. This is due to the air-sea gas exchange that occurs at the boundary between the ocean surface and the atmosphere, a physiochemical process driven by differences in air and sea concentrations of a given gas (NOAA n.d.[b]) The process is constantly working to maintain an equilibrium between atmospheric concentration and aqueous concentration, adjusting to address undersaturation or oversaturation of a gas in either realm. When there is more atmospheric CO_2, the rate of ocean carbon uptake increases to account for the rise in concentration and maintain equilibrium (NOAA n.d.[b]).

Several chemical reactions occur as the ocean absorbs atmospheric CO_2. The first reaction is the change in state of CO_2 to aqueous as atmospheric CO_2 dissolves into seawater:

$$CO_2\ (atm) \leftrightarrow CO_2\ (aq)$$

The second set of reactions occurs when aqueous CO_2 reacts with water to create H_2CO_3. The H_2CO_3 dissociates into an acidic hydrogen ion (H^+) and an alkaline bicarbonate ion (HCO_3^-), and is followed by an acid-base reaction that produces two hydrogen ions and one carbonate ion (CO_3^{2-}):

$$CO_2\ (aq) + H_2O\ (l) \leftrightarrow H_2CO_3\ (aq) \leftrightarrow H^+\ (aq) + HCO_3^-\ (aq) \leftrightarrow 2H^+\ (aq) + CO_3^{2-}\ (aq)$$

This reaction occurs in a matter of seconds. Under average ocean conditions, roughly 90% of aqueous carbon exists as HCO_3^-, 9% exists as CO_3^{2-}, and 1% exists as H_2CO_3 and some remaining CO_2 (aq). Most resulting H^+ reacts with CO_3^{2-} to produce additional HCO_3^- (Feely et al. 2009).

As the amount of atmospheric CO_2 and the rate of ocean carbon uptake increase, more H_2CO_3 is produced and, as a result, more H^+ is produced (Feely et al. 2009). When there is more H^+ present in a solution, the solution becomes more acidic. Acidity and alkalinity of a solution are measured using the pH scale, which ranges from 0 to 14. A pH value less than 7 indicates an acidic solution and a pH value greater than 7 indicates a basic (or alkaline) solution. Pure distilled water is the only solution with a pH of exactly 7. Acidic solutions are associated with having more H^+ whereas basic solutions are associated with having more OH^- (NOAA n.d.[c]). When more H^+ is produced because of higher ocean carbon uptake, the pH of seawater decreases, thus indicating greater acidity. In addition, the increased production of H^+ reduces the amount of CO_3^{2-} in seawater, as the production of additional HCO_3^- also increases (Feely et al. 2009). CO_3^{2-} is a moderately strong base and the reduction of available CO_3^{2-} in seawater contributes to the overall increase in acidity (Feely et al. 2009).

Since the late 1980s, pH of surface-level seawater has decreased on average 0.017 – 0.027 pH units per decade (IPCC 2019) Projected values for atmospheric CO_2 have a direct influence on the level of future acidification. Under RCP 8.5, the most dramatic projected carbon scenario, surface pH is likely to decrease by 0.30 – 0.32 pH units before the end of the century, relative to the average surface pH of 2006–2015 (IPCC 2019; IPCC 2014). This would result in an average surface water pH of less than 7.8 (Figure 9). Under RCP 2.6, surface pH is likely to decrease by

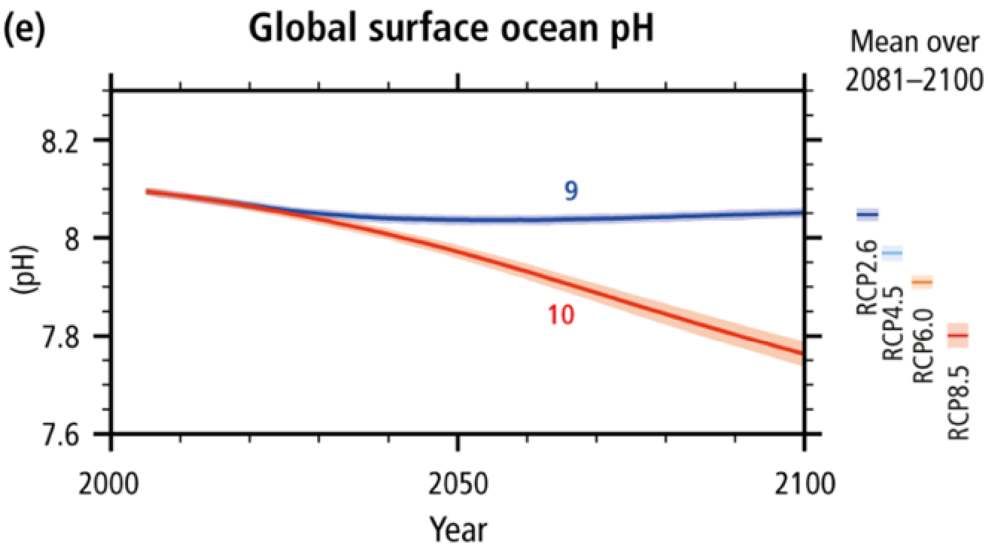


Figure 9: Projected global surface seawater pH through 2100 based on IPCC RCP 2.6 (blue) and RCP 8.5 (red) (IPCC 2014).

0.06 – 0.07 pH units relative to 2006 – 2015 (IPCC 2014), resulting in an average surface water pH of approximately 8.0 (Figure 9). Although these values appear small, their effect on acidification would be extreme. The pH scale is a logarithmic scale, a non-linear scale often used to represent large differences in quantity (Hanania et al. 2021). A 1-unit decrease in pH indicates an increase in acidity by a factor of 10. For example, a pH of 7 is 10 times more acidic (i.e., has 10 times the concentration of H^+) than a pH of 8, and 100 times more acidic than a pH of 9. Because of this, the projected declines in surface water pH indicate significant changes in ocean acidity. A decrease of 0.30 – 0.32 pH units as projected under RCP 8.5 indicates a 100-109% increase in acidity, and a decrease of 0.06 – 0.07 pH units as projected under RCP 2.6 indicates a 15-17% increase in acidity. (IPCC 2014). Many organisms are highly sensitive to seemingly small changes in pH, and these scenarios beg the question of how marine and estuarine organisms and ecosystems will adapt to unprecedented acidity.

4.1.3 Ocean heat uptake and sea-surface temperature

As GHG emissions increase, more infrared energy is absorbed by atmospheric GHG molecules and emitted back towards the surface of the earth in the form of heat energy. This is known as the greenhouse effect or global warming and is a major facet of anthropogenic climate change. The ocean plays a critical role in mitigating the intensity of global warming by taking in excess heat energy emitted by atmospheric GHG molecules, a process known as ocean heat uptake (Gleckler et al. 2016). Since the 1970s, the ocean has absorbed and stored over 90% of excess heat associated with anthropogenic global warming and even delayed the onset of atmospheric warming (IPCC 2019; Gleckler et al. 2016; Levitus et al. 2005). Recent estimates of annual ocean heat uptake for the period between 1993 and 2017 range from 9.2 ± 2.3 zetta (10^{21}) Joules (ZJ) to 12.1 ± 3.1 ZJ (IPCC 2019). For context, the global human population consumed 0.5 ZJ of energy in the year 2005 (Tomabechi 2010). This gives perspective to the magnitude of ocean heat uptake and the degree to which it mitigates atmospheric warming. Under RCP 8.5, ocean heat uptake is projected to increase by a magnitude of 5-7 times the total observed ocean heat uptake of the last five decades, reaching approximately 2,400 ZJ of total ocean heat content by 2100 (Figure II) (IPCC 2019). Ocean heat uptake is projected to increase by 2-4 times total observed ocean heat uptake since 1970 under RCP 2.6, resulting in approximately 1,000 ZJ total ocean heat content by 2100 (Figure 10) (IPCC 2019).

As the ocean absorbs heat energy from the atmosphere, ocean temperature rises. The global ocean temperature has increased unabated since 1970, and the rate at which the ocean is warming has increased more than two-fold since 1993 due to anthropogenic global warming (IPCC 2019). Climate change models project that, throughout the 21st century, the ocean will reach unprecedented temperatures. Global mean SST is projected to increase by 4ºC under RCP 8.5 and by roughly 1ºC under RCP 2.6, relative to the global mean during the period from 1986-2005 (Figure 10) (IPCC 2019). Because of this, the frequency, magnitude, and duration of marine heatwaves (MHW) is also projected to increase throughout the 21st century. MHW are defined as periods of time ranging from days to months in which observed daily SST is greater

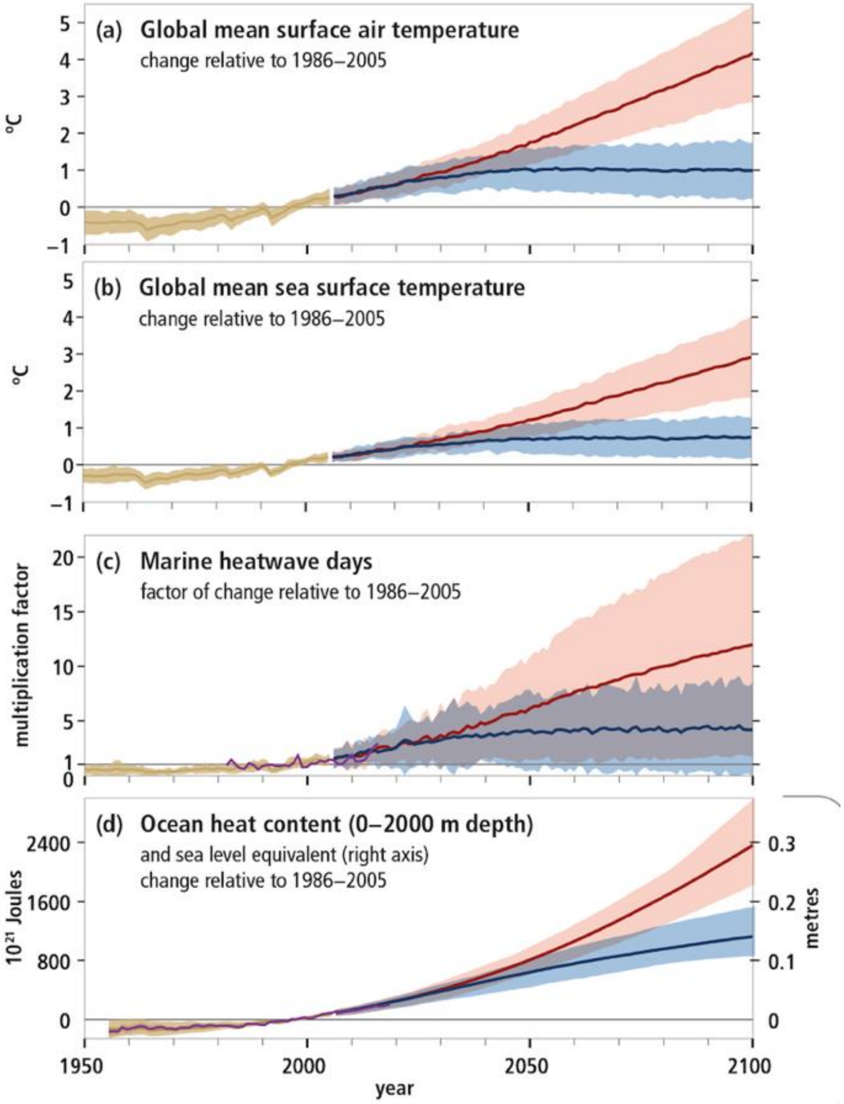


Figure 10: Global average air temperature, SST, number of MHW days/year, and ocean heat content through 2100 based on IPCC RCP 2.6 (blue) and RCP 8.5 (red) (IPCC 2019).

than the 99th percentile of local ocean temperature for the period between 1982 and 2016 (IPCC 2019). Since 1982, the number of MHW days per year has doubled and the frequency, duration, and geospatial distribution of MHWs has risen due to anthropogenic global warming and consequent increase in ocean heat uptake (IPCC 2019; Frölicher et al. 2018). Presently, the average duration of MHWs is between 15 and 33 days and the maximum annual mean intensity is between 0.6 and 1ºC, compared to 6-14 days and 0.3-0.5ºC in pre-industrial times (Frölicher et al. 2018). Under RCP 2.6, the number of MHWs per year is projected to increase by a factor of 5, and, under RCP 8.5, a factor of approximately 12 (Figure 10) (IPCC 2019). At an increase in global temperature of 3.5ºC, which closely corresponds to the RCP 8.5 projection, the average duration of MHWs is likely to reach 112 days and a maximum mean intensity of 2.5ºC (Frölicher et al. 2018). This raises significant concern on how increased SST for longer periods of time will impact marine ecosystems and organisms.

The relationship between SST and acidification is not yet fully understood by the scientific community. Both parameters are known to independently affect water chemistry and water quality, but their combined effects and the ways in which one may exacerbate or mitigate the other are still being evaluated (Trnovsky et al. 2016). One way in which changes to SST may exacerbate acidification is due to Le Châtelier's Principle, which states that, when one factor in a dynamic equilibrium changes, the other factor will change in the opposite way to compensate for the shift in equilibrium (Bodner Research Web n.d.). For example, when SST increases, the equilibrium shifts, and something must occur to compensate for that shift. To account for the increase in temperature, the ocean will absorb additional heat, an endothermic reaction, to lower its temperature and return to equilibrium. This reaction produces additional H^+ that affect seawater pH and can contribute to acidification (Gillespie 2018). Coastal ecosystems are particularly susceptible to increased acidity due to rising SST, as they experience both warmer temperatures and more acidic conditions due to terrestrial runoff and freshwater inputs. The addition of more H^+ would likely exacerbate acidification in these regions and contribute to the negative effects of ocean and coastal acidification on aquatic ecosystems and organisms.

4.1.4 Average annual precipitation

In addition to pH and SST, precipitation is projected to undergo significant changes in response to anthropogenic climate change. Several major patterns have been observed in analyses of both historical and projected precipitation data. Under all RCP scenarios, the frequency and magnitude of precipitation extremes (i.e., extreme storm events, extreme drought) are projected to increase globally, but with significant geographic variation in the type of extreme (Dore 2005; IPCC 2014; O'Gorman 2015). High latitude regions, including much of the United States, are likely to experience an increase in storm events and the amount of precipitation by 2100, whereas dry mid-latitude and subtropical regions, including southern China, Australia, and the Pacific Islands, are expected to experience increased drought (Figure 11) (IPCC 2014; O'Gorman 2015). In general, the variation in precipitation can be thought of as wet regions becoming wetter and dry regions becoming more arid (O'Gorman 2015). It is also projected that climate change will affect the frequency, magnitude, and duration of large-scale patterns of precipitation, such as El Niño and La Niña, or El Niño-Southern Oscillation (ENSO) (O'Gorman 2015). Presently, scientists do not have a clear understanding of the effects of climate change on ENSO beyond this (IPCC 2014; O'Gorman 2015).

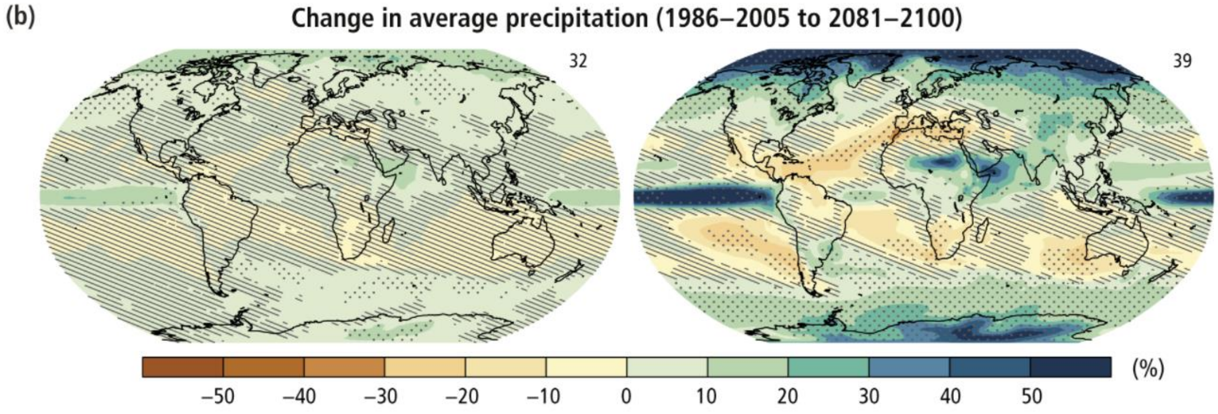


Figure 11: Change in global average precipitation. The left image depicts average precipitation between 1986-2005 and the right image depicts average precipitation between 2081-2100 (IPCC 2014).

Coastal regions that are projected to experience more frequent and intense storm events are likely to encounter concomitant increases in coastal acidification. More extreme and frequent precipitation results in greater terrestrial runoff (Bricknell et al. 2021) and coastal flooding (IPCC 2014) in systems that are already highly susceptible to acidification (Waldbusser et al. 2011; Farr et al. 2021). Terrestrial runoff deposits large nutrient loads into coastal waters, which can result in eutrophication of nearshore systems. This in combination with increased SST creates favorable conditions for phytoplankton to proliferate and amass into algal blooms (Clark et al. 2022). Decomposition of organic matter such as algae occurs, and a key product of these reactions is CO_2, which is released throughout the water column as decaying organic matter floats towards the waterbody floor (Maine State Legislature et al. 2015). The resulting aqueous CO_2 contributes to the formation of additional H^+ ions and drives coastal acidification. Apart from contributing to coastal acidification, large volumes of decaying phytoplankton can also create hypoxic conditions in waterbodies as dissolved oxygen is consumed during decomposition (Clark et al. 2022). This can result in increased mortality of other marine organisms that require certain concentrations of dissolved oxygen to survive.

Already, an increase in the severity and geographic distribution of HABs in nearshore marine regions, particularly those composed of the phytoplankton species *Pseudo-nitzschia australis*, has been observed in the past decade (Clark et al. 2022). *Pseudo-nitzschia australis* blooms have been observed in areas where the species has not previously existed and have caused economic losses upwards of several million USD due to their negative impacts on fisheries, shellfisheries, human recreation, and more (Clark et al. 2022). Coastal ecosystems are particularly vulnerable due to the combined effects of both coastal and ocean acidification, making it likely that these systems will experience intensified effects of acidification before most other water bodies (Waldbusser et al. 2011; Barton et al. 2015). Increased precipitation will exacerbate this vulnerability and raise concerns about the effects of acidification on the numerous ecologically and economically significant aquatic species that reside in and are cultivated in coastal systems.

4.2 Gulf of Maine ecosystem exposure to projected acidification

In addition to assessing climate change on a global scale, CO_2 emissions scenarios can be applied to smaller systems and used to evaluate the future status of environmental indicators in those regions. In this section, I evaluate projections of seawater acidity, SST, and precipitation that are specific to the GOM region. These projections can be used to determine potential exposure of calcifying organisms such as the Eastern oyster to intensifying acidification throughout the region. Coupled with an analysis of the sensitivity of Maine coastal communities to the potential loss of oyster production, this assessment of potential ecological exposure is a major component of the overall vulnerability of the Gulf of Maine oyster aquaculture industry to acidification.

4.2.1 Gulf of Maine pH projections

The natural variability of GOM seawater parameters makes it difficult to model accurate projections of pH in the region through the end of the century. As described in section 2.4, several strong physical processes, including large tides, wind-driven mixing, and coastal currents, cause high natural variability in annual observations of seawater conditions (Salisbury and Jönsson 2018). Sea-surface temperature and salinity notably experience large swings in average annual observation over time. Records of offshore GOM conditions spanning from 1950 to 2015 show a 15.5ºC range in annual SST observations and a 2.2-unit range in annual salinity observations (Richaud et al. 2016). These swings in SST and salinity have subsequent effects on seawater pH. Using the approximate mean GOM salinity (32.2) and other average ambient conditions (i.e., total alkalinity and pCO_2 concentration at the air-sea interface), swings in SST alone over 5–10-year timescales can cause changes in GOM pH of up to 0.013 units (Salisbury and Jönsson 2018). The natural variability of these parameters and their effect on the GOM carbonate system can either exacerbate or obscure underlying acidification derived from anthropogenic sources (Salisbury and Jönsson 2018). Because of this, it is difficult for researchers to ascertain how anthropogenic acidification alone will influence pH in the GOM as climate change progresses.

In place of pH, there is a related seawater parameter that can be used to assess future acidity in the GOM, the saturation state of aragonite (Ω_{ar}). Marine carbonate chemistry is dictated by a series of chemical reactions, the first two of which are described in Section 4.1.2. These reactions are catalyzed by the dissolution of CO_2 from the atmosphere into seawater, followed by the hydration of CO_2 to form H_2CO_3 and subsequent acidic and alkaline products (Feely et al. 2009):

$$1.\ CO_2\ (atm) \leftrightarrow CO_2\ (aq)$$

$$2.\ CO_2\ (aq) + H_2O\ (l) \leftrightarrow H_2CO_3\ (aq) \leftrightarrow H^+\ (aq) + HCO_3^-\ (aq) \leftrightarrow 2H^+\ (aq) + CO_3^{2-}\ (aq)$$

The third reaction that occurs in the series is the precipitation of solid $CaCO_3$ minerals calcite and/or aragonite. This reaction requires a positively charged calcium (Ca) ion and a negatively charge CO_3^{2-} ion produced in the second reaction:

$$Ca^{2+}\ (aq) + CO_3^{2-}\ (aq) \leftrightarrow CaCO_3\ (s)$$

The product of this reaction is solid-phase $CaCO_3$ that takes the form of calcite or aragonite. Calcite and aragonite are both $CaCO_3$ minerals with the same chemistry, but they take on different structures depending on their surrounding conditions (Chandler 2015). Aragonite is formed in seawater and is used by calcifying aquatic organisms to produce their shells and skeletons. It can transform into calcite over time or when exposed to high temperatures (Chandler 2015). Both calcite and aragonite are ionic compounds containing CO_3^{2-}, an alkaline, or basic, molecule. In a solution, the solubility of basic compounds such as CO_3^{2-} increases as the pH of the solution decreases i.e., CO_3^{2-} dissolves more readily in more acidic solutions (Khan Academy 2014). Compared to calcite, aragonite is a relatively unstable base, meaning it has lower electronegativity and a weaker hold on its electrons (Azetsu-Scott et al. 2010). This makes aragonite more vulnerable than calcite to dissolution under acidified conditions, meaning that the availability of aragonite in seawater will likely decline as acidification intensifies worldwide.

Saturation state (Ω) represents the potential of seawater to corrode aragonite found not only in the water column but also in the shells and skeletons of calcifying marine organisms (Azetsu-Scott et al. 2010). When Ω_{ar} is greater than 1, calcification is favored over dissolution, meaning more aragonite is produced than is dissolved into separated Ca^{2+} and CO_3^{2-} ions (Feely et al. 2009). Chemically, Ω_{ar} is defined as:

$$\Omega_{ar} = ([Ca^{2+}] * [CO_3^{2-}]) / K^*_{sp}$$

In this equation, the brackets represent the concentration of the given solute and K^*_{sp} represents a constant known as the apparent solubility product. The apparent solubility product varies with changes to seawater temperature, salinity, and pressure, and thus changes to these parameters directly affect Ω_{ar} (Azetsu-Scott et al. 2010). At equilibrium, K^*_{sp} equals the concentration of Ca^{2+} multiplied by the concentration of CO_3^{2-} (Feely et al. 2009):

$$K^*_{sp} = [Ca^{2+}] * [CO_3^{2-}]$$

This means that, at equilibrium, Ω_{ar} is equal to 1. When Ω_{ar} is greater than 1, seawater is considered supersaturated with aragonite. Many marine calcifers favor and even require supersaturated aragonite conditions. If Ω_{ar} falls below 1, then seawater is considered undersaturated with aragonite, and dissolution is favored over calcification (Feely et al. 2009). Currently, much of the global ocean is supersaturated with aragonite, with average Ω_{ar} values of 2-4 depending on the region (Feely et al. 2009). Tropical and subtropical regions with warmer average SST have higher Ω_{ar} than polar and subpolar regions (Jiang et al. 2015). On average, the Pacific and Indian oceans have Ω_{ar} values between 3 and 4, whereas the Arctic and Southern oceans have Ω_{ar} values between 2 and 3 (Feely et al. 2009).

Although many regions of the world's oceans currently experience supersaturated aragonite conditions, acidification caused by intensified ocean carbon uptake has caused a decline in both global and regional Ω_{ar} over time and is projected to cause further declines

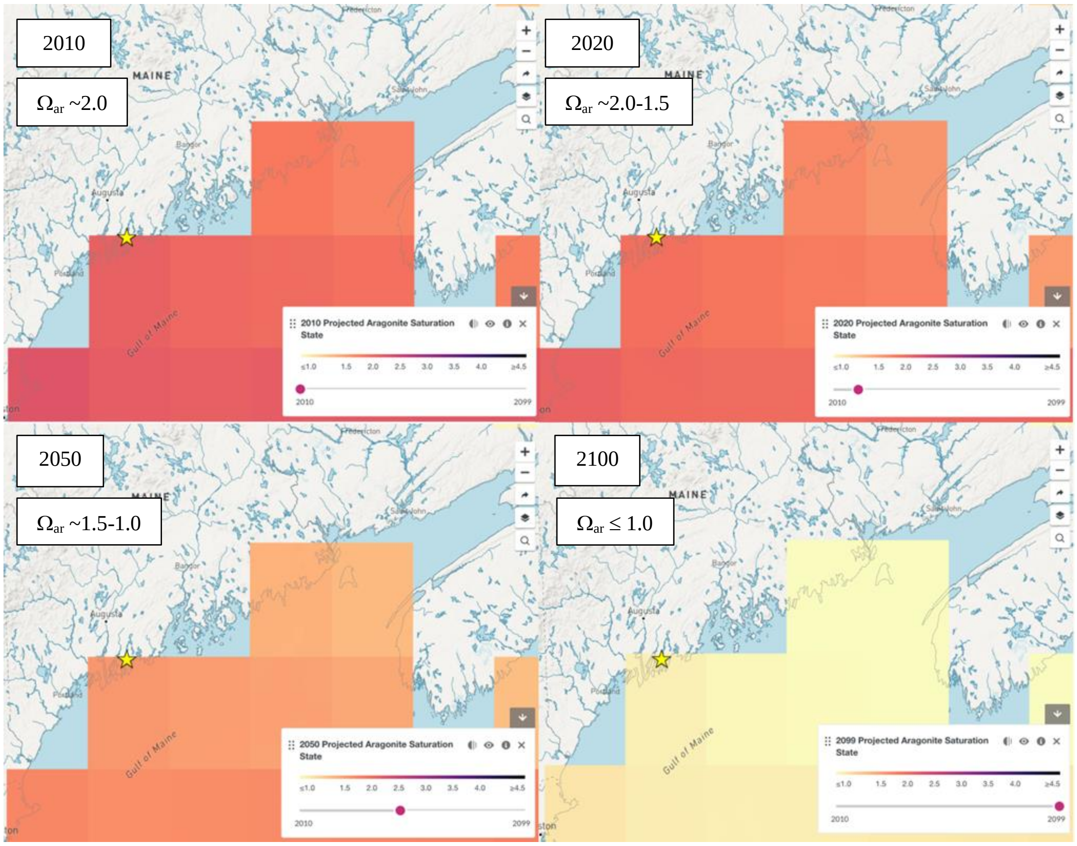


Figure 12: Projected aragonite saturation in the Gulf of Maine for 2010, 2020, 2050, and 2099 based on IPCC RCP 8.5. Projections and adjusted to mean and annual observations from 1982-2005. The Damariscotta River is symbolized with a yellow star to represent approximate Ω_{ar} conditions near important oyster aquaculture operations (van Hooidonk et al. 2014).

throughout the remainder of this century (Feely et al. 2009; Jiang et al. 2015; Siedlecki et al. 2021). By the year 2000, global Ω_{ar} decreased approximately 16% relative to pre-industrial conditions, and it is likely to decrease an additional 34% by 2100 (Jiang et al. 2015). These projections are likely to be an underestimate within the GOM system due to the strong influx of low-aragonite polar seawater from the Labrador Current and of freshwater from inland riparian systems. Nearshore regions of the GOM are already experiencing $\Omega_{ar} < 1.5$ between 9 and 41% (approximately 1-4 months) of the year depending on the degree of freshwater input (Siedlecki et al. 2021). Under RCP 8.5, the entire GOM is projected to experience $\Omega_{ar} < 1.5$ between 50 and 75% (6-8 months) of the year by 2050, and Ω_{ar} of nearshore regions will likely fall below 1 by the end of this century (Figure 12) (Siedlecki et al. 2021). These projections raise great concern for the development and survival of GOM marine calcifers, many of which are found in nearshore coastal regions and are of high ecological and economic importance to the region, such as Eastern oysters, blue mussels, and soft-shell clams.

4.2.2 Gulf of Maine sea-surface temperature projections

Rising SST and prolonged duration of the warm water season have been observed in the GOM since the beginning of the 21st century (Bricknell et al. 2021). Between 2004 and 2013, GOM SST increased at a rate of 0.23ºC per year (Pershing et al. 2015). At this rate of temperature increase, which has continued through present-day, the GOM is warming faster than 99% of all other marine water bodies worldwide (Torrent 2019). The decade between 2010 and 2020 was the warmest decade on record for SST in the GOM, a trend which is projected to continue throughout this century (Pershing et al. 2015). Since 2010, the GOM warm water season has occurred for 3-4 weeks longer than average historical observations, particularly in nearshore regions such as the DRE (Thomas et al. 2017). SST observations taken in West Boothbay Harbor, a couple of miles from DRE oyster farms, show an annual average increase of 2.4ºC between 1905 and 2018 (Maine DMR 2019).

Marine heatwaves have become more prevalent in the GOM (Oliver et al. 2019), including one extreme event that occurred in 2012, during which the average surface water temperature was approximately 2ºC higher relative to the 1981-2018 average (NOAA Fisheries 2022). This unprecedented MHW was the result of a significant northward shift of the warmer Gulf Stream current, which flows into the GOM, coupled with atmospheric patterns that caused atypical warm weather across the region (Bricknell et al. 2021). The 2012 MHW event lasted for more than a year and brought persistent anomalous warm water to the GOM. Numerous ecological and socioeconomic impacts resulted from this event, including dramatic effects on lobster and cod fisheries, as ecosystems and natural resource management in the region were adapted to cold water conditions and were ill-prepared for major warming (Pershing et al. 2018).

Sea surface temperature in the GOM is projected to continue to rise under all IPCC RCP scenarios. Across the various scenarios, GOM SST is likely to increase between 0.5ºC and 3.5ºC relative to recent observations by 2100 (Bricknell et al. 2021). Under RCP 8.5, the atypical warmth observed in the GOM over the past decade will become the norm by mid-century, and any anomalous years would experience temperatures not yet observed to date (Bricknell et al. 2021). Relative to historical and present-day temperatures, this scenario would effectively subject the GOM to a state of permanent MHW with large-scale impacts on Maine ecosystems and coastal communities (Oliver et al. 2019). If this were the case, the GOM would shift towards more temperate conditions and the subpolar cold-adapted species would be pushed out of the region. The habitats of more than 75% of commercially harvested aquatic species in the GOM would be impacted, with some expanding but the majority lessening in size and quality (Torrent 2019).

Although it is virtually certain that overall GOM SST will continue to increase over time, it is critical that the natural variability of conditions in the GOM is considered when analyzing the effects of SST on ecosystems and aquatic organisms. Any mitigation or adaptation efforts must include planning for periods of time that bring unexpected cooling to the region (Bricknell et al. 2021). Average annual GOM SST sharply declined following the intense 2016 MHW and, in 2019, reached one of the lowest points observed since the early 2000s (Bricknell et al. 2021). These major swings in SST present significant risk to GOM species that are adapted to the region's average temperatures and require a certain temperature range for growth and survival. Additionally, it has been observed that the natural variability of GOM conditions can mask the extent of acidification impacts and may prevent the severity of the issue from being fully realized (Salisbury and Jönsson 2018).

4.2.3 Gulf of Maine precipitation projections

Although increases in annual precipitation are being experienced across the U.S., the most notable changes have been measured in the northeast (Chisholm et al. 2021). Observations from land-based precipitation measurement stations across Maine show an approximately 15% increase in average annual precipitation between 1895 and 2020 (Fernandez et al. 2020). This increase in precipitation occurred largely in the form of rainfall as opposed to snowfall, as annual snowfall decreased by approximately 20% over the same period (Fernandez et al. 2020). Like SST, the rate of increase in annual precipitation has disproportionately accelerated in recent decades. Since 1960, annual precipitation has increased at an average rate of approximately 0.1" per year, whereas the long-term average prior to 1960 was less than 0.05" per year (Fernandez et al. 2020).

The increased volume of annual precipitation can be attributed not only to more frequent storm events, but also more intense events. Heavy precipitation events have become more common across the broader northeast U.S., including Maine (Easterling et al. 2017). Data from one precipitation measurement station in Farmington, Maine, approximately 70 miles inland, show that events with greater total rainfall are becoming more common over time. Most of the annual precipitation between 2005-2014 was derived from smaller events with 1-2" of total rainfall; however, relative to the beginning of the 20th century, 2" events are 2 times more common, 3" events are 3.5 times more common, and 4" events are 3 time more common (Fernandez et al. 2020). This data indicates that both smaller and heavier precipitation events are occurring more frequently across Maine. It is important to note that these values are likely greater in Maine's coastal locations, as these systems are experiencing more dramatic changes to the intensity of precipitation events due to their proximity to the ocean (Agel et al. 2015).

The changes to annual precipitation in Maine and the broader northeast region can be attributed to atypical wet conditions throughout the summer and early fall seasons (Bricknell et al. 2021). These anomalies are likely connected to larger changes in circulation patterns around the northern hemisphere, which are projected by climate models to undergo further changes throughout the 21st century. Projected rises in global temperature will have an intensifying effect on the global hydrologic cycle and will likely cause further increases in the frequency and magnitude of storm events across the globe, including the northeast U.S. (Easterling et al. 2017).

Under RCP 8.5, the GOM is expected to experience a 4.6% increase in total annual precipitation relative to 1986-2005, and, under RCP 2.6, a 2.2% increase (Chisholm et al. 2021).

The combination of rising GOM SST and precipitation is projected to increase the magnitude, frequency, and distribution of HABs in the GOM. HAB-causing phytoplankton favor warmer water temperatures and nutrient-rich systems, and the region is already experiencing the increased abundance and distribution of HABs. In 2016, the GOM experienced an unprecedented *Pseudo-nitzschia australis* HAB. Although 14 species of *Pseudo-nitzschia* had previously been observed in the GOM, *P. australis* had not been observed prior to 2016 (Clark et al. 2022). *Pseudo-nitzschia* phytoplankton produce a neurotoxin known as domoic acid, which can bioaccumulate in shellfish during an algal bloom and cause paralytic shellfish poisoning in humans if affected shellfish are consumed (Kvrgic et al. 2022). For this reason, GOM shellfisheries were required to shut down until the bloom receded; this was the first time domoic-acid induced closures had ever been required in the region (Clark et al. 2022). Since 2016, *P. australis* HABs have been observed in the GOM every year, indicating that environmental changes are creating more favorable conditions for these phytoplankton to proliferate (Clark et al. 2022). In addition to *P. australis* and other *Pseudo-nitzschia* species, HABs composed of the phytoplankton *Alexandrium catentella*, known for its production of saxitoxin and associated paralytic shellfish poisoning, are also projected to increase in magnitude and frequency across the northeast nearshore regions of the GOM (Seto et al. 2019). In addition to toxic effects, the escalation of HAB intensity in the GOM will contribute additional CO_2 to the system as the phytoplankton die and decompose, exacerbating coastal acidification.

4.3 Dependence of Maine communities on the Eastern oyster aquaculture industry

To wholly assess the vulnerability of an industry to an environmental harm, it is important to consider not only ecosystem exposure to that harm but also the sensitivity of participating social systems to the potential reduction or loss of the industry. The socioeconomic impacts of loss of oyster aquaculture production due to acidic conditions have already been felt in other regions of the United States. In the late 2000s, oyster hatcheries throughout the coastal Pacific Northwest experienced a rapid and devastating increase in larval mortality of Pacific oyster (*Crassostrea gigas*) directly attributed to increased ocean and coastal acidification (National Science Foundation 2012; Barton et al. 2012, 2015; Ko et al. 2014; Gimenez et al.

2018). This resulted in major aquaculture production shortages, costing approximately USD 110 million and directly or indirectly 3,200 jobs (Cole et al. 2016). A similar analysis of economically measurable impacts is necessary to understand the dependence of Maine coastal communities on oyster aquaculture and their sensitivity to the potential loss of oyster aquaculture production.

4.3.1 Overall economic contribution of Eastern oyster aquaculture industry in Maine

In this section, the overall economic contribution of the Eastern oyster aquaculture industry will be measured using total immediate harvest value (IHV), employment, and labor income. The data on total IHV was sourced from the Maine DMR Aquaculture Harvest, Lease, and License Data webpage (Maine DMR 2022), and the data on employment and labor income was sourced from the Maine DOL Industry Employment and Wages webpage (Maine Dept. of Labor 2022). In just five years, total Eastern oyster harvest in the Gulf of Maine doubled, increasing from approximately 7.6 million pieces (individual oysters) in 2015 to just below 14 million pieces in 2019. Total IHV correspondingly doubled from roughly USD 5 million in 2015 to USD 10 million in 2019 (Figure 13; Table 7) (Maine DMR 2022). Although Eastern oysters comprised less than 15% of annual total Maine aquaculture IHV (i.e., aquaculture of any species in Maine) between 2015 and 2020 (Figure 14; Table 5), they are on average the third most valuable species in terms of sales revenue and the fastest growing aquaculture sub-sector in the state (Cole et al. 2016).

Table 6: Gulf of Maine Eastern oyster aquaculture harvest (pieces) and immediate harvest value (IHV) (USD). Annual harvest and IHV almost doubled between 2015 and 2019, indicating rapid growth of the industry (data sourced from Maine DMR, accessed April 27, 2022).

Year	Total harvest (pieces)	Total IHV (USD)
2015	7,600,314	$4,898,154.00
2016	8,804,391	$5,964,214.00
2017	10,716,197	$7,193,925.00
2018	11,891,465	$8,054,957.00
2019	13,889,299	$9,670,100.00
2020	10,060,919	$7,041,070.00

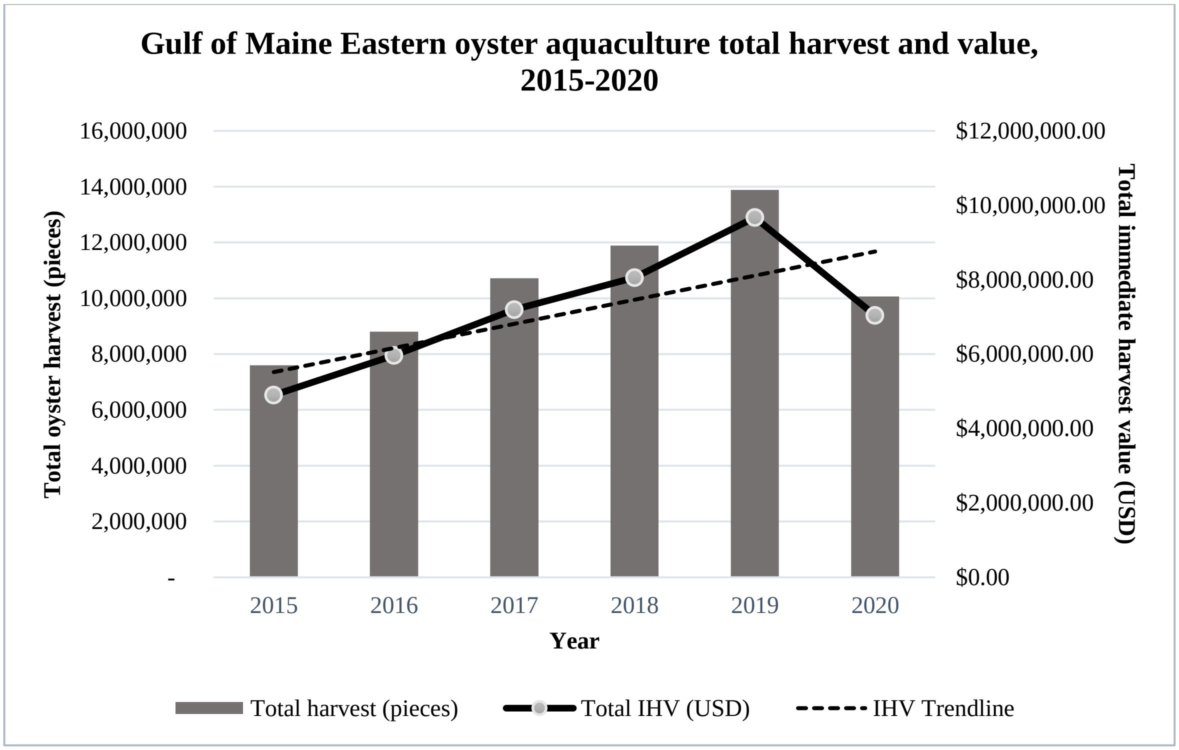


Figure 13: Total GOM Eastern oyster harvest (pieces) and IHV (USD) from 2015 to 2020. Total harvest is represented on the primary y-axis and total IHV is represented on the secondary y-axis, while year is represented on the x-axis. Total harvest is symbolized using bars and total IHV is symbolized using a line. Although there is a decline in harvest and IHV from 2019 to 2020, the linear trend shows an overall average increase in IHV over the 6-year period (data sourced from Maine DMR, accessed April 27, 2022).

Table 7: Percentage of total Maine aquaculture immediate harvest value (IHV) derived from Eastern oyster aquaculture each year from 2015 to 2020 (data sourced from Maine DMR, accessed April 27, 2022).

Year	**Total Maine aquaculture IHV (USD)**	**Total Eastern oyster aquaculture IHV (USD)**	**% oyster IHV of total IHV**
2015	$32,221,580	$4,898,154	15%
2016	$82,550,294	$5,964,214	7%
2017	$62,058,671	$7,193,925	12%
2018	$71,750,076	$8,054,957	11%
2019	$88,408,714	$9,670,100	11%
2020	$48,638,549	$7,041,070	14%

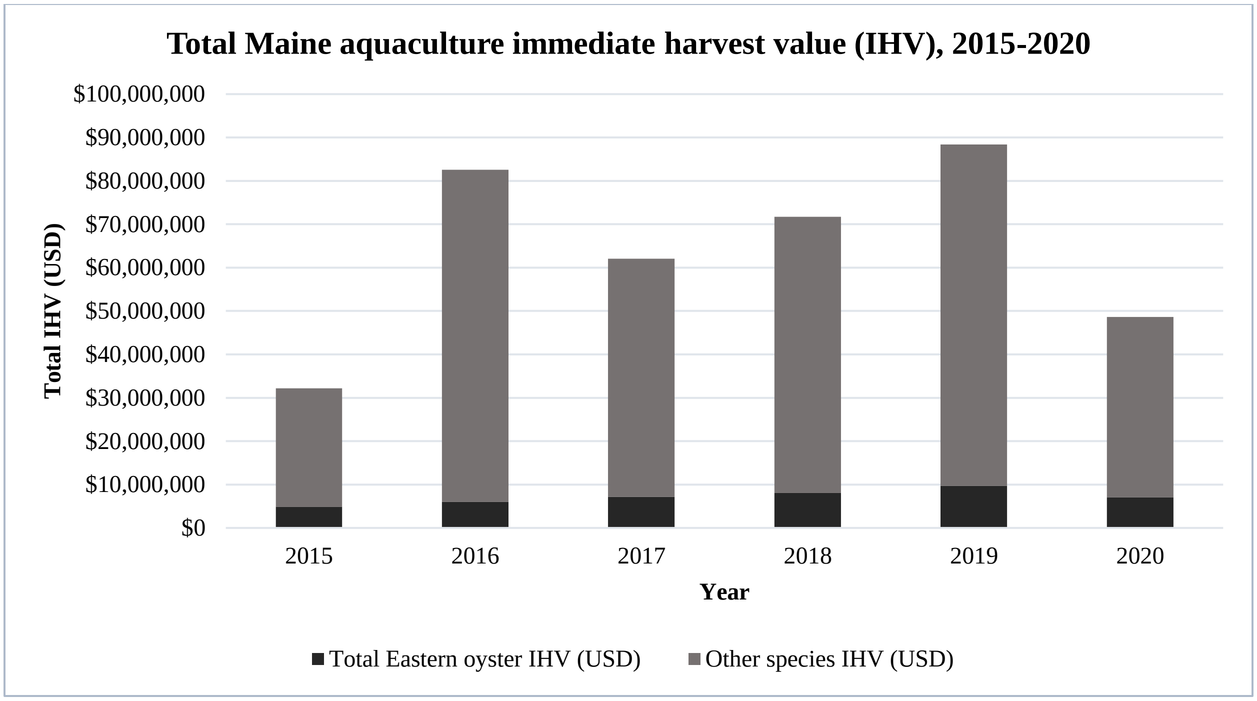


Figure 14: Proportion of total Maine aquaculture IHV derived from Eastern oyster aquaculture each year from 2015 to 2020, symbolized using stacked columns. Total IHV (USD) is represented on the y-axis and year is represented on the x-axis. Total Eastern oyster IHV is symbolized using blue and IHV derived from aquaculture of other species in Maine is symbolized using orange (data sourced from Maine DMR, accessed April 26, 2022).

In addition to value derived directly from the harvest of oysters themselves, the economic contribution of the oyster aquaculture industry in Maine includes employment and labor income (i.e., employee wages). The Maine DOL publishes employment and wage data by sector to their public webpage, but the available data on aquaculture does not distinguish by species. The most relevant available data is the average employment and total wages of persons working in the shellfish aquaculture sub-sector, which includes not only Eastern oysters but also blue mussels, Atlantic sea scallops, European oysters (*Ostrea edulis*), Northern quahogs (*Mercenaria mercenaria*), and hen clams (*Spisula solidissima*). Of these species, Eastern oysters are the top species for shellfish aquaculture in Maine in terms of the number of active aquaculture businesses (Maine DMR 2022). Like total oyster harvest and IHV, the number of employees working in the Maine shellfish aquaculture industry almost doubled over a 9-year period, increasing from 46 in 2010 to 98 in 2018 (Figure 15, Table 6) (Maine DOL 2022). The total wages distributed to shellfish aquaculture employees increased from roughly USD 1.3 million in 2010 to USD 3.7 million in 2018. The increase in employment and concomitant labor income underscores the rate at which the GOM oyster aquaculture industry has expanded in recent years and suggests that this growth will continue.

Table 8: Average employment (persons) and labor income (USD) of the Maine shellfish aquaculture industry each year from 2010 to 2018 (data sourced from Maine DOL, accessed April 26, 2022).

Year	Average employment (persons)	Labor income (USD)
2010	46	$1,300,471.00
2011	43	$1,056,559.00
2012	48	$1,241,132.00
2013	48	$1,479,774.00
2014	53	$1,682,057.00
2015	64	$1,984,678.00
2016	68	$2,412,933.00
2017	85	$3,113,255.00
2018	98	$3,677,704.00

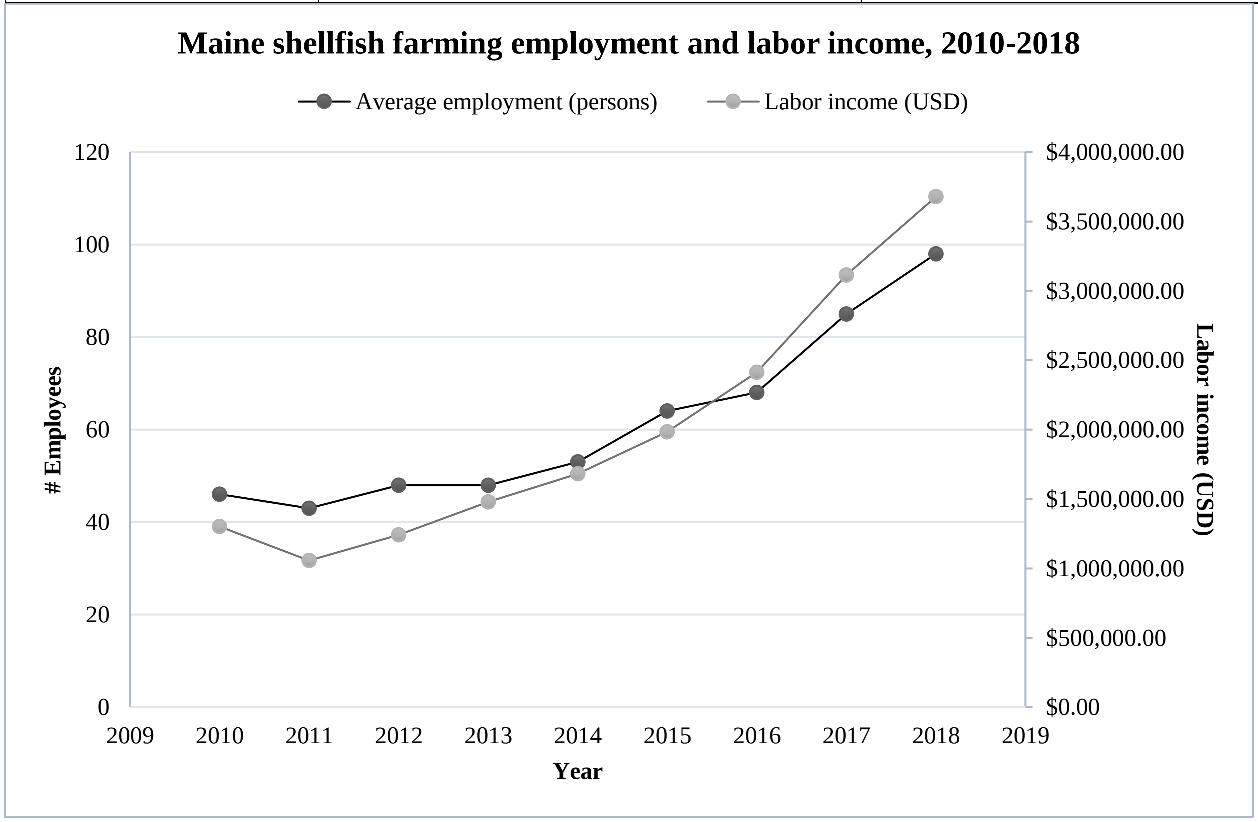


Figure 15: Number of employees working in the Maine shellfish aquaculture sector and total labor income per year from 2010 to 2018 (data sourced from Maine DOL, accessed April 26, 2022).

4.3.2 Regional economic importance of Eastern oyster aquaculture in Maine

Throughout Maine, certain communities are likely to be more impacted by changes in the GOM Eastern oyster aquaculture industry due to intensifying acidification. For example, demographic data demonstrate that the regions where oyster aquaculture businesses are the most abundant may have greater social sensitivity (i.e., dependency on the proper functioning and economic contributions) to the impacts of acidification than the state overall. The top three waterbodies in Maine by number of active oyster aquaculture businesses: DRE, Casco Bay, and Taunton Bay. As of 2021, the 33 active oyster farms in the DRE produce over two-thirds of Maine's annual Eastern oyster harvest (Figure 5). Within the DRE region, the towns that house oyster aquaculture businesses are Damariscotta, Newcastle, Bristol, South Bristol, and Edgecomb (Maine DMR 2022). Maine oyster aquaculture began in Damariscotta in 1975 and is a major aspect of the town's history and cultural identity (Lackovic 2019). Damariscotta and Newcastle have 2-3 times the number of oyster farms than any other town in the state, with 13 and 12 farms respectively (Maine DMR 2022). Although similar in this way, demographic data on the two towns show major economic differences; in 2020, Damariscotta reported a MHI of just below USD 49,000 and a poverty rate of 24% and Newcastle reported a MHI of above USD 99,000 and a poverty rate of 6% (Figure 16) (US Census 2020).

Overall, oyster aquaculture towns of the DRE region had an average MHI of USD 69,000 and an average poverty rate of 11% (Table 7). Towns within the Casco Bay region, to the south of the DRE, had an average MHI of USD 78,000 and an average poverty rate of 8% (Table 7) (US Census 2020). The Casco Bay region includes much of Cumberland County, Maine's wealthiest county, and Portland, the most populous city in the state (Maine DOL 2022). The town of Yarmouth houses the most oyster farms, six, within the Casco Bay region (Maine DMR 2022), but also has the highest poverty rate (Figure 17) (Maine DOL 2022). Within the Taunton Bay region, north of the DRE, only two towns, Franklin and Hancock, house active oyster farms. In 2020, the average MHI was approximately USD 54,000 in Franklin and USD 60,000 in Hancock, and both had a poverty rate of 16% (Table 7) (US Census 2020). These data demonstrate that, even between the regions and waterbodies in Maine where oyster aquaculture is more abundant, certain communities are more vulnerable and sensitive to the potential impacts of acidification on oyster aquaculture than others.

Table 9: Average median household income and poverty rate of towns that contain oyster aquaculture businesses within the DRE, Casco Bay, and Taunton Bay regions (data sourced from US Census, accessed April 27, 2022).

Region	**Average median household income (USD)**	**Average poverty rate (% pop.)**
DRE	$68,730	11%
Casco Bay	$78,491	8%
Taunton Bay	$57,034	16%

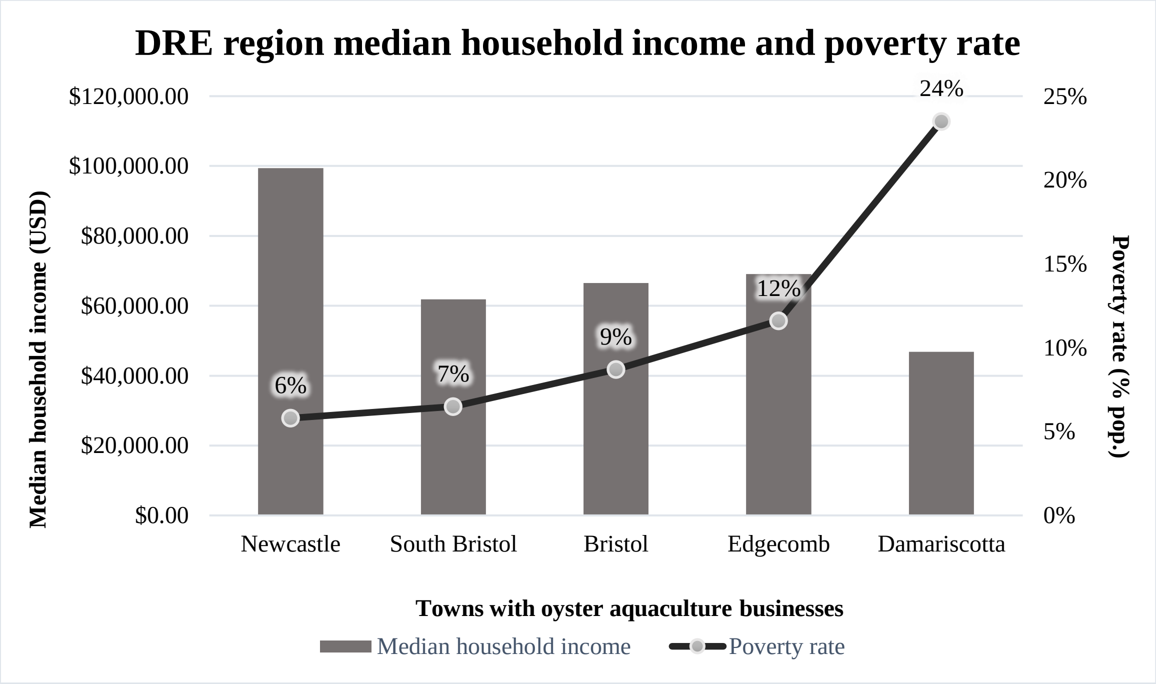


Figure 16: Median household income (MHI) and poverty rate of each town containing oyster aquaculture businesses in the DRE region. Newcastle has the highest MHI and lowest poverty rate, while Damariscotta has the lowest MHI and highest poverty rate (data sourced from the US Census, accessed April 27, 2022).

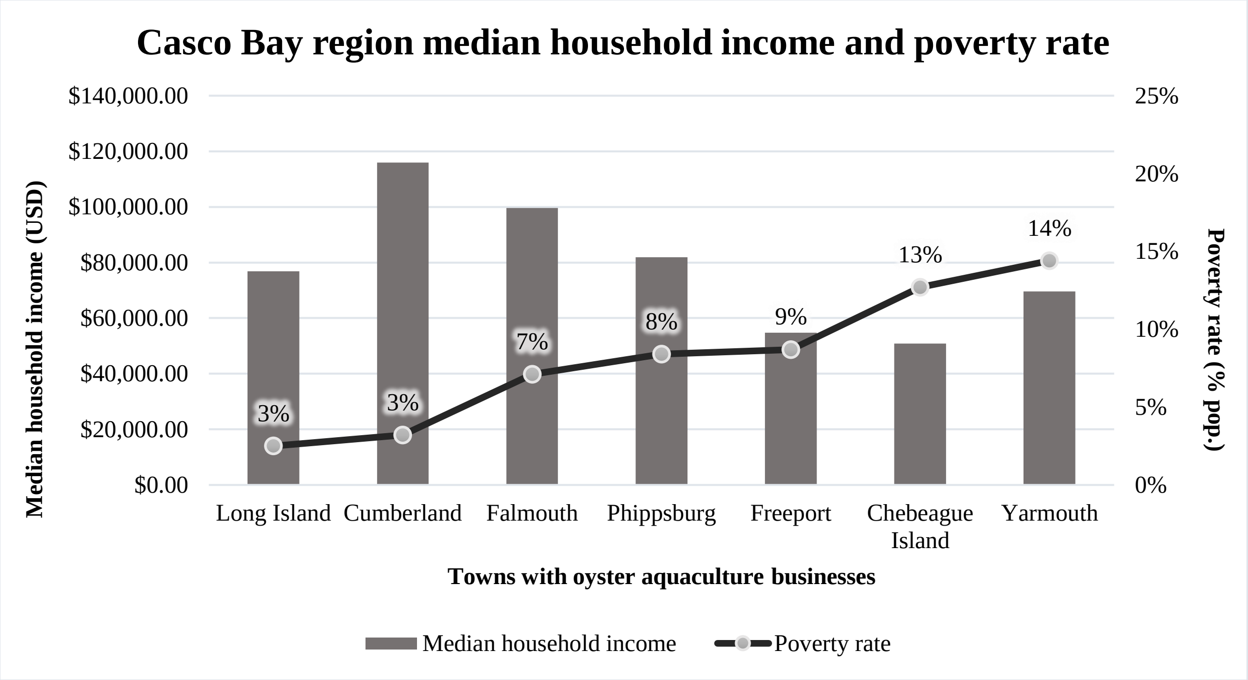


Figure 17: Median household income (MHI) and poverty rate of towns containing oyster aquaculture businesses in the Casco Bay region. Cumberland has the highest MHI and is tied with Long Island for lowest poverty rate. Chebeague Island has the lowest MHI, and Yarmouth has the highest poverty rate (data sourced from the US Census, accessed April 27, 2022).

4.4 Existing adaptive capacity to the impacts of acidification in the Gulf of Maine

The concept of adaptive capacity within a vulnerability assessment framework refers to the existing assets available to a social system that can aid in preparation for, avoidance of, and adaptation to impacts of an environmental harm (Ekstrom et al. 2015). These assets can include government policies and legislation focused on addressing the environmental harm and the availability of relevant scientific research. For the purposes of this report, the adaptive capacity of the GOM Eastern oyster aquaculture industry to the impacts of acidification is evaluated by assessing existing goals and recommendations for OA mitigation and remediation by relevant state legislation, quantifying current statewide acidification monitoring capacity, and identifying additional adaptive initiatives.

4.4.1 Commission goals and recommendations

The Commission to Study the Effects of Coastal and Ocean Acidification and Its Existing and Potential Effects on Species That Are Commercially Harvested and Grown Along the Maine Coast (henceforth referred to as the "Commission") was established by the 126th Maine State

Legislature in 2014. The Commission was comprised of 16 members, including two state senators, three state representatives, two representatives from environmental or community groups, one commercial fisherperson, two aquaculturists, three ocean and/or coastal acidification research scientists, the Commissioner of Marine Resources, the Commissioner of Environmental Protection, and the Commissioner of Agriculture, Conservation, and Forestry (Maine State Legislature 2015). Two subcommittees were formed within the Commission, the State of Science, Research, and Monitoring Priorities Subcommittee and a subcommittee tasked with reviewing the Washington State Blue Ribbon Panel of Ocean Acidification report and determining the possibility for those recommendations to be applied to Maine (Maine State Legislature 2015).

The Commission was required to research existing scientific literature about acidification as was relevant to commercial fishing and aquaculture in the GOM, as well as develop goal and recommendations for mitigation, remediation, and public awareness. Their findings, including six goals and 25 accompanying recommendations, were compiled into a 123-page report submitted to Maine State Legislature in December 2014 and published the following year. The six goals are as follows, taken directly from the report (Maine State Legislature 2015):

1. Invest in Maine's capacity to monitor and investigate the effects of ocean acidification and determine the impacts of ocean acidification on commercially important species and the mechanisms behind the impacts.
2. Reduce emissions of carbon dioxide.
3. Identify and reduce local land-based nutrients and organic carbon that contribute to ocean acidification by strengthening and augmenting existing pollution reduction efforts.
4. Increase Maine's capacity to mitigate, remediate, and adapt to the impacts of ocean acidification.
5. Inform stakeholders, the public and decision-makers about ocean acidification in Maine and empower them to take action.
6. Maintain a sustained and coordinated focus on ocean acidification.

These goals represent existing efforts to enhance and expand Maine's adaptive capacity to the potential impacts of acidification on economically significant aquatic species within the Gulf of Maine. Although these goals are broad and do not specifically address the Eastern oyster aquaculture industry, actions taken to meet these goals (i.e., implementation of recommendations) would directly benefit the industry and potentially limit the ecological exposure of this industry to the impacts of acidification.

4.4.2 Current monitoring capacity

Robust consistent monitoring of water quality parameters is crucial in understanding and identifying trends in regional water chemistry and changes to historical observations. In addition to analyzing past and present conditions, thorough time-series of historical data can be used to make predictions about future conditions of a waterbody. In this way, monitoring data contributes to a system's adaptive capacity and ability to prepare for and adapt to environmental changes. In the Gulf of Maine, there are several monitoring programs overseen by federal, state, and local agencies and organizations that record data pertinent to ocean and coastal acidification (Maine Ocean and Coastal Acidification Partnership [MOCA] 2020).

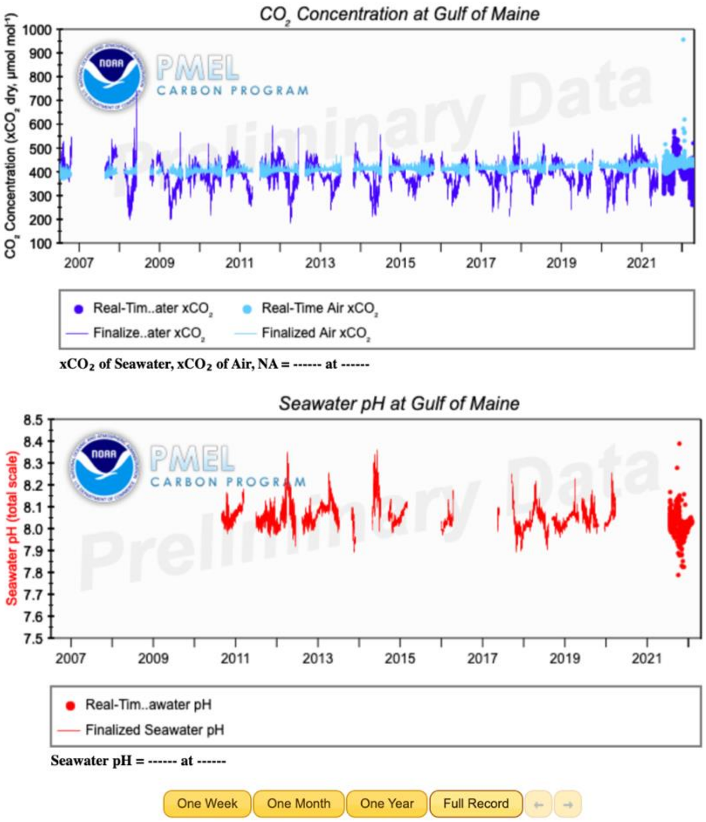


Figure 18: The full record of monitoring data on GOM CO_2 concentration and seawater pH measured by the Coastal Western GOM mooring (PMEL 2022).

Offshore water quality monitoring is primarily conducted by NOAA as part of their Ocean Acidification Program (OAP) and in conjunction with other agencies and organizations. One stationary buoy, the Coastal Western GOM mooring, has collected high precision offshore data every three hours from July 13, 2006, to present day (NOAA Pacific Marine Environmental Laboratory [PMEL] 2022). The buoy is located approximately 10 kilometers off the New Hampshire shore and is part of the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS). This location was selected in part due to the role of the University of New Hampshire (UNH) Coastal Carbon Group in the initiation of this project (NOAA PMEL 2022). In addition to recording dissolved organic carbon, a pH sensor was added to the mooring in 2010 (Figure 18) (NOAA PMEL 2022). Additional offshore observations of GOM conditions were recorded during the first NOAA East Coast Ocean Acidification research cruise that was conducted from June 19 to July 24, 2015 (NOAA OAP 2015).

The majority of nearshore water quality monitoring throughout the GOM occurs over a 4–6-month period spanning the summer months (MOCA 2020). Major contributors of nearshore observations include: the Northeast Coastal Acidification Network (NECAN); Mook Sea Farm, the largest oyster farm in Maine and located on the Damariscotta River; Shoals Marine Lab operating on Appledore Island in the GOM; Maine DMR; and researchers from Southern Maine Community College, UNH, Bowdoin College, and the University of Maine (MOCA 2020). These nearshore monitoring efforts are non-consistent in terms of when they are conducted, how frequently and for how long, and in what parameters they are measuring (MOCA 2020). This makes it difficult to compare observations from different locations and/or from different years. The only consistent year-round nearshore data are recorded by three continuous monitoring stations operated by the Friends of Casco Bay (or Casco Baykeeper), a local environmental organization focused on the environmental health of Casco Bay (Friends of Casco Bay [FOCB] 2022). The organization raised USD 1.5 million for the acquisition, implementation, and continued servicing of the three stations, which are located off Yarmouth, Harpswell, and Portland, Maine (FOCB 2022). These stations record hourly data on temperature, pH, total alkalinity, Ω_{ar}, pCO_2, dissolved oxygen saturation, salinity, dissolved inorganic carbon concentration, and turbidity, all of which can be accessed through their website (FOCB 2022). Both offshore and nearshore monitoring efforts could be improved by increasing the number of monitoring devices (i.e., buoys, continuous monitoring stations) and by ensuring that consistent, comparable measurements are recorded in each location. This is a necessary step to create long-term records of water quality observations that can be used to identify patterns in seawater acidity, concentration of dissolved inorganic carbon, temperature, and more throughout the GOM.

4.4.3 Additional initiatives

Additional actions apart from legislation and monitoring have been taken in recent years that contribute to Maine's capacity to adapt to impacts of acidification on the Eastern oyster aquaculture industry. The Commission's 2015 report encourages municipalities and regulatory agencies to coordinate on the implementation of local oyster shell recycling programs (Maine State Legislature 2015). This led to the initiation of Ocean to Plate to Ocean, a pilot-scale program led by the Casco Bay Estuary Partnership and Maine Coastal Program (Lusignan 2019). The recycling program received approximately USD 100,000 in funding from the EPA Climate Ready Estuaries program (MOCA 2020). The pilot program coordinated recycling of oyster shells from 10 restaurants in the Portland area (MOCA 2020) to create cultch, or crushed shell material that can be used to add $CaCO_3$ minerals to a waterbody. Cultch can also be used in oyster reef restoration, as juvenile oysters attach to old shells in layers and form hard reeflike structures that can control coastal erosion in addition to buffering acidified water. In April 2021, cultch created from the recycled shells was distributed by researchers from the Downeast Institute and volunteers across 120 plots on a tidal flat in South Portland near the Fore River/Casco Bay tidal interface (Bouchard 2021). If successful, the pilot-scale program will expand its efforts statewide in hopes of implementing shell recycling programs in shellfish production areas affected by acidification (MOCA 2020).

Oyster hatcheries are major stakeholders in the oyster aquaculture industry, as they develop and provide larval and juvenile oysters to aquaculture farms for cultivation. They are also uniquely positioned in terms of adaptation to acidification; although acidification poses the highest risk to larval oysters, which cannot properly develop and survive in acidic conditions, hatcheries are able to monitor and manipulate the acidity of seawater that flows into their systems before it impacts larval health (MOCA 2020). Additionally, hatcheries scientists are able to selectively breed oyster larvae that possess genetic traits that make them resilient in acidified seawater and resistant to calcium carbonate dissolution (Barton et al. 2015; de Melo et al. 2016).

The practice of adding alkaline material to buffer incoming acidic seawater is becoming increasingly common throughout oyster aquaculture businesses that operate in the GOM, but further research is necessary to assess the full adaptive potential of oyster hatcheries (MOCA 2020).

Another practice that may augment an oyster aquaculture business' adaptive capacity to the impacts of acidification is multi-trophic aquaculture, in this case, the concurrent cultivation of kelp, eelgrass, and other submerged aquatic vegetation (SAV) and oysters. Photosynthetic SAV have been shown to increase surrounding seawater pH and enhance favorable conditions for oyster growth and development (Spencer et al. 2019; Ricart et al. 2021a, 2021b). Furthermore, many types of SAV grow faster in warmer acidified water, meaning that conditions will become more favorable for SAV growth as the effects of climate change are increasingly felt in aquatic ecosystems (Spencer et al. 2019; Ricart et al. 2021a, 2021b). Research on the relationship between kelp and eelgrass aquaculture and oyster aquaculture in the GOM has been conducted by the Bigelow Laboratory for Ocean Sciences, the Island Institute, UNH, and Atlantic Sea Farms, a Maine-based kelp aquaculture business (MOCA 2020). Their findings support the indication that SAV reduces seawater acidity both at and around where it is planted. Other SAV-related in Maine efforts include mapping and protecting natural SAV habitat and developing programs that provide education on multi-trophic aquaculture to oyster and other shellfish farmers (MOCA 2020).

5. Overall Vulnerability

The overall vulnerability of the GOM Eastern oyster aquaculture industry to the projected impacts of ocean and coastal acidification was estimated by assigning scores to the ecological exposure, social sensitivity, and adaptive capacity of the system. In regard to ecological exposure, the GOM is arguably one of the most vulnerable waterbodies on the globe to intensifying acidification because of its rapid warming and high level of freshwater inflow. Regardless of the effects of anthropogenic climate change, the GOM experiences significant variability in its water quality and chemistry on a seasonal, annual, and decadal basis. This alone can cause swings in factors related to acidification, including pCO_2, pH, total alkalinity, Ω_{ar}, and more, that can positively or negatively affect the ability to cultivate Eastern oysters and other commercially important species. In recent years, however, rising atmospheric CO_2

concentrations have ramped up ocean carbon uptake, altering SST and Ω_{ar} beyond critical thresholds for oyster growth and survival. As time goes on and carbon emissions are either curbed by stringent mitigation policies (i.e., RCP 2.6) or continue to increase relatively unchecked (i.e., RCP 8.5), the level of acidification in the GOM may range from moderate at best to severe. If RCP 2.6 is achieved and local management actions are taken to augment conditions for larval growth, the industry may be able to continue operating as it does today, as adult Eastern oysters are fairly unaffected in moderately acidic conditions. However, if the future pans out as projected under RCP 8.5, it is likely that the GOM would no longer be able to sustain its expanding oyster aquaculture industry. For these reasons, the GOM receives an ecological exposure score of 3 (Table 10).

Maine coastal communities, particularly those that house Eastern oyster aquaculture businesses, are highly economically sensitive to changes in the industry. The economic contributions of the GOM Eastern oyster aquaculture industry have steadily increased over time, including notably rapid growth observed in recent years. The annual IHV of farmed Eastern oysters essentially doubled between 2015 and 2019, accompanied by similar expansion of the oyster aquaculture workforce and labor income. Not only does the industry play an increasingly large role in the statewide economy, but in the local economies of oyster aquaculture businesses, many of which report below average MHI and above average poverty rates. As the economic contributions of the industry continue to grow, so does the dependency of local communities on those contributions and sensitivity to their potential decline or loss. For these reasons, the social sensitivity of Maine communities to changes in the GOM oyster aquaculture industry is also given a score of 3 (Table 10).

Acidification poses a major threat to the ecological and social aspects of the GOM Eastern oyster aquaculture industry, and assessments of this threat paint a bleak picture of the industry’s future. However, one silver lining of the urgency of this issue is that it has already garnered attention from agencies and organizations that have the capacity to address the problem before it reaches its most severe potential. Not only are there numerous adaptive initiatives in place by government agencies, research institutions, and environmental non-profit organizations, but also many more are planned to go into effect in the near future. This significantly increases the oyster industry’s ability to prepare for, prevent, and adapt to the current and projected impacts of acidification. So long as this issue continues to command the focus of agencies and organizations, the strong adaptive capacity of the industry lowers its overall vulnerability to the impacts of acidification. For this reason, adaptive capacity receives a score of 1 (Table 10).

Table 10: Overall vulnerability scoring method applied to GOM oyster aquaculture ecological exposure, social sensitivity, and adaptive capacity to the current and projected impacts of acidification. The parameters assigned to the industry are highlighted in yellow.

Ecological Exposure	Social Sensitivity	Adaptive Capacity	Score
Current high exposure and projected to intensify	High economic dependency	No adaptive initiatives in place and none planned	3
No current high exposure, but likely in the future	Medium economic dependency	No adaptive initiatives in place, but some planned	2
No current high exposure and unlikely in the future	Low economic dependency	Adaptive initiatives in place and more planned (or no need for adaptive initiatives)	1

Table 11: Based on ecological exposure, social sensitivity, and adaptive capacity, the GOM Eastern oyster aquaculture industry is at medium-high risk (i.e., is medium-highly vulnerable) to the impacts of current and projected acidification.

Risk Level	Total Score
High risk	9
Med-high risk	7, 8
Medium risk	6
Med-low risk	4, 5
Low risk	3

By combining the ecological exposure, social sensitivity, and adaptive capacity scores, the overall vulnerability of the GOM Eastern oyster aquaculture industry receives a score of 7, indicating a medium-high risk level (Table 11). It is noteworthy that the adaptive capacity score is what lowers the risk level from high to medium-high, which reiterates the need for continued focus on mitigation, remediation, and adaptation to acidification. In the following section, I describe five management recommendations that center around further enhancing and expanding adaptive capacity of the GOM oyster aquaculture industry.

6. Management Recommendations

Increasing awareness of the threat that acidification poses to many of Maine's commercially important aquatic species has activated a number of efforts to expand adaptive capacity on a statewide and local scale by government agencies, research institutions, and environmental organizations. Many of the goals and recommendations put forth by the Commission in their 2015 report (State of Maine 2015) are ecosystem-level actions that address both the direct and indirect sources and impacts of acidification. Taking ecosystem-level actions is typically a strong approach to environmental mitigation, remediation, and adaptation, as ecosystems are dynamic networks of interactions between species and populations, and it is absolutely critical for environmental managers to encompass as many of these nuances as possible when planning. Addressing threats to aquaculture, however, may be benefitted by the incorporation of some species-specific approaches, as many businesses focus on the cultivation of a single species. Each of the following five management recommendations serve to augment the adaptive capacity of the GOM Eastern oyster aquaculture industry to the current and imminent impacts of ocean and coastal acidification.

Recommendations one and two are oriented towards community engagement and education of oyster aquaculture stakeholders, including the public. Empowering community members is a necessary step in any environmental management approach and should be the short-term focus of GOM environmental managers. Recommendations three and four present science-based options for preventing and adapting to increased ecological exposure to acidification. These should also be implemented in the short-term and can be adjusted as acidification fluctuates due to climate change and the natural variability of the GOM. Finally, recommendation five employs geospatial technologies, namely ArcGIS Pro, to consider the vulnerability of oyster cultivation in various regions on national, regional, and local scales. Regions identified as less vulnerable may be more viable for oyster cultivation if acidification becomes too severe in areas where it currently exists.

<u>1. Provide education and opportunities for collaboration among Maine oyster farmers and other key stakeholders:</u>

Education of and collaboration between Maine oyster farmers and other key stakeholders on the causes and impacts of acidification, as well as mitigative and adaptive management efforts, would enhance GOM oyster aquaculture resiliency. Participation of all major oyster aquaculture stakeholders would create a more holistic and unified approach to acidification management. Just as acidification is a relatively emerging issue on a global scale (i.e., awareness of this issue has expanded mostly in the last 20 years), awareness and knowledge of the issue has not been widely disseminated to GOM oyster aquaculture stakeholders. There are existing efforts to improve stakeholder awareness, such as the Shellfish Growers Climate Coalition, a national partnership between the Nature Conservancy and shellfish aquaculturists, hatcheries operators, salespeople, and restauranteurs from coastal areas in the US and Canada (The Nature Conservancy 2021). One of the founding members of the Coalition is Bill Mook, founder and owner of Mook Sea Farms, the largest oyster aquaculture business in Maine. In addition, there are several existing GOM-specific organizations dedicated to awareness and education of this issue and other water quality issues in the region, including MOCA, the GOM Research Institute, the Island Institute, FOCB, and the GOM Coastal Program. These organizations should be augmented and supported by federal, state, and local agencies that are able to provide funding, employment, and other necessary resources for success.

2. Bolster local community engagement to raise public awareness of current and future acidification:

The public is a major stakeholder in almost any environmental management project, as people exist within natural environments and directly impact ecosystem functioning and health. In regard to GOM Eastern oyster aquaculture, the entire public, including Maine residents, tourists, and more can play a role in addressing the issue of acidification and its impacts on GOM oyster aquaculture. More specifically, however, the local communities in which GOM oyster aquaculture businesses operate should be directly engaged in increasing industry resiliency to acidification. Existing programs include oyster shell recycling programs that engage restauranteurs and community volunteers, presentations on OA in local school systems, and “Shell Day: Marine Monitoring Blitz” hosted by Maine Sea Grant in collaboration with 57 water-quality related organizations from the GOM to Long Island Sound (MOCA 2020).

3. Expand the role of oyster hatcheries in the cultivation process:

Currently, several GOM Eastern oyster hatcheries monitor and adjust the acidity of seawater that flows into their tank systems so as to favor proper larval growth and development. All oyster hatcheries should be equipped with the necessary tools to implement this process, such as pH sensors and alkaline buffering material. If funding cannot be directed to the acquisition of necessary tools, then incentives for farmers to acquire and install equipment should be investigated. If all hatcheries were able to implement this process of monitoring in-flow seawater, then oyster larvae, the most at-risk life stage to acidification, could be protected and cultivated populations could remain abundant. Additionally, the development of hatcheries specifically dedicated to research and development of mitigation, remediation, and adaptation techniques for oyster aquaculture should be supported. These research hatcheries could develop efficient buffering techniques for acidic seawater, contribute monitoring data to larger networks, and select for acidification-resistant traits when breeding new stock.

4. Augment and expand multi-trophic aquaculture initiatives at oyster farms:

Research on the benefits of multi-trophic aquaculture and the ability of SAV to modulate seawater acidity should continue to be conducted and should be expanded to include regions outside of Casco Bay. Similar to oyster hatchery augmentation, educational and incentive programs should be developed to inform GOM oyster aquaculturists of the benefits of planting SAV among oyster infrastructure. Cultivation of SAV may also present an additional economic opportunity for oyster aquaculturists and allow them to diversify their product and sources of revenue. Diversification of revenue streams could prevent farms from facing major economic losses if oyster aquaculture is significantly impacted by acidification.

5. Conduct site-suitability analyses of GOM waterbodies for Eastern oyster growth and development:

Geospatial information systems (GIS) and other spatial analysis tools can be used to conduct site-suitability assessments based on given parameters. These assessments may be helpful in identifying which areas in the GOM will be suitable for Eastern oyster cultivation as acidification intensifies. Relevant parameters for oyster aquaculture site suitability could include pH, Ω_{ar}, water temperature, the magnitude of local freshwater input, and more. Different site suitability assessments could be conducted using projections under the IPCC RCP scenarios to evaluate site suitability under various degrees of atmospheric CO_2 concentration.

The non-definitive scoring method created for and used in this project could be applied on a local level to various oyster aquaculture regions throughout the GOM, such as the DRE, Casco Bay, Taunton Bay, and more. Each region's scores for ecological exposure, social sensitivity, and adaptive capacity could be used to determine site suitability using ArcGIS Pro. The combined scores could be used to determine suitable regions for potential relocation of oyster aquaculture if current regions become inhabitable due to climate change.

7. Conclusion

Ocean and coastal acidification are environmental harms on par with global warming in regard to the magnitude of their effect on ecosystem health and survival. Marine calcifers are significantly weakened by acidified seawater, and thus industries that rely on the abundance of these organisms are threatened by intensifying acidification. The GOM Eastern oyster aquaculture industry is particularly threatened, as the GOM will acidify at a faster rate than many other waterbodies around the world. There is hope, however, in how government agencies, research institutions, and environmental organizations have already initiated a strong adaptive response to this issue. Their response goes beyond solely Eastern oyster aquaculture and aims to encompass the large number of species, communities, industries, and more that are at risk. It is imperative that these agencies and organizations maintain a continued and collaborative focus on ocean and coastal acidification and engage stakeholders and Maine community members every step of the way.

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