EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

Ocean Chemistry Coastal Community Vulnerability Assessment

A Report by the
SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The purpose of the Subcommittee on Ocean Science and Technology (SOST) is to advise and assist on national issues of ocean science and technology. The SOST contributes to the goals for federal ocean science and technology, including developing coordinated interagency strategies and fostering national ocean science and technology priorities. The SOST reports to both the NSTC Committee on Environment and the Ocean Policy Committee.

About the Interagency Working Group on Ocean Acidification

The Interagency Working Group on Ocean Acidification (IWG-OA) advises and assists the SOST on matters related to ocean acidification, including coordination of federal activities on ocean acidification and other interagency activities as outlined in the Federal Ocean Acidification Research And Monitoring Act of 2009 (P.L. 111-11, Subtitle D).

About this Document

This document was developed by the SOST IWG-OA and published by OSTP. In 2020, the Coordinated Ocean Observations and Research Act (P.L. 116-271) mandated that the IWG-OA write an "Ocean Chemistry Coastal Community Vulnerability Assessment" that include the following:

- Identify gaps in ocean acidification monitoring by public, academic, and private assets in the network of regional coastal observing systems
- Identify geographic areas which have gaps in ocean acidification research
- Identify United States coastal communities, including island communities, fishing communities, low-population rural communities, Tribal and subsistence communities, and island communities, that may be impacted by ocean acidification
- Identify impacts of changing ocean carbonate chemistry on the communities described, including impacts from changes in ocean and coastal marine resources that are not managed by the federal government

- Identify gaps in understanding of the impacts of ocean acidification on economically or commercially important species, particularly those which support United States commercial, recreational, and Tribal fisheries and aquaculture
- Identify habitats that may be particularly vulnerable to corrosive sea water, including areas experiencing multiple stressors such as hypoxia, sedimentation, and harmful algal blooms
- Identify areas in which existing National Integrated Coastal and Ocean Observation System assets, including unmanned maritime systems, may be leveraged as platforms for the deployment of new sensors or other applicable observing technologies

The IWG-OA was also instructed to collaborate with representatives from the National Marine Fisheries Service, NOAA's Office for Coastal Management, regional coastal observing systems, regional ocean acidification networks, and Sea Grant programs, and to consult experts, including subsistence users, academia, and stakeholders familiar with the economic, social, ecological, geographic, and resource concerns of coastal communities in the United States. Input for the report was primarily coordinated through the Coastal Acidification Networks: the Northeast Coastal Acidification Network, the Mid-Atlantic Coastal Acidification Network, the Southeast Coastal Acidification Network, the Gulf of Mexico Coastal Acidification Network, the Alaska Ocean Acidification Network, and the California Current Acidification Network. A full list of individuals who contributed are acknowledged below.

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Executive Summary

The ocean is acidifying due to absorption of anthropogenic carbon dioxide emissions, eutrophication, and other human-driven processes. This report explores how ocean and coastal acidification negatively affect marine species and ecosystems of ecological, cultural, and economic importance. Coastal communities and industries that rely on these species are vulnerable, although large unknowns remain around exactly how they will be impacted by increasing acidification in the future. Additional research will allow communities to understand their vulnerability and take action in developing mitigation and adaptation strategies.

This report describes the vulnerability of coastal communities to acidification in seven different regions—each detailed in its own chapter. Each chapter describes the communities and industries in the region that are dependent on marine resources that may be impacted by acidification. These include the commercial and recreational fishing industries, aquaculture, Tribal communities, communities engaged in subsistence fishing, communities reliant on coastal ecosystem services, and others that receive value from the ocean, such as artists and spiritual communities. In most cases, more research is needed to estimate how each group may be impacted by acidification. Advances in social science research will improve understanding of the vulnerability of these groups. Common recommendations across regions include: collecting and synthesizing additional socioeconomic data; improving social-ecological models; developing social indicators relevant to acidification; researching factors that increase sensitivity to impacts from acidification; and considering acidification in the context of other social stressors.

The chapters also highlight how community's can better prepape for and respond to the impacts of acidification. Policy or management frameworks could help communities to further adapt, but more research is needed to identify these pathways. Organizations also play a crucial role in supporting adaption, including groups that educate communities, help develop mitigation strategies, make data and research more accessible, and allow for community perspectives to be incorporated in strategies.

We cannot understand social vulnerability to acidification without addressing existing monitoring and biological research gaps. Improved monitoring and modeling will lead to better characterization of how habitats or areas of interest are or will be impacted by acidification. While each region has specific needs, common themes nationwide include: increasing paired chemical and biological observations, monitoring in estuaries, and monitoring in subsurface and benthic surfaces, especially those that provide habitat to valuable species. Similarly, advances in biological research will increase certainty about how acidification will impact important species, as research on some species is limited to date. Research that incorporates multiple life stages and multiple generations, considers adaptation potential, and supports population- and ecosystem-level modeling has been limited to date but remains necessary to inform impacts to society. This work will be most useful when acidification is considered with environmental multi-stressors in models at local-to-regional scales.

Understanding social vulnerability to ocean acidification is a complex topic. While great strides have been made in monitoring acidification and researching how species may be affected, continuing to address gaps in these areas and in social science as laid out in this report is necessary to assess how vulnerable communities are and what can be done to help them adapt.

Introduction

Ocean and Coastal Acidification

When carbon dioxide (CO_2) is released into the atmosphere, approximately one third is absorbed by the ocean. The CO_2 then undergoes a series of chemical reactions with seawater that results in lower pH and greater acidity. Ocean acidification refers to the reduction of pH and accompanying chemical changes, such as the amount of carbonate ions, that is primarily driven by the uptake of anthropogenic CO_2. Since the industrial revolution, atmospheric CO_2 concentrations have increased from 280 to over 410 parts per million due to the burning of fossil fuels, along with land use changes. During the same time period, the surface ocean's pH has declined by 0.1 units on the pH scale, which represents about a 30% increase in hydrogen ions. Estimates of the decline by the end of the century vary by emission scenario, but pH could decline by another 0.3 units, leading to conditions that would have dramatic biological consequences.

Other processes can also contribute to changes in the ocean's chemistry and increases in acidity; this primarily takes place in coastal regions. For example, rivers bring freshwater, organic matter, and nutrients, which can all change the chemistry of coastal waters. There are a variety of other factors that affect coastal waters, such as run-off, eutrophication, upwelling (the movement of deep, more-acidic waters to the surface), changes in currents, and changes in temperature and salinity. These factors can be influenced by a changing climate, as well as increased urbanization in the coastal zone, contributing to increased acidity beyond the decline in pH caused by absorption of atmospheric CO_2. This is often referred to as coastal acidification. In this report, the socioeconomic impacts of ocean and coastal acidification are considered together.

Ocean and coastal acidification have well-documented negative impacts to ecologically and economically important marine species. Acidification results in a decrease of carbonate ions, which can make it difficult for calcifying organisms, such as shellfish and corals, to build and maintain calcium carbonate structures. In addition to decreased calcification rates, ocean and coastal acidification can affect growth, survival, and physiology for a number of shellfish, crustacean, fish, and coral species, with most effects observed in larval life stages. Impacts to plankton and other species at the base of the food chain may cascade to affect other species in the food web. Ocean and coastal acidification is happening in conjunction with a variety of other environmental stressors, including ocean warming, hypoxia (i.e., low oxygen levels), and harmful algal blooms. Many of the species vulnerable to acidification are economically, socially, and culturally valuable, leading to concern within many coastal communities about how ocean and coastal acidification could affect them. The aquaculture industry was the first to be impacted by acidification; oyster hatcheries in the Pacific Northwest faced production failures starting in 2007 when more-acidic water caused mass larval mortality. Communities remain concerned about how ocean and coastal acidification will affect species that hold value for aquaculture, commercial, and recreational fishing, in addition to holding cultural and spiritual value. Coastal communities themselves are facing co-stressors, including environmental threats such as sea-level rise and harmful algal blooms, and economic or social threats, such as the COVID-19 pandemic and gentrification pressure. This report discusses the vulnerability of both ecological and social systems to ocean acidification, while taking into account the multi-stressor environment.

Vulnerability

This report discusses the vulnerability of human communities to ocean and coastal acidification. The Intergovernmental Panel on Climate Change (IPCC)'s definition of vulnerability is widely used by researchers and provides a useful framework for this report. According to the IPCC's third assessment report, vulnerability represents the intersection between an organism's or system's exposure, sensitivity, and adaptive capacity to an environmental stressor [1]. Exposure refers to the extent that biophysical, social, and economic systems or organisms are exposed to a stressor [2-5]. Sensitivity is defined as the degree that biophysical, social, and economic systems or organisms are prone to stress and effects by a stressor [2-5]. Lastly, adaptive capacity refers to the biophysical, social, and economic systems or organism's ability to prepare for, adjust, and cope with a stressor [2-6].

In the context of ocean acidification, ecosystem vulnerability can be thought of as the exposure of marine ecosystems to ocean acidification, the biological response or sensitivity of species and ecosystems to acidification, and the ability of species and ecosystems to cope or adjust to acidification as a stressor. Social vulnerability can be described using a similar framework, where exposure is the impact to marine resources in a coastal community, sensitivity is related to the social and economic dependence on these affected marine resources, and adaptive capacity is the ability to prepare for, adjust to, and cope with impacts from acidification.

This report focuses on the vulnerability of coastal communities in each region of the United States by discussing potential socioeconomic impacts to communities and their capacity for adaptation and mitigation, as well as discussing gaps in monitoring, modeling, and biological research in the region. Improved monitoring, modeling, and research will reduce uncertainty in projections of the progression of acidification and how species will respond. This will better inform predictions of how human communities will be affected and inform their response. While each chapter has regional-specific information, the rest of the introduction summarizes information on social vulnerability, monitoring, and biological research that is nationally applicable.

Social Vulnerability to Ocean and Coastal Acidification

The chapters in this report describe the economic and cultural values provided to communities by marine species that could be affected by ocean and coastal acidification. Acidification may affect various aspects of the blue economy (i.e., industry connected to the oceans and coasts), such as commercial and recreational fishing, aquaculture, and tourism. It may also affect subsistence fishing and ecosystem services.

Uncertainty in ocean chemistry, ecosystem response, economics, and human behavior makes it difficult to predict economic and cultural impacts of ocean and coastal acidification. There is a need to develop new ocean acidification-relevant social-ecological conceptual models and use these coupled models to estimate potential impacts to humans and community well-being (e.g., cultural, livelihood, and health) and the distribution of impacts across sectors and social and demographic factors. The collection and synthesis of additional socioeconomic data will support these models by better informing the importance of species sensitive to acidification to different communities; understanding the value of marine resources at finer, localized scales will be especially valuable. The development of social indicators specific to ocean and coastal acidification may help measure impacts to communities; see below for information on social indicators developed by the National Oceanic and Atmospheric Administration (NOAA) for fishing communities that may serve as an example. Overall, this will inform development of feasible adaptation strategies, thus allowing communities to decrease their vulnerability. Ultimately, these strategies should be informed by and tailored to specific communities, with acknowledgement of barriers to implementation. There is an opportunity to advance environmental justice and equity through this work, as communities vulnerable to acidification may include those who are underserved.

Research around factors that may increase sensitivity of communities will also inform future vulnerability assessments. For example, the relative economic importance of commercial species that may be impacted by acidification or the diversity of species harvested may influence the sensitivity of a fishing community. Communities could also be sensitive due to impacts from other environmental stressors, such as warming. There is also a need to better understand what institutions or policies could assist in building adaptive capacity (i.e., the ability to prepare for and respond to the threat of ocean and coastal acidification). For example, fishermen may be able to switch to another species, or a shellfish hatchery could use real-time data to monitor when intake water needs to be buffered. Communities may be able to apply mitigation strategies to reduce overall stress and ocean acidification impacts to species such as improving wastewater treatment or restoring habitat. However, there are many gaps in understanding of what factors are most important for improving resilience to acidification. For example, certain community and fishing characteristics, such as labor dynamics, social services, vessel mobility, and species allocations, could shape how they respond to impacts from acidification. Aspects of port infrastructure or fisheries permitting systems could either support or limit adaptation to ocean acidification. Overall, this information could help managers and policy makers respond to increasing acidification.

NOAA Fisheries developed a suite of indicators that characterize and evaluate fishing communities' vulnerability and are used to evaluate their resilience to various disturbances. Indicators fall into five categories: fishing engagement and reliance, environmental justice, climate change, economic, and gentrification pressure.

- The fishing engagement and reliance indices measure the importance of commercial or recreational fishing in communities and could be used to identify communities that are most dependent on fishing.
- Environmental justice indices include poverty, population composition (corresponding to demographic makeup), and personal disruption (measuring personal capacity to adapt through data such as unemployment status and education); a high ranking for any of these indicators demonstrates vulnerable populations.
- Climate change indicators include sea level rise risk and storm surge risk. These are environmental conditions that may affect the sustainability of fishing businesses and infrastructure, adding to their vulnerability.
- Economic indicators include labor force structure (characterizing the availability of employment) and housing characteristics (measuring infrastructure vulnerability to coastal hazards and including median rent and mortgage); these characterize the strength and stability of the workforce and housing.
- Gentrification pressure indicators include housing disruption (itself including factors that indicate a fluctuating housing market that could lead to displacement) and retiree migration (a higher number of retirees could make an area more vulnerable to gentrification).

NOAA Fisheries developed an interactive nationwide map to display communities' rankings for each indicator; a high ranking indicates greater vulnerability.

Ocean and Coastal Acidification Monitoring and Modeling

Monitoring is key for understanding the progression of ocean and coastal acidification and understanding conditions that sensitive marine species are exposed to. Because acidification results in other changes to ocean carbonate chemistry in addition to decreasing pH, other parameters of carbonate chemistry are measured as well, such as dissolved inorganic carbon (DIC), the partial pressure of carbon dioxide ($p\mathrm{CO}_2$), and total alkalinity (TA). A higher total alkalinity corresponds to water having a higher buffering capacity, that is, an ability to resist changes in pH. When at least two of the four parameters are measured, aragonite saturation state can be calculated as a biologically relevant parameter. Aragonite is a form of calcium carbonate that is commonly used by marine species, and when the saturation state falls below a certain threshold, shells and other carbonate structures can become weaker and thinner. Additionally, species may have different responses to separate changes in the four parameters, and the parameters themselves may respond differently to changes in temperature and salinity.

Monitoring is conducted using fixed sensors or moorings, research cruises, autonomous unmanned vehicles, and by taking discrete samples. These different approaches range in spatial and temporal coverage, from infrequent cruises that cover entire regions, to fixed high-frequency sensors that may take measurements ranging from every hour to fifteen minutes at a specific location. Increasingly, it is becoming a priority to pair chemical monitoring with biological observations to better inform how species will respond to acidification.

Monitoring also gives valuable information on the processes controlling the rate and variability of acidification, such as ocean currents and circulation patterns, atmospheric exchange, temperature, salinity, stratification, and biological production and respiration. In addition to monitoring the carbonate system, biogeochemical measurements of various factors—including salinity, temperature, oxygen, nutrient, calcium, chlorophyll a, and even carbon isotope data—are often needed to elicit an understanding of the underlying processes of acidification. These direct observations are used for assessing, validating, and improving model performance to best project ocean and coastal acidification within the region. It is a priority for researchers to establish long-term trends in carbonate chemistry through hindcasting to the pre-Industrial period, forecasting conditions at weekly-to-seasonal scales, and projecting long-term changes under various greenhouse gas emission scenarios. Biogeochemical models play an important role in understanding the progression of acidification, as it is not feasible to monitor in all places.

Research on Biological Response to Ocean and Coastal Acidification

While substantial progress has been made on understanding the biological impacts of ocean and coastal acidification, gaps remain, some of which are nationally applicable and described below.

Most research has focused on early life stages, when effects are more acute. However, the consequences of a life-stage impairment for population abundance depends on both the size of the impairment and the demographic importance of that life stage. Research should study multiple life stages or the entire life cycle when possible. Additionally, research that considers multiple generations and multiple populations will help increase understanding of how biological impacts could translate to species abundance and community structure, which could lead to further ecosystem impacts. Research on single species should also focus on understanding an organism's resilience and adaptive potential. Organisms that are more resilient will be able to acclimate or adapt to future increases in acidity, but more research is needed to understand when and why this occurs. Understanding both phenotypic plasticity and the potential for heritable adaptation requires further genetic studies within and across populations, which will further inform predictions of future impacts to populations. Experiments can study the mechanisms and physiology of energetic costs of acclimating to acidification, as well as the rates and mechanisms for adaptation and acclimation under constant and varying conditions and the role that food quality plays.

Many species experience wide fluctuations in carbonate chemistry conditions within a short timescale, especially in estuaries and other near-shore environments. More research is needed to understand if this long-term exposure leads to species being acclimatized and, therefore, more resilient to future ocean and coastal acidification; understanding their vulnerability will also need to take into account whether species are mobile and can shift the habitat they occupy in response to unfavorable acidification conditions. Research should also incorporate a range of ocean acidification levels that reflect both current and future conditions and consider how current exposure to variability will affect future sensitivity. It is also important that acidification is studied in the context of other environmental stressors, such as hypoxia, warming, increased storm activity, sedimentation, and harmful algal blooms. Modeling the combined effects of these stressors on localized scales will provide the most useful information products for managers to identify at-risk communities, habitats, and species assemblages and for prioritizing management responses.

The effects of ocean acidification need to be considered at the ecosystem level and not just in the context of single species. Species of concern should be studied in an ecological context, as impacts from acidification to prey and predators could lead to cascading effects. Both changes in predator-prey relationships and changes in species' ranges could lead to ocean acidification having broader scale effects on food webs. This is important for investigating the potential effects of acidification on higher trophic levels, such as sea birds, sea turtles, whales, and seals. These species are protected and are listed as threatened or endangered under the Endangered Species Act. They provide economic benefits to communities through tourism, and hold inherent value to communities. While marine mammals, turtles, and seabirds are not expected to be directly impacted by acidification, they may be indirectly impacted by trophic impacts or altered food webs.

1.0 Northeast Region

Key Points

- Many communities in the Northeast are economically and culturally dependent on commercial fishing, which may increase their vulnerability to ocean and coastal acidification.
- Many economically important species, including the Atlantic sea scallop, American lobster, and hard clams, have demonstrated some sensitivity to acidification in lab experiments, but additional research is needed to understand how these species will be impacted at the population level, and how they may depend on the health of other aquatic life that may also be sensitive to ocean and coastal acidification.
- The dynamics of ocean and coastal acidification are affected by a number of factors, including increasing temperatures and precipitation driven by climate change, as well as nutrient pollution associated with increased urbanization near estuaries.

The Northeast region refers to the coastal and ocean waters of Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut, including the Gulf of Maine, Georges Bank, Narragansett Bay, and Long Island Sound. Many communities in the Northeast have long-standing economic and cultural ties to the marine environment. There is a history of extensive commercial fishing, and marine aquaculture is expanding in every state of the region. These industries may be impacted by ocean and coastal acidification, which could have important economic consequences.

The region is strongly influenced by the Labrador Current, which carries cold, low-salinity water into the poorly buffered Gulf of Maine. In estuaries and coastal waters, other processes such as coastal upwelling, tidal exchange, river discharge, and eutrophication caused by nutrient enrichment also affect acidification [7]. The influence of these factors varies over time, leading to dynamic ocean and coastal acidification conditions seasonally and throughout the region. Across the region, seasonal maximums of ocean and coastal acidification tend to occur in the early spring, although observations from Casco Bay and Narragansett Bay show most severe conditions in the fall, likely due to seasonal build-up of acidified bottom waters and the poor vertical exchange with well-mixed surface waters that occurs during late summer and early fall [8].

Climate change introduces further complexity to ocean and coastal acidification regionally. Warming in the Gulf of Maine over the past 15 years has reduced absorption of atmospheric CO_2 by seawater, as warmer water holds less CO_2, and ocean acidification has actually diminished in recent years [9]. Recent forecast projections suggest these compensatory effects will be overcome by 2050, with acidification conditions throughout much of the Gulf of Maine predicted to be stressful to shelled marine life year-round [10]. Additionally, the frequency of high intensity precipitation events are expected to increase, increasing outflow from large river systems, such as the Kennebec. This increased outflow could generate larger and more persistent acidified river plumes, as the rivers bring large amounts of freshwater with low alkalinity and high nutrient concentrations, potentially impacting aquaculture operations [11, 12].

1.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

It's important to understand how increasing ocean and coastal acidification will affect the economic and social wellbeing of coastal communities in the Northeast. This section outlines the value of marine resources to communities in the Northeast, along with factors that impact their sensitivity to ocean and coastal acidification and their ability to adapt.

Economic Impacts from Ocean and Coastal Acidification

There are a number of economically valuable industries in the Northeast that could potentially be impacted by ocean and coastal acidification, including commercial and recreational fisheries, aquaculture, and tourism.

Commercial Fisheries: The Northeast region has historically benefitted from highly productive seafood industries. In 2019, commercial fishermen landed over 516.7 million pounds of fish and shellfish valued at over $1.5 billion [13].

Table 1 details the economic impact of commercial fisheries by each state in the region. The most important species include American lobster, Atlantic sea scallop, cod, haddock, flounders, squid, hard clam and Atlantic herring. The species that are most economically significant vary by state. For example, Massachusetts reported that most of their shellfish landing revenue is derived from sea scallops, whereas the lobster fishery is the most valuable in Maine [14]. The importance of species can also differ at finer geographical scales within each state. While many of these species are expected to be adversely impacted by acidification, it's largely unknown how these biological impacts will translate into economic ones. It is important to understand how acidification will affect the abundance, harvestability, and economics of commercial fish stocks, as it is essential for communities to know which fisheries are potentially vulnerable and what can be done to increase their resilience. The economic impacts to communities may depend on additional factors, such as their reliance on a single vulnerable species versus harvesting a diverse selection of species.

Table 1: The economic impact of the seafood industry in 2019 by state in the Northeast region, including imports [13]. Landings revenue is the price fishermen are paid for their catch, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Landings Revenue	Jobs	Sales	Income
MAINE	$657,033,000	45,674	$3,641,818,000	$1,076,489,000
NEW HAMPSHIRE	$39,550,000	6,155	$837,995,000	$204,694,000
MASSACHUSETTS	$681,044,000	148,437	$16,334,748,000	$4,044,374,000
RHODE ISLAND	$109,306,000	8,024	$886,930,000	$239,748,000
CONNECTICUT	$16,600,000	3,069	$589,593,000	$123,125,000

Additional research is needed to link ecological modeling that predicts the impact of acidification to shellfish and other species to economic models that project outcomes for fisheries sectors and communities under a range of adaptive management scenarios. When possible, species-specific data should be used to predict impacts on individual stocks, also taking the impacts of acidification to the broader ecosystem into account. This could lead to useful information, such as when harvesting a specific species could become unprofitable. Changes to marketable stocks due to acidification and other environmental changes could lead to economic tipping points where certain fisheries are no longer profitable absent adaptive measures, but more research on this is needed [15]. Research on impacts from acidification could be linked to ongoing climate change scenario planning for fisheries on the East Coast.

Recreational Fishing: Although economic impacts of acidification to commercial fisheries could be larger, local communities perceive many economic and social benefits from recreational fisheries, which could also be impacted by ocean and coastal acidification through direct and indirect effects. Table 2 details the relative value of recreational fishing to each state.

Table 2: The economic impact of recreational fishing expenditures 2019 by state in the Northeast region [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
MAINE	730	$79,136,000	$28,411,000
NEW HAMPSHIRE	258	$26,113,000	$10,673,000
MASSACHUSETTS	2,602	$313,363,000	$150,864,000
RHODE ISLAND	891	$94,558,000	$46,904,000
CONNECTICUT	895	$108,405,000	$45,953,000

Aquaculture: The 2018 USDA Census of Aquaculture reported Northeast aquaculture sales from 321 farms valued at $123,453,000, with 291 farms using 29,161 acres of saltwater [16]. Cultured species primarily focused on Atlantic salmon, trout, eel, oysters, mussels, clams, and crabs. In some areas, oyster aquaculture in estuaries is increasing dramatically, including Casco Bay, Maine, and Duxbury Bay and Wellfleet Harbor, Massachusetts. Oyster aquaculture is valued at near $30 million in Massachusetts alone [14]. In addition to commercial activities, some coastal managers have promoted oyster aquaculture to mitigate nutrient enrichment. While aquaculture is increasing in the region, ocean and coastal acidification is expected to increasingly threaten shellfish. Predictions of tipping points of when and where aquaculture will not be feasible would be helpful for future planning. While aquaculture managers have demonstrated effective adaptive measures to mitigate against coastal acidification within hatchery operations, grow out operations remain largely vulnerable to changes in the field environment.

Ecosystem Services: Coastal habitats provide a variety of economically important ecosystem services, including protection against coastal flooding and sea level rise, and improved water quality. Oyster reefs are one habitat that performs these important functions and may be at particular risk in regions of increasing coastal acidification [17, 18]. In recent years, several groups have supported efforts to restore oyster reefs in the region, including in Buzzards Bay and Wellfleet, Massachusetts. Future analysis of property value and infrastructure being threatened by sea level rise should consider the ecosystem services that may be lost to acidification.

Cultural Impacts from Ocean and Coastal Acidification

The marine resources threatened by ocean and coastal acidification do not simply provide economic benefits; they also provide cultural, social, and spiritual value to many communities in the Northeast. Many groups receive value from the ocean, including artists, religious groups, and towns and families with historical ties to marine industries. In some coastal communities, recreational shellfish harvesting is an important cultural service with considerable value. This has not been fully characterized but should be included in future vulnerability assessments. Tribal communities with ties to coastal resources may be especially vulnerable to cultural impacts and should be engaged in ocean and coastal acidification assessments, as their traditional ecological knowledge will be important to include.

Sustenance fishing is a designated use protected by the Clean Water Act (P.L. 92-500) and has been established as a subcategory of Maine's fishing use for certain designated waters. Maine amended 38 M.R.S.A. §466 to add new subsection 10-A, which establishes and defines a "sustenance fishing designated use" as "a subcategory of the applicable fishing designated use that protects human consumption of fish for nutritional and cultural purposes[…]" Maine has adopted the sustenance fishing designated use (SFDU) subcategory of its fishing use for waters "where there is or may be sustenance fishing or increased fish consumption by members of the Indian Tribes in Maine or other Maine citizens." Ocean and coastal acidification may threaten the ability of water quality managers to protect this use, which they are regulatorily bound to do.

Evaluating Sensitivity of Communities: Current Work and Research Gaps

To understand the vulnerability of communities in the Northeast, continued investigation is needed to recognize what increases the sensitivity of coastal and fishing communities. The development of climate-induced social vulnerability indices (CSVIs) specific to ocean and coastal acidification can assist in evaluating the sensitivity of communities to acidification and their potential for resiliency. These may be informed by NOAA Fisheries community social vulnerability indicators (see page 3), which have already been applied to develop measures of climate change vulnerability on the East Coast [19].

There are few projects that specifically address social vulnerability to acidification in the Northeast. One nationwide assessment of the vulnerability of shellfisheries to acidification identified that many areas in the Northeast would be socially vulnerable, mostly due to high sensitivity from economic dependence on shellfish resources [4]. A regional vulnerability assessment currently underway is assessing the vulnerability of the Atlantic Sea Scallop fishery, which has the second highest fisheries revenue in the country. The project aims to understand the dependency of communities on sea scallops, as well as what influences the well-being and sustainability of the fishery, to determine the best adaptation and management solutions. The researchers are collaborating with sea scallop fishermen, related industry members, and managers to identify recommendations to help navigate changes in the fishery from projected ocean acidification and temperature changes in the Northeast. Future research of this kind will refine our understanding of how vulnerable Northeast communities are to ocean and coastal acidification.

Adaptive Capacity of Communities

A large portion of communities' vulnerability to acidification depends on their adaptive capacity, or their potential to mitigate acidification or adapt industry practices to bolster resilience against the impacts. Reducing regional vulnerability requires timely delivery of science products and tools to inform decision makers and impacted industries in an actionable format that is fit for purpose.

Resource managers, fishery and aquaculture businesses, and state water quality agencies are a few of the key decision makers that are being engaged to serve as users of agency research outputs.

Managers of fisheries and aquaculture may vary in their preparedness to modify their business models to account for ocean and coastal acidification. Businesses are already needing to adapt to a host of changes, such as 1) new predictions of animal (e.g. shellfish) grow-out periods in response to changing temperatures and seasonal fluctuations, as well as water quality; 2) changes in nutrient requirements of cultured finfish and feed formulations that have minimal environmental impacts; 3) outbreaks from existing and emerging pests and pathogens; 4) changing parameters for prediction of conditions that endanger food safety; 5) changes in the way fish and shellfish are harvested given impacts of climate change; and 6) extreme weather events. Active research is underway examining how ocean and coastal acidification interacts with a range of these covariates, which can be complex. Responding to these stressors may complicate a manager's adaptive capacity to acidification.

The Northeast region has robust existing efforts in ocean planning and regional fisheries management; these existing frameworks should be leveraged to increase adaptation to acidification. This will also be important for ensuring that acidification is considered in the context of other management concerns, including the development of offshore wind farms. Government agencies continue to invest in research that helps to inform policies promoting sustainably managed fisheries and aquaculture, with minimal impact on the environment. There is also growing interest in marine carbon dioxide removal, which has potential for locally mitigating coastal acidification. Seaweed culture, seagrass restoration, and ocean alkalinity enhancement are some of the strategies that have been proposed to sequester CO_2, but more work needs to be done around these topics to understand potential impacts, scaling, and likelihood of success.

Fisheries are managed by the New England Fisheries Management Council together with NOAA Fisheries, and by state fishery departments. Comprehensive management strategy evaluations and scenario development could help assess the ability of fisheries management to react to changes in harvested populations due to acidification. There is also a need to evaluate how fishermen themselves will respond to these changes. Economic modeling and sociological studies can help determine the ability of fishers to alter fishery practices as harvested populations change. In some areas, small-scale fishermen may not be equipped to adapt to fishing further offshore if a species' habitat changes due to increasing acidification, which increases their vulnerability [15]. Adaptive responses that may be needed include harvesting different species or seeking non-fishing-dependent employment, but there may be barriers to these actions. Additionally, more work is needed to understand what mitigation actions could be effective for fisheries. Currently, researchers at the Downeast Institute are investigating how adding crushed shells to mudflats could increase buffering, as well as protect against predators as a means of mitigation.

The Northeast Coastal Acidification Network (NECAN) engages in regional capacity building around ocean and coastal acidification. NECAN is a partnership among federal and state government agencies, industry members, and the scientific community that helps to communicate the latest ocean and coastal acidification science to decision makers and stakeholders and identify regional research and information needs. NECAN's Industry Working Group specifically facilitates communication with industry members; in 2018, they conducted a survey that documented industry members' understanding of ocean acidification and how it could impact them, what they viewed as environmental threats, and information about when and where they were harvesting [20]. In general, education about ocean and coastal acidification raises the adaptive capacity of a community by increasing awareness and allowing for the community to make informed decisions and build a community of practice among industry partners.

There are other organizations that increase scientific capacity, provide decision-support tools, and conduct community outreach that make important contributions to addressing acidification. These include state Sea Grant programs, and the Environmental Protection Agency (EPA) National Estuary Program sites, among others.

States have also taken an active role in addressing acidification, either through specific reports or through the inclusion of the topic in broader climate plans. Further support from states has the potential to increase adaptive capacity for their communities.

- **Maine**: Maine's legislature formed an ocean and coastal acidification commission, which released a report in 2015 with goals that included increasing the state's capacity to mitigate and adapt and informing stakeholders and decision makers about acidification. In response, the Maine Ocean and Coastal Acidification (MOCA) partnership formed, and they have worked on motivating collaborations, updating Maine communities, and fostering monitoring, legislative, and outreach efforts. MOCA developed an action plan and supplemental report based on workshops held in 2019. Maine joined the International Ocean Acidification Alliance in 2020. Ocean and coastal acidification were also included in the Main Climate Council's climate action plan and scientific assessment of climate change impacts.
- **New Hampshire**: In 2017, the state's Coastal Marine Natural Resources and Environmental Commission released a report on ocean acidification. Recommendations included developing a monitoring plan and research agenda, as well as identifying mitigation strategies.
- **Massachusetts**: The Massachusetts Ocean Acidification Commission released a report in 2021 on the status of acidification in the state that included policy recommendations. These included developing best practices for shellfishing and marine industries, addressing the role of nutrients in acidification, and creating a permanent ocean acidification council and adaptive fund.
- **Connecticut**: The Governor's Council on Climate Change released a report in 2020 on climate change action, which included recommendations for addressing coastal acidification and the impacts to the shellfish industry.

1.2 Knowledge Informing Social Vulnerability

1.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

The Northeast's current ocean and coastal acidification monitoring regime includes monitoring buoys and stations (e.g., monitoring done by EPA's National Estuary Program in Casco Bay, Massachusetts Bay, and Long Island Sound, and by Friends of Casco Bay, among others), research cruises (e.g., NOAA's East Coast Acidification Cruise), discrete sampling (e.g., monitoring done by NSF's Northeast U.S. Shelf Long-Term Ecological Research (LTER), among others) and continuous underway monitoring on ships of opportunity (research or private vessels that agree to operate a sensor). Monitoring occurs both nearshore in coastal environments and offshore, and sometimes is targeted to understand certain ecosystems and habitats. An updated monitoring inventory was recently published in Siedlecki et al. 2021 that provides details on the parameters collected by various assets [10].

Citizen science has also been utilized to collect acidification data in the Northeast. A capacity-building activity known as "Shell Day" coordinated regional citizen scientists and eight laboratories to participate in a single-day ocean and coastal acidification sampling event along the coast from Long Island Sound to Downeast Maine. As part of this effort, community science programs were inventoried, with the hope of increasing collaboration with state-based water quality monitoring programs. This event demonstrated the latent capacity of the regional citizen scientist groups to serve as a valuable source of data not readily possible by other means [21]. While this model can continue to be improved to ensure both optimal use of volunteers and that high data quality is achieved, this model could be scaled up to meet future monitoring needs.

There is a need for a more comprehensive monitoring network with better spatial and temporal coverage that can differentiate the relative importance of processes that control acidification dynamics at scales relevant to regional biological processes. Throughout much of the region, there are gaps in high-frequency monitoring needed to capture short-term episodic events, which could pose acute risk to marine resources of interest to regional industries and marine resource managers. There are also gaps in the number of high-frequency observations that measure more than one of the four carbon parameters, limiting determination of aragonite saturation state, as well as the extent of potential impacts to organisms. To more quantitatively evaluate the specific observing needs for the region, NOAA has sponsored a series of studies aimed at evaluating the current state of the observing system and how best to efficiently augment it to achieve maximum science return on investment, and two of these studies are underway in the Northeast.

Considerable observational gaps remain with regards to spatial coverage, and obtaining high-quality measurements of acidification remains technical and costly. Monitoring station distribution is uneven across the region; there are three monitoring stations within 12 miles of Portsmouth, New Hampshire, as compared to only one station within 40 miles of Rhode Island. Comprehensive monitoring of coastal acidification is a challenge given the complex nature of the Northeast coastline, which is over 7,500 miles; strategic decisions about placement of additional monitoring should be made to best inform regional and local modeling efforts, which will more cost-effectively offer better synoptic coverage (see next section). Climate-quality observations (i.e. those of sufficient quality to detect long-term trends with a defined level of confidence) that can quantify changes in acidification caused by various processes are necessary to track the progression of ocean acidification, which will be especially important as climate change drives changes in warming and precipitation [22]. However, lower-cost alternatives can also serve an important role in measuring fine-scale processes useful in improving short-term model forecast accuracy.

Most of the existing monitoring is limited to surface observations, but there is a need to increase subsurface monitoring to understand how conditions vary at depth. Species that may be sensitive to more acidic conditions occupy a variety of habitats, including benthic and pelagic environments. Ocean and coastal acidification can vary greatly throughout the water column, with events such as recurring surface blooms leading to corrosive subsurface conditions when biological material sinks and its carbon is released to the water column during decomposition. The development and use of new autonomous technologies can increase observations throughout the water column and benthic environments. There is also a need to implement long-term carbonate chemistry benthic monitoring at targeted locations, as many susceptible species (e.g. sand lance, Atlantic sea scallop) inhabit benthic habitats where acidification may be exacerbated [15].

There are gaps in monitoring in estuaries, which have higher variability in conditions (e.g., experience daily changes in acidification conditions greater than decadal changes measured offshore) and are home to shellfish and other calcifying organisms susceptible to coastal acidification. This includes clams, oysters, scallops and mussels, which are harvested by commercial and recreational shellfishermen and provide water quality mitigation. Estuaries are also potential sites for mitigation of coastal acidification, as many groups are investigating the role of seagrass in locally ameliorating acidification. Guidelines for coastal acidification monitoring best practices have only been recently published, and coastal managers and academic scientists in New England are increasing capacity to conduct this monitoring [23, 24].

Monitoring data are important for various management needs. For example, monitoring (or high-fidelity modeling) would be valuable to inform the siting or effectiveness of living shoreline restoration projects, aquaculture, or potential marine carbon sequestration efforts. Additional biological monitoring paired with carbonate chemistry monitoring will better inform how species are responding to changing acidification conditions. This will in turn better inform laboratory and field studies, allowing for better predictions of fisheries implications. The needs of resource managers should be considered when deciding how additional monitoring investments will be made.

Leveraging existing monitoring programs and assets will likely be the most cost-efficient way to expand ocean and coastal acidification monitoring and address gaps. One way to do this is to equip existing stations with sensors to monitor carbonate chemistry parameters, such as buoy and autonomous underwater vehicle systems run by the Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS). Other opportunities for leveraging existing monitoring will be covered in the IWG-OA's monitoring prioritization plan.

Ocean and Coastal Acidification Modeling

Monitoring alone will likely remain unattainable for much of the Northeast, and, instead, high-resolution biogeochemical models will likely serve as the basis for generating operational products in coming years. As an example, one such model currently offers short-term acidification forecast for the Chesapeake Bay. Similar capabilities are now under development for the Northeast region. Models can provide valuable insight into the future state of acidification in the Northeast. A recent model inter-comparison effort projected ocean and coastal acidification conditions in the Gulf of Maine out to 2050, using regional high-resolution simulations that incorporated coastal processes. Declines in aragonite saturation are predicted for the entire area, with the largest impacts near the coast, in subsurface waters, and associated with increased freshwater input [10]. While ocean and coastal acidification are expected to be partly compensated for by projected warming, by 2050 under a projected high-emissions climate scenario, the entire region is still expected to exhibit acidification conditions considered stressful to marine shellfish year-round.

NERACOOS is currently working with partners on a project to add carbonate chemistry to the existing Northeast Coastal Ocean Forecast System. This will allow for predictions of acidification conditions through short-term forecasts and longer-term predictions of climate effects. The project is aiming to deliver mitigation strategies to water quality managers and monitoring systems, oyster growers, and the wild harvest shellfishing industry, all of whom need to be able to plan, respond, and adapt to acidification.

Additionally, researchers have developed a coupled physical-biogeochemical model of the Gulf of St. Lawrence that includes dissolved oxygen and carbonate system components [25]. The model shows the importance of the remineralization of organic matter and helps quantify the impact of river inputs. Future studies are planned that will use the model to analyze the seasonal variability of the carbonate system in the area.

It is a priority to continue improving and operationalizing regional and subregional biogeochemical models with enhanced data assimilation to capture land-sea, benthic, and physical processes. Development of additional hindcasts, forecasts at weekly to seasonal scales, and projections of long-term changes under various Intergovernmental Panel on Climate Change (IPCC) scenarios will all provide useful information. Additional research and monitoring is needed to understand the relative importance of different influences, such as freshwater input from rivers, on carbonate chemistry dynamics; being able to quantify the magnitude of changes caused by different drivers will support improvement of these models and development of new regional products. This will be particularly important for estuaries, as there are still large gaps in the community's ability to project conditions at a fine-scale on the coast, partially due to the complex processes at play. Validating carbonate chemistry in these areas will be difficult without more observational data.

1.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

Research has shown that a number of species in the Northeast may be sensitive to increasing acidification. One analysis predicts that 27% of 82 species in the area will be sensitive to changes in the biogeochemical environment [26]. Many bivalve larvae (e.g., **hard clam, eastern oyster, bay scallop**) experience negative impacts to growth, survival, and calcification rates when exposed in the laboratory, with shell dissolution also being observed [22]. The minimum threshold aragonite saturation state needed to ensure survival and settlement of early life stages of shellfish is estimated to be 1.6, although additional field and lab experiments can give more confidence to biological thresholds for various taxa [27]. Present conditions already fail to meet the threshold of aragonite saturation state of 1.6 on a seasonal basis in some areas of the Northeast, including benthic habitats where bivalves reside [10]. However, effects will depend on the duration of these acidification events and whether they coincide with sensitive life stages [28]. In addition, sublethal effects on shell integrity are likely to worsen vulnerability to predators, including crab species that have recently invaded the region [28]. Additional research is needed on later life stages (juveniles and adults), to understand the effects of acidification to species at the population level.

Some laboratory experiments have focused on commercially and ecologically important species, with resulting impacts varying across life stages. Experiments on **American lobster** have shown negative responses to elevated CO_2 at various life stages, including changes to swimming speed and feeding rates of larvae, reduced length and biomass and increased susceptibility to shell disease in juveniles [29, 30]. Experiments with **summer flounder** found that survival of embryos to hatching was lower under elevated CO_2 [31]. Experiments on **Atlantic silverside** and **inland silverside** provided evidence of complex responses when considering the effects of acidification in isolation versus in combination with other stressors, highlighting the need for realistic multi-stressor frameworks [32, 33].

Needed Research on Economically Important Species

The five states making up the Northeast region of the United States collectively harvest 173 species of fish, shellfish, and seaweeds; some of the most economically important species for aquaculture and commercial fisheries include **Atlantic sea scallops, American lobster, hard clams, blue mussels, and eastern oysters** [13]. The well-being of these aquatic organisms, whether cultured or in the wild, depends on many factors that are impacted by ocean and coastal acidification and climate change, primarily water quality and temperature, but also include altered ecosystems, rising sea levels, and changes in salinity. Additional studies are needed to evaluate the sensitivity of commercially important species, including **American lobster, blue crab, Jonah crab, rock crab, horseshoe crab, Atlantic sea scallop, Atlantic surf clams, and many finfish**, to ocean and coastal acidification.

When sub-optimal water quality or environmental conditions exist, organisms are stressed, reducing their capacity to resist infections from pests and pathogens, and diverting physiological processes away from growth and reproduction. When pushed to extremes, populations must demonstrate resilience, adapt to changing conditions, migrate towards better conditions, or face endangerment. Additional research is needed to help aquaculture and fisheries managers understand the physiological limits of each species and their adaptive capacity to thrive in warmer temperatures and ocean and coastal acidification. Managers can implement artificial selection through selective breeding by identifying stocks with superior genetic merit in response to changing marine environments to create future generations. The large diversity of economically important marine species in the northeast presents an expensive and complex logistical challenge in terms of defining the physiological limits of each species, their capacity for adapting to new conditions, and establishment of effective breeding programs.

Aquaculture and fisheries managers need to consider the direct biological impacts of ocean and coastal acidification on economically important aquatic organisms, as well as the broader effects on ecosystems, pests and pathogens, predator-prey relationships, and overall marine environments. Not mitigating these impacts will result in threatening the ability of these species to survive in the region, replacement by other species that may not have as much economic value, and loss of the economic benefits and critical ecosystem services these organisms provide. Efforts are underway to address this; one current research project funded by NOAA is testing the efficacy of various diet regimes to bolster the resilience of hatchery-reared **blue mussels** to ocean and coastal acidification and warming. While there is increasing interest in conservation and restoration of marine habitats in the Northeast, a research gap remains in understanding how these activities may impact acidification locally or change ecological resilience to acidification.

Current and Needed Research on Impacts to Populations and Ecosystems

Research on the biological impacts of acidification should be linked to both single-species and ecosystem models to improve predictions of biological response in the region. The Northeast Fisheries Science Center's Atlantis model was used to consider both indirect and direct effects of ocean acidification on species and found that the impacts to the food web extended beyond species that were considered most vulnerable, which could lead to changes in fisheries yield and ecosystem structure [34]. Additionally, integrated assessment models for **Atlantic sea scallops** found that under high acidification conditions, there is a potential to reduce the sea scallop biomass by approximately 13% by the end of the century [35, 36]. Those conducting biological experiments should continue collaborating with modelers to identify key processes and details that are needed to enhance ecosystem models and improve predictions about how species biomass or habitat range may change. There are larger gaps in estuarine ecosystem modeling compared to open ocean modeling.

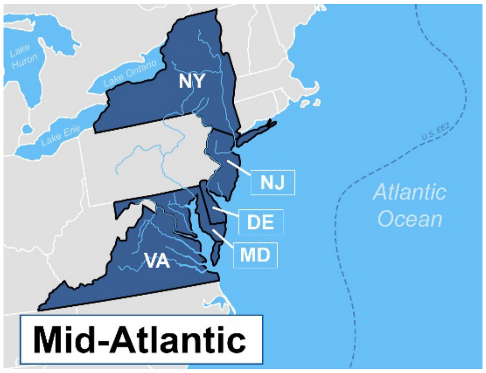
Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

The effects of acidification on both species and entire ecosystems need to be considered in the context of other environmental changes and stressors. The Northeast region is undergoing rapid temperature changes in both surface and bottom waters, and it is important to understand how warming will interact with the carbonate system and influence the impact to marine species [37]. Bottom waters in nearshore areas and on Georges Bank are warming the fastest, but information on subsurface carbonate chemistry is lacking. Organisms may also experience stress from low oxygen and nutrient pollution. Multi-stressor frameworks are needed to understand how species will respond to acidification in the context of these other environmental changes and how their adaptive capacity may be changed. These stressors should also be considered in model development.

2.0 Mid-Atlantic Region

Key Points

- The Mid-Atlantic is characterized by a large number of estuary systems, where nutrient pollution and biological activity have strong influence on coastal acidification.
- There has been substantial research on the impacts of ocean and coastal acidification on the eastern oyster, but more research is needed on other economically important species, such as the Atlantic sea scallop.
- Aquaculture is expanding throughout the region, and there is interest in offshore aquaculture development. This industry may be vulnerable due to the negative impacts of ocean and coastal acidification on shellfish.
- There is growing interest in state actions to address ocean and coastal acidification.



The Mid-Atlantic region includes the coastal and ocean waters of Virginia, Maryland, Delaware, New Jersey, and New York. The region is home to many important commercial shellfish and finfish fisheries and aquaculture industries that could be economically impacted by acidification. These industries and other marine resources also have important cultural meaning for the Mid-Atlantic states.

This region is characterized by a large continental shelf, multiple shelf break canyons, distinct estuary ecosystems (Chesapeake Bay, Delaware Bay, and the coastal bays in Maryland and Virginia), and barrier islands that enclose shallow coastal bays. Ocean and coastal acidification are affected by a variety of processes and factors, including seasonal changes in net-community production, nutrient loading, temperature, salinity, physical mixing, and air-sea gas exchange [15]. In the open ocean off the Mid-Atlantic, temperature and salinity are influenced both by polar water from the Labrador Current and warmer water from the Gulf Stream [38, 39]. Conditions vary along a latitudinal gradient, as the Gulf Stream waters are better buffered and less acidic compared to the colder currents flowing from the North. The water column is well-mixed from storms in the fall, but a thermocline develops during the spring, leading to a mid-shelf "cold pool" linked to distribution and recruitment for many ecologically and commercially important species [40]. There are also several upwelling regions on the coast and along the shelf [41].

Eutrophication and biological activity on or near the shore drive much of the variability in acidification in coastal regions [42, 43]. Estuaries are strongly impacted by riverine inputs, which contain freshwater, nutrients, and organic matter, all of which can affect the chemistry of coastal systems. In addition to spatial variation, large variation in ocean and coastal acidification has been observed, on decadal, seasonal, diel, and event-scale timescales. Seasonal stratification results in differing conditions between the surface waters and benthic environments, with increased acidification in bottom waters of eutrophic estuaries during the summer.

2.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

Understanding how the progression of ocean and coastal acidification and subsequent impacts to marine species and ecosystems will translate into impacts to human communities in the Mid-Atlantic is a high priority. More research is needed to understand community reliance on the resources at risk from increasing acidification, as well as what external or societal factors contribute to the sensitivity and adaptive capacity of communities.

Economic Impacts from Ocean and Coastal Acidification

The Mid-Atlantic supports a multitude of commercially and recreationally important finfish species, as well as critical shellfish fishing grounds, hatcheries, aquaculture beds, and oyster restoration areas. These industries provide economic value to the states and local communities, so it is essential to understand how they may be impacted by increasing acidification. The evaluation of the effects of ocean and coastal acidification to fisheries must be taken within the context of other changes, because landings and revenue can be driven by many factors – e.g. ecosystem and stock production, management actions, market conditions, and environmental change. This information will also be useful for understanding the costs and benefits of mitigation and adaptation strategies for communities, ecosystems, and economies, and can help promote integration of ocean and coastal acidification into regional planning and management.

Commercial Fisheries: In 2019, commercial fisheries landings for Virginia, Maryland, Delaware, New Jersey, and New York totaled $497 million [13]. Reedville, Virginia ranked fourth in the country for ports with the highest amount of fisheries landings. Fisheries economic information for each state is shown in Table 3. Valuable species in the region include **American lobster, Atlantic surfclam, blue crab, eastern oyster, menhaden, quahog clam, Atlantic sea scallop, squid, striped bass, and summer flounder**. Several of these are benthic calcifiers, which are expected to be sensitive to ocean and coastal acidification and may be exposed to more acidic conditions sooner. This includes the Atlantic sea scallop, which is one of the most important fisheries in the region, earning $134 million in landings revenue in 2019. While researchers are studying the impacts of acidification to some of these species, there is a need to link predictions of impacts to shellfish and finfish to economic models that project outcomes for fisheries sector and communities, taking into account concurrent environmental stressors, such as hypoxia and eutrophication [15]. Fisheries models could also help predict the threshold at which acidification will make harvesting or growing shellfish unprofitable by creating habitat suitability maps and incorporating changes in acidity. This is already underway in the New York Bight with research looking at the sea scallop fishery.

The vulnerability of fisheries will likely depend on the relative economic value of affected species. Surfclams and ocean quahogs primarily drive the declines in commercial revenue in the region (landings have been below quota and market dynamics have led to falling prices), and these are two of the species expected to be sensitive to increasing acidification [44]. Additionally, fisheries may already be vulnerable due to other environmental stressors, which could affect fishery sensitivity to future acidification. For example, warming seems to be shifting the distribution of surfclams and ocean quahogs, resulting in areas with overlapping distributions of species and increased mixed landings [44]. The cost of fishers relocating or taking other mitigation actions in response to acidification and other factors shifting the location of species is largely unknown and should be evaluated [15]. Given the regulations governing mixed landings, this could become problematic in the future and is currently being evaluated by the Mid-Atlantic Fishery Management Council. Overall, more research is needed to understand the impact of warming and other climate change impacts to fisheries and markets.

Table 3: The economic impact of the seafood industry in 2019 by state in the Mid-Atlantic region, including imports [13]. Landings revenue is the price fishermen are paid for their catch, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Landings Revenue	Jobs	Sales	Income
NEW YORK	$42,176,000	42,006	$6,492,898,000	$1,346,110,000
NEW JERSEY	$181,741,000	52,262	$10,808,641,000	$2,238,502,000
DELAWARE	$11,831,000	774	$156,991,000	$29,749,000
MARYLAND	$77,944,000	18,248	$2,778,243,000	$645,919,000
VIRGINIA	$184,269,000	23,523	$3,230,751,000	$803,235,000

It will also be important to evaluate the vulnerability of fisheries in the context of other economic drivers, such as maritime transportation and the potential for developing offshore wind sites. If all of the proposed sites in the Mid-Atlantic were developed, it could result in the displacement of an estimated 2-24% of total average revenue for major species in lease areas. However, impacts will differ spatially throughout the region, and more research is needed to understand how resulting changes to fishing effort and methods will impact the species and the industry [44]. Vulnerability assessments for each commercial species can be continually improved by assessing more localized data, such as at the state, county, or port level, as the importance of species will vary within the region. For example, the sea scallop industry is the most valuable in New Jersey; declines in sea scallop populations could impact the commercial fishery as well as the shoreside infrastructure supported by revenue from the fishery [36]. Lastly, potential impacts from other regions also need to be factored into assessments, as ocean connectivity inextricably links fishery populations throughout the eastern seaboard.

Recreational Fishing: Recreational harvest has been declining in the Mid-Atlantic due to multiple climate change factors, including warming temperatures, which can exacerbate ocean processes that may lead to ocean and coastal acidification. Key recreationally important species include: **striped bass, summer flounder, Atlantic croaker, black sea bass, bluefish, weakfish, scup, and spot tautog**. The decline of some of these species has been witnessed firsthand by many recreational anglers seeing shifts in target species populations and declining habitat quality. There is a need to research how ocean and coastal acidification and other environmental factors change the availability of suitable habitat for economically important species. Recreational fisheries remain an important industry; the majority of Mid-Atlantic catch comes from recreational rather than commercial fishing for some species, such as summer flounder and striped bass [13]. Many anglers support increased monitoring throughout the Mid-Atlantic and the expansion of existing monitoring systems to include broader habitat types (location, depth, etc.). Similar to commercial fisheries, studies have been conducted on several key recreational species (e.g. **summer flounder**) and forage fish (e.g. **Atlantic silversides**) at the base of the food web that support these fisheries; predicted impacts have not yet been linked to economic outcomes for the recreational industry [45]. Table 4 details the economic impact of recreational fishing for each state.

Table 4: The economic impact of recreational fishing expenditures 2019 by state in the Mid-Atlantic region [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
NEW YORK	10,360	$1,123,921,000	$479,264,000
NEW JERSEY	14,395	$1,900,220,000	$814,677,000
DELAWARE	1,534	$172,848,000	$63,097,000
MARYLAND	7,692	$839,473,000	$334,833,000
VIRGINIA	6,504	$711,537	$275,441

Aquaculture: Marine aquaculture represents another industry that may be impacted from ocean and coastal acidification and therefore needs to be evaluated for vulnerability. Aquaculture is expanding in every state in the region, with the potential for the development of offshore aquaculture throughout the coastal zone [15]. While the harvest of wild oysters is in decline, oyster aquaculture has increased significantly in Virginia and Maryland over the past decade [44]. Virginia ranks first in the country for hard clam production and first on the East Coast for eastern oyster production, with the aquaculture industry valued at $53 million in 2018. The State of Delaware has expanded shellfish aquaculture in the inland bays in the last decade (H.B.160, 2013), and has been encouraging the growth of the industry to meet economic and water quality goals. The number of shellfish hatcheries are increasing, along with increased production, and support an increasing number of jobs [46, 47]. Expanding monitoring at hatcheries and shellfish aquaculture sites could increase understanding of shellfish vulnerability and inform adaptation strategies.

Ecosystem Services: Oyster reefs act as natural infrastructure and provide important ecosystem services by mitigating the impacts of storms and flooding through shoreline stabilization and wave energy dampening, and by improving water quality [48, 49]. States in the Mid-Atlantic are also investing significant amounts of money into oyster restoration and oyster sanctuaries. Reefs could be impacted by changing ocean and coastal acidification, reducing their ecosystem services and putting state investments at risk. Research in the Chesapeake has detailed the economic value of the ecosystem services provided by oysters, conservatively putting the economic value of oyster habitat between $5,500 and $99,000 per hectare per year, excluding oyster harvesting, with oyster reefs recovering their restoration cost in 2-14 years [17].

Cultural Impacts from Ocean and Coastal Acidification

Many of the marine resources and industries that could be impacted by ocean and coastal acidification have cultural value that should be considered in future vulnerability assessments. Several economically important species such as blue crab and oysters have significant cultural value for the Mid-Atlantic. Many communities have historical ties to the fishing industry and consider it an important part of their heritage. Additionally, Tribal governments and Indigenous communities may have cultural or spiritual ties to marine resources; they should be engaged in science and monitoring and included in future vulnerability assessments. Some Tribes in the area have spiritual ties to marine mammals, some of which are endangered. While ocean and coastal acidification is not expected to affect marine mammals directly, there is potential for eventual indirect impacts via the food chain if their prey is impacted. This should be considered in future research.

Submerged maritime cultural resources, such as historic shipwrecks, may also be impacted by ocean and coastal acidification. Increasing acidification may weaken metal hulls or metal cargo on the vessels, but more research is needed to know at what pH this may happen. In addition to having historic value, heritage tourism is also an important contributor to Maryland's economy. There is also a need to understand how aquaculture and fishing contribute to food security in the Mid-Atlantic. The number of communities that depend on subsistence harvesting has not been quantified, but this could be incorporated into future vulnerability assessments.

Evaluating Sensitivity of Communities: Current Work and Research Gaps

Additional research is needed to determine exactly what factors should be used to analyze the social vulnerability of fishing industries and communities to ocean and coastal acidification. It is a NOAA priority to develop Climate-Induced Social Vulnerability Indices (CSVIs) with respect to ocean and coastal acidification to improve the understanding of how communities might respond to acidification in a resilient way. It may be useful to leverage existing work to characterize the general vulnerability of fishing communities (see information on NOAA Fisheries community social vulnerability indicators on page 3).

A nationwide vulnerability assessment published in 2015 assessed the vulnerability of U.S. shellfisheries to ocean and coastal acidification [4]. Communities in the Mid-Atlantic ranged from low to high vulnerability based on their assessment. There are two ongoing regional vulnerability assessments in the Mid-Atlantic that were funded to evaluate the vulnerability of the shellfish industry to ocean and coastal acidification. The first project was led by the Virginia Institute of Marine Sciences (VIMS) and focused on informing the vulnerability of shellfish hatcheries in the Chesapeake Bay to ocean and coastal acidification. This is important to understand, as the Chesapeake Bay is home to commercial shellfish hatcheries that supply seed to hundreds of shellfish farms within the Chesapeake. The shellfish industry relies on consistent hatchery production to sustain and expand operations that could greatly benefit from regional ocean and coastal forecasts and metrics. This project synthesized recent CO_2 system observations with long-term water quality parameters and combined observations in an existing baywide, high-resolution three-dimensional model. They developed forecasts of acidification and acidification metrics tailored to support decision-making needs of commercial shellfish hatchery and nursery operators.

A second project led by VIMS and Oregon State University is assessing the vulnerability of oyster aquaculture and restoration to ocean and coastal acidification and other co-stressors in the Chesapeake Bay. This project aims to identify when and where areas of the Bay will move beyond critical thresholds for successful oyster growth, along with where and when oyster stakeholders will abandon their ventures. With information on if and where it is wise to invest in growing oysters, those whose livelihoods are tied to healthy oysters and a healthy Bay will be able to better plan for the future.

Adaptive Capacity of Communities

When assessing social vulnerability, it will also be important to consider factors that increase the adaptive capacity of an industry or community. The following entities may serve to increase adaptive capacity to acidification by affecting the management of species or by involving industry and other community members in learning about and addressing ocean and coastal acidification. Engaging with stakeholders to understand what impacts their vulnerability and to collaborate in developing mitigation strategies is key.

- **Mid-Atlantic Fishery Management Council and Atlantic States Marine Fisheries Commission**: Both organizations contribute to fisheries management in the region. Management actions could be used to respond to future threats to managed resources, but there is a need to identify alternative strategies that maximize fisheries yield in increasing ocean and coastal acidification. Comprehensive management strategy evaluations and scenario developments will help assess the ability of fisheries management to react to changes in harvested populations. There will need to be support for economic modeling and sociological studies to determine the ability of fishers and aquaculturists to alter practices as populations change.
- **Mid-Atlantic Council on the Ocean (MARCO):** MARCO was established in 2009 by the governors of the five Mid-Atlantic coastal states. MARCO is the recognized Regional Ocean Partnership in the Mid-Atlantic, which seeks to protect and improve the health of the Mid-Atlantic region's ocean and coastal ecosystems and economies through regional ocean planning, data sharing, and collaborative efforts.
- **Mid-Atlantic Coastal Acidification Network (MACAN):** MACAN builds regional capacity around acidification by sharing information and coordinating with scientists, resource managers, government representatives, Tribes, industry members, and stakeholders. In addition to promoting research and monitoring priorities, MACAN facilitates information to policymakers, enhances awareness through stakeholder engagement, and works with industry representatives to share information about acidification and learn about their needs through surveys and meetings.
- **Mallows Bay-Potomac River National Marine Sanctuary**: This sanctuary protects the remnants of more than 100 World War I-era wooden steamships and other maritime resources and cultural heritage dating back nearly 12,000 years. The sanctuary's community partnerships could present an opportunity to engage the public on ocean and coastal acidification, as they are developing new public education opportunities and materials.
- **Northeastern Regional Aquaculture Center (NRAC)**: This is one of five regional aquaculture centers funded by USDA. Based in Maryland, NRAC has invested in salmon and oyster research, and could potentially support ocean and coastal acidification mitigation.
- **Sea Grant**: Sea Grant programs in each Mid-Atlantic state play a key role in supporting coastal research, education, and outreach. They are also well-poised to help communities identify needed adaptation measures through their aquaculture and fisheries specialists.

Additionally, the states in the Mid-Atlantic play an especially important role in building adaptive capacity. Each state in the Mid-Atlantic region has initiated efforts to address ocean and coastal acidification through state-led planning efforts. While these efforts have varied by each state, they represent an important opportunity to support monitoring and research needed to identify potential impacts to each state, to increase education and awareness to stakeholders, to identify impacts to economies and communities, and to build support for adaptation and solutions. States are exploring potential mitigation strategies (buffering incoming seawater at hatcheries, submerged aquatic vegetation restoration) that could increase adaptability if implemented.

- **Virginia**: Virginia plans to incorporate ocean and coastal acidification action planning during development of a comprehensive Virginia Ocean Plan.
- **Maryland**: Maryland's General Assembly established the Task Force to Study the Impact of Ocean Acidification on State Waters in 2014; the following year, the group published a report detailing the potential impacts of acidification to Maryland and recommendations for mitigation. In 2019, Maryland became a member of the International Alliance to Combat

Ocean Acidification (OA Alliance), and the next year the state published their ocean acidification action plan, which emphasizes their commitment to reducing greenhouse gas emissions and nutrient additions to waterways.

- **Delaware**: Delaware's Coastal Management Program is currently exploring how ocean acidification action planning can be incorporated into a statewide Ocean Resource Plan.
- **New Jersey**: New Jersey is in the process of developing an Ocean Action plan under the direction of the New Jersey Coastal Management Program. The state joined the OA Alliance in 2021 and is in the process of developing an Ocean Acidification Action Plan.
- **New York**: The NY Ocean Acidification Task Force has prepared a draft Ocean Acidification Action Plan to identify ways to mitigate acidification and minimize its adverse impacts to New Yorkers. This plan stems from the New York Ocean Action Plan's Action 15, which lists dedicated steps to combat ocean and coastal acidification and increase the resilience of ocean resources.

2.2 Knowledge Informing Social Vulnerability

2.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

The Mid-Atlantic region has some of the most widely studied estuarine and coastal systems in the world, which presents opportunities to maximize existing investments in monitoring infrastructure and utilize historical data to explain change over time. However, key questions about the attribution of specific drivers to acidification impacts on ecosystems and organisms require a more complete assessment of the carbonate system and land-sea interactions beyond the current monitoring design. Advancements in acidification monitoring could be made by enhancing existing platforms, filling research and monitoring gaps at key temporal and spatial scales, and building the capacity of the region to produce high-quality data for entry into shared repositories.

The monitoring system in the Mid-Atlantic has limitations that need to be addressed; information on existing monitoring assets is shown on a series of maps on the Mid-Atlantic Ocean Data Portal. Currently, data are, "too sparse/infrequent to describe variability at the precision required to validate regional biogeochemical models" and the observing system, "needs to better quantify primary drivers of vertically-resolved carbonate dynamics with emphasis at reactive interfaces (e.g., sediment boundary, land-ocean, etc.)" [15]. In order to design realistic exposure scenarios for biological experiments, researchers need better quantification of the controls on future acidification conditions, including anthropogenic CO_2, eutrophication, temperature, salinity, sea level rise, and freshwater runoff [50].

In 2019, representatives from the Mid-Atlantic Coastal Acidification Network (MACAN) assessed current monitoring of ocean and coastal acidification-relevant parameters to find where improvements are needed to advance understanding of regional acidification trends and impacts [40]. Overall, the network primarily consists of surface measurements within estuaries and near-shore coastal areas. The most widely measured parameter is pH, though at a low precision, and pCO_2, which is often measured at short time scales in a limited area (e.g. sensors installed on docks or buoys). Automated sensors for TA and DIC are still being developed, so the full carbonate system is rarely measured, with few exceptions, generally limited to studies of larger estuaries and coarse resolution sampling of the Mid-Atlantic coast [38, 51-58].

The first practical step in expanding the number of observations is to enhance existing monitoring; information on existing assets that can be leveraged will be described in the IWG-OA's monitoring prioritization plan. Future advancements to the monitoring network may focus on addressing gaps in spatial coverage, sampling frequency, and biological co-monitoring of ecological regions associated with biodiversity, commercial species, or restoration. Spatial needs include better vertical resolution with expanded depth profiling, benthic monitoring, especially in habitats of interest (e.g. oyster reefs, submerged aquatic vegetation beds), and attention to variations in riverine and marsh inputs [15]. Additionally, the region needs better coverage of key ecological features like the Mid-Atlantic Bight cold pool and deep sea coral, and more frequent shelf monitoring than occasional East Coast Acidification cruises offshore.

To improve temporal coverage, the Mid-Atlantic needs high-resolution, *in situ* monitoring, particularly near shore, to provide better understanding of short-term variability and distinguish the acidification impact of episodic events. While measuring all four parameters of the carbonate system at as many sites as possible is a good first step, next steps include concurrent monitoring of biological activity, co-stressors (hypoxia, temperature, eutrophication, riverine input, upwelling), and use of integrative monitoring measurements, such as carbonate dissolution and aragonite saturation states. These are important in understanding the natural conditions experienced by organisms, detecting the impact of co-stressors on these organisms, determining ecological repercussions of multiple species responses, and informing management. Currently, water quality and shellfish health monitoring are not always co-located, though collaborations with hatcheries could be leveraged for research and to provide acidification forecasts [15].

Ocean and Coastal Acidification Modeling

In the Mid-Atlantic, a wealth of high-quality models, particularly for the Chesapeake Bay, gives the region an advantage in turning new monitoring data into knowledge useful for understanding and predicting acidification. The EPA Chesapeake Bay Program and the NOAA Chesapeake Community Modeling Program have a suite of models of the watershed, estuary, airshed, and land use, which allow for scenario building to explore the impact of management actions and environmental changes. Additionally, there are two major, regional research groups currently involved in modeling acidification: VIMS and the University of Maryland Center for Environmental Science (UMCES). The VIMS Chesapeake Bay Environmental Forecast System (CBEFS) provides current and two-day forecasts of major biogeochemical parameters (salinity, water temperature, dissolved oxygen, and acidification). CBEFS will soon be available as an app and provide forecasts at smaller spatial scales, improving its utility for community stakeholders. VIMS also runs the Chesapeake Hypoxia Analysis and Modeling Program (CHAMP), which predicts impacts of climate change based on management actions. The UMCES group forecasts Chesapeake Bay seasonal hypoxia each year and has investigated the role of past, current, and future acidification and basification in Chesapeake Bay using a coupled biogeochemical-hydrodynamic modeling system called ROMS-RCA-CC (Regional Ocean Modeling System-Row Column AESOP-Carbonate Chemistry). These biogeochemical models include coupling to oyster growth models that include the effects of temperature, food availability, temperature, dissolved oxygen, and acidification, with data for 180 shallow-water sites where historical monitoring has taken place.

Most modeling work in the region is focused on understanding complex abiotic estuarine dynamics, and predicting biogeochemical conditions. Consequently, there are modeling gaps in the capability to predict acidification impacts on the environment, organisms, and communities. Major goals for filling those gaps in the Mid-Atlantic should include "improv[ing] ocean acidification forecasts on daily to decadal timescales in context with other environmental change [15]" and quantifying regional drivers of acidification (eutrophication, anthropogenic CO_2, freshwater runoff, temperature, river and marsh input, etc.) and how they affect biogeochemical processes that drive carbonate system dynamics [50], essential information for management decisions. Models will need to not only have predictive power, but allow researchers to interpret relationships between parameters, requiring both numerical and statistical modeling approaches.

Another critical need for models is understanding human vulnerability to acidification impacts, so models will need to integrate ecological and socioeconomic information. One example of a regional effort to do that is a NOAA Ocean Acidification Program-funded project at VIMS called Shellfish Thresholds and Aquaculture Resilience. The project will generate a tool for forecasting acidification thresholds for regional commercial shellfisheries by integrating a high-resolution biogeochemical model with information from studies of oyster physiology and sociological research into the local oyster industry. The model will predict when and how acidification may exceed thresholds of resilience identified by stakeholder groups, so they can take appropriate remedial action. UMCES is also in the final stages of a project that is linking biogeochemical conditions under future climates to metrics of oyster growth in aquaculture settings to inform an economic model of the vulnerability of oyster culture and potential for mitigation.

There are several priorities that would enhance the capabilities of Mid-Atlantic acidification monitoring to meet the aforementioned goals. First, a high-quality, integrated regional monitoring plan, as described earlier, would be key to quantifying the influences of various drivers and natural processes, and covering missing spatial areas, like the sediment-water interface. Yet, it is also clear that there is a need to invest more in synthesis of existing data to validate models of carbonate chemistry, characterize variability, and identify areas of vulnerability [15, 59]. More regional coverage could be achieved by supporting downscaling models, like the regional ocean modeling system (ROMS), to hindcast, nowcast, forecast, and predict acidification on the continental shelf [15]. Further, modeling effort must be directed not only at predicting future conditions, but at explaining the relative controls on carbonate system conditions and their expected duration and intensity. The former would inform future management actions, and both would be needed to design experiments that would allow for meaningful modeling of species and ecological responses. Finally, more specificity about the priority management questions and capabilities needed by the region would make the most of existing capacity and increase the alignment between model outputs and stakeholder needs. Regional organizations should consider everything from the local priority questions (e.g. What will the water chemistry conditions be in this aquaculture permit area in 2030? How do we ensure the population of a vulnerable species of interest remains at a particular level?) to the level of precision and certainty required for the answer. Such specificity will help focus modeling investments on the greatest needs, and make sure that outputs are provided at scales that are actionable.

2.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

The impacts of ocean and coastal acidification on species and habitats vary dramatically across the Mid-Atlantic region. Research indicates a high amount of variability, species-specific responses, and potential for phenotypic plasticity among bivalves, crustaceans, and fish [59]. In laboratory studies of acidification impacts, bivalves (i.e., **eastern oyster and hard clam**) had reduced larval growth, calcification, and survivorship [60-63], and changes in physiology (i.e., respiration, feeding rates) [64, 65]. Vulnerability also varies throughout the stages of larval development for bivalves, which will be important to consider in models [66]. Ocean acidification also negatively impacted juvenile **blue crab** survival, respiration, growth, development, and food consumption, with increased temperatures exacerbating these effects [67-69]. Additionally, experimental studies on finfish indicate negative impacts including diminished survival and accelerated developmental rate of **summer flounder** larvae in elevated CO_2 [31]. However, evidence is building that estuarine species like blue crab and summer flounder are likely to be more resilient to ocean and coastal acidification than off-shore species [70]. Moreover, studies on fishes of different ages suggest older fish are more tolerant than younger fish (e.g., juvenile scup) [71]. Submerged aquatic vegetation habitats, which are key nursery grounds and could possibly buffer against acidification locally, could be affected by acidification. Research in New York suggested that under more acidic conditions, seagrass would be outcompeted by macroalgae [72]. Current scientific knowledge highlights the complex responses of marine organisms to acidification and drives the need for further research.

Needed Research on Economically Important Species

While there has been significant research on certain species, studies on other species, particularly those that are economically valuable, are lacking. Of the 35 species managed by the Mid-Atlantic Fisheries Management Council, 24 (69%) have not been researched for ocean and coastal acidification, including several species important to the fishing industry [50]. While the **eastern oyster** has been well-studied, **sea scallops, ocean quahog, blue crabs, summer flounder, and longfin squid** have not been studied as extensively [59]. New research on **Atlantic surf clams** and the environmental factors that affect recruitment is underway in New York. **Hard clams** are an important aquaculture industry, but little is known about their physiological tolerance to acidification. Regarding oyster aquaculture, farmers are concerned about effects on top shell brittleness and brininess of meat (important for restaurants), seed mortality, and consistency of flavor [73]. In New York, Sea Grant is funding research on the resilience of **blue mussel** seed stock to ocean and coastal acidification from different regions for offshore aquaculture applications in Long Island Sound. These issues could be solved via breeding OA-resilient oyster species along with research on oyster species that occupy naturally low-pH waters [59].

Future studies on these species must include impacts to various life stages, potential for acclimation, adaptation, and transgenerational responses [59]. Future research should also include potential thresholds of acidification for a species and how acidification-induced changes in biotic interactions will affect food webs, population dynamics, and community structure [59]. For example, changes in planktonic communities can disrupt carbon transportation to subsurface and benthic waters [59]. More experiments are needed to address population and life-stage responses to ocean and coastal and other environmental stressors, including direct and indirect effects (predator-prey interactions, disease, pathogens) [15]. For wild-caught species, research needs to include field studies and observational efforts to understand natural conditions, how seasonality of conditions corresponds to timing of life stages, and *in situ* responses to acidification and dissolved oxygen [59]. Research on economically valuable species is critical for future management, as well as for the future of the communities whose income depends on the fisheries.

Current and Needed Research on Impacts to Populations and Ecosystems

Biologically informed models are needed to capture and enable population projections for population, community, ecosystem responses to ocean and coastal acidification, and co-stressors [15]. Models should be compared for sensitivity and robustness in the Mid-Atlantic, and experiments will be needed to ground truth predictions. Experiments should move beyond single-species models to incorporate predator-prey interactions, food web, and multiple stressors to describe ecosystem response and enable better predictions of the ecological impacts of acidification [59]. This research should also include indirect and direct effects and consider invasive species and changes to competition between species [73]. Moreover, there is a need to study multi-species assemblages in the lab and *in situ*. In the lab, research needs to incorporate natural variability of single and multi-stressors, and to differentiate whether pH, pCO_2, or saturation state is causing the effect on an organism [50]. In field research, studies need to include Free Ocean CO_2 Enrichment (FOCE) system experiments. Comprehensive, biologically informed models that are ground-truthed can not only fill current knowledge gaps but also advise future management of species populations. Ecological research and modeling will be valuable for informing potential impacts to restoration sites for oysters and submerged aquatic vegetation, aquaculture leases, and future projected suitable habitat areas.

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

The Mid-Atlantic region is experiencing changes in temperature, precipitation, and eutrophication [15]. However, it remains to be seen how these co-stressors will impact species vulnerability to ocean and coastal acidification, particularly estuarine-dependent species, as many of these co-stressors occur in estuaries and bays. It is also possible that climate change could reduce or change the location of suitable habitat for species, causing additional stress. An analysis of taxa studies found that 27% of taxa in the Northeast Continental Shelf Region, which includes the Mid-Atlantic Bight, were vulnerable to climate-related changes [26]. In bivalves, decreased salinity and increased temperature negatively impacted calcification [74, 75]. Multi-stressor ocean and coastal acidification studies (i.e., combined effects of CO_2 and hypoxia) on bivalve larvae reported decreased growth and survival [4, 61, 76]. Moreover, eutrophication may amplify ocean and coastal acidification and increase vulnerability of benthic shellfish in estuaries [4]. Future multi-stressor experiments on estuarine species should include temporally varying stressors that mimic environmentally relevant patterns [15]. This will assist in understanding how multiple stressors limit suitable habitat for various life stages.

3.0 Southeast and Caribbean Region

Key Points

- While much of the Southeast and Caribbean region has higher seawater alkalinity and lower carbon dioxide levels than in other regions, many coastal areas are experiencing higher rates of acidification than in the open ocean.
- The Southeast region has one of the largest recreational fishing industries and a growing aquaculture industry; many stakeholders are less concerned about ocean and coastal acidification compared to other co-stressors, such as hypoxia and harmful algal blooms.
- Coral reefs provide important coastal resilience, support a large tourism industry, and provide social value for communities in the Southeast and Caribbean; they are expected to be adversely impacted by ocean and coastal acidification.

This chapter covers the Southeast and U.S. jurisdictions in the Caribbean. The Southeast region, including North Carolina, South Carolina, Georgia, the east coast of Florida, and the Florida Keys, spans subtropical to tropical climate zones and encompasses diverse ecosystems and environmental conditions. Much of the coastal and shelf seawater chemistry is influenced by relatively high alkalinity waters of the Gulf Stream, with lower CO_2 levels and higher aragonite saturation states than

other U.S. regions [73, 77]. The Florida peninsula sits on a carbonate platform, which potentially contributes to the buffering capacity of the region, resulting in reduced rates of ocean and coastal acidification when compared to offshore waters [78]. In other coastal areas of the Southeast, the rate of acidification is higher than in the open ocean [79-81] due to strong influence from export of terrestrial carbon and organic matter to coastal waters from rivers, estuaries, and salt marshes; eutrophication-driven acidification; increasing water temperatures; and dredging/other management practices [82]. In the Caribbean, Puerto Rico, the U.S. Virgin Islands, and the surrounding waters between the Gulf of Mexico and the Atlantic Ocean also have higher aragonite saturation states than other oceanic regions at higher latitudes; however, they have experienced some of the most rapid rates of acidification and warming since pre-Industrial times [83-85]. Throughout the Southeast and the Caribbean, there can be high variability in the carbonate system, on timescales ranging from hourly to decadal, driven by factors such as temperature, nutrient enrichment, terrestrial runoff, tidal cycles, light-mediated primary productivity and respiration, changes in ocean currents and circulation patterns, salinity, and stochastic events [86, 87].

The Southeast and Caribbean include diverse habitats and ecosystems such as coral reefs, mangroves, seagrass beds, salt marshes, and other carbonate-dominated environments. Impacts of acidification to corals and coral reefs have been well-documented and include decreased growth rates and other physiological effects, and dissolution of carbonate seafloor sediments. These impacts are compounded by other stressors, such as increasing temperature, coral disease, and other human-induced stresses contributing to coral reef degradation. Estuarine and coastal marsh waters often have higher CO_2 levels and lower pH than offshore locations [77, 88-91], and mangrove lagoons and channels with reduced tidal flushing already experience low pH similar to conditions predicted for the open ocean at the end of the century [92]. Economically important shellfish species in these habitats are particularly vulnerable to impacts from acidification. However, seagrass beds may benefit from acidification, can elevate seawater pH and carbonate saturation states locally, and may provide a potential refuge for corals, shellfish, and other calcifying species [93, 94]. Additionally, episodic events such as tropical cyclones and harmful algal blooms can contribute to periods of aragonite undersaturation and higher acidity as a result of reduced photosynthesis and stress-driven increases in respiration [86, 95]. There is also evidence that *Sargassum* blooms can significantly decrease pH and oxygen when washed up in coastal areas [96]. The relative importance of these stochastic events varies greatly across the region.

The Southeast and Caribbean represents a wide range of communities and cultures, and many have important ties to the marine environment. Fishing and coral reefs are economically important, especially to tourism and recreational fishing industries, and also provide cultural value, including heritage, sense of place, identity, and pride, among others. Those that practice subsistence or traditional fishing are particularly dependent on marine resources for their well-being. The region is also experiencing rapid population growth and contending with other environmental concerns, such as harmful algal blooms and sea level rise. Puerto Rico and the U.S. Virgin Islands are small island territories where life is intrinsically linked to the ocean. The islands are distinct in their geography, culture, economy, and how they rely on the ocean [97]. It is important to understand how they will be impacted by ocean and coastal acidification, especially in the face of other environmental and social stressors, such as hurricanes, warming, sea level rise, higher poverty rates, and COVID-19.

3.1 Social Vulnerability: Understanding Impacts to Communities and Their Adaptive Capacity

Understanding how human communities will be impacted by future ocean and coastal acidification requires first identifying who is dependent on the species and habitats that are threatened. It is also key to understand a community's adaptive capacity: their ability to prepare for and respond to the threats of ocean and coastal acidification. Overall, little research has been done on the social or economic impacts of ocean and coastal acidification in the Southeast and Caribbean regions.

Economic Impacts from Ocean and Coastal Acidification

The following sections describe the various economic sectors that ocean and coastal acidification may impact, as well as factors that may affect the vulnerability of different industries or communities to these changes. Marine resources in the Southeast and Caribbean provide important value for communities, by supporting fisheries and active tourism industries, and by providing coastal protection. Ecosystems at risk from ocean and coastal acidification are inexorably linked to coastal communities, but there are severe gaps in evaluating the vulnerability of communities to acidification. How chemical and biological changes resulting from increased acidification translate into social and economic impacts is not well-understood; additional research on this will inform effective management, mitigation, and adaptation.

Commercial Fisheries — Southeast: Commercial fisheries have important economic value in the Southeast, with total commercial landings in 2019 valued at over $232 million. Table 5 shows the landing values, jobs, sales, and income by state. Major fisheries in the Southeast include **oysters, clams, lobster, shrimp, blue crab, stone crab**, and finfish (**flounders, groupers, king mackerels, snappers, swordfish, and tunas**); there is a relatively low diversity of commercially harvested species [13, 98]. Limited research indicates direct and indirect impacts of ocean and coastal acidification on some of these economically valuable species. For example, acidification reduced larval survival of blue crab, stone crab, hard clams, and eastern oysters in lab experiments (see section 3.2.2 for more information on biological impacts from acidification). However, there is a high degree of uncertainty in how these species will respond to increasing acidification in the Southeast and how this will translate to population effects, which limits predictions of economic impacts. Some commercial species in the Southeast have already experienced declines during the past decade, such as blue crab and shrimp, but the causes of these declines have not been identified.

Table 5: The economic impact of the seafood industry in 2019 by state in the Southeast region, including imports [13]. Landings revenue is the price fishermen are paid for their catch, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars. Data for Florida is for the entire state, although this chapter focuses on the East Coast.

	Landings Revenue	Jobs	Sales	Income
NORTH CAROLINA	$87,463,000	8,784	$947,383,000	$255,891,000
SOUTH CAROLINA	$25,113,000	1,739	$168,148,000	$51,035,000
GEORGIA	$24,271,000	19,883	$3,278,306,000	$725,453,000
FLORIDA	$237,631,000	81,647	$19,373,993,000	$3,619,588,000

Recreational Fishing — Southeast: The Southeast region has a large amount of recreational fishing. In both North Carolina and South Carolina, recreational fisheries are more valuable than commercial fisheries [13]. Key recreational species in the Southeast include **black sea bass, bluefish, dolphinfish, drum (Atlantic croaker and spot), drum (spotted seatrout), king mackerel, porgies (sheepshead), red drum, sharks, and Spanish mackerel**. Table 6 details the economic value of recreational fishing for each state in the Southeast. Similar to commercial fisheries, little is known about whether the industry is vulnerable to ocean and coastal acidification, although these species could be impacted directly or by indirect impacts to their prey.

Table 6: The economic impact of recreational fishing expenditures 2019 by state in the Southeast region [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
NORTH CAROLINA	16,421	$1,667,085,000	$584,477,000
SOUTH CAROLINA	9,109	$823,546,000	$273,012,000
GEORGIA	2,417	$206,670,000	$67,761,000
EAST FLORIDA	13,097	$1,345,167,000	$456,601,000

Commercial and Recreational Fisheries — Caribbean: In the Caribbean, commercial fisheries are largely artisanal or smaller in scale than in other regions. Research is needed to examine how ocean and coastal acidification will affect these fisheries and what the potential economic impacts could be, as direct links to acidification have yet to be made. **Caribbean spiny lobster**, **Queen conch,** and **cobia** are some of the species with economic importance. Fisheries may also be facing stress from other factors, such as illegal fishing or warming; this stress could be compounded by acidification, but more research is needed.

The U.S. Virgin Islands reported that there are about 250 licensed commercial fishers in the territory. Fishing has historically had profound importance in the U.S. Virgin Islands, and the territory's culture remains tied to the sea, its fisheries resources, and the livelihoods supported by the sea [97]. In St. Croix, fishing is less important economically than other industries, but remains important for sustenance and supports the island's tourism industry [99]. In St. Thomas, fishing is also deeply tied to the social identity of the community, but also has greater economic importance [100]. Researchers conducted a survey and collected data on fishermen and various aspects of their business, such as whether they owned their own vessel or what gear they used. They used cost information along with reported landings for the participants to estimate their profitability. They found that the low median fishing income was not sufficient to survive on the island [97]. These types of economic surveys may help evaluate the vulnerability of these communities, as fishermen struggling to make ends meet may be extremely sensitive to further declines driven by ocean and coastal acidification.

In Puerto Rico, commercial fisheries are an important source of income, sustenance, and employment to many coastal communities [101]. In 2008, the Puerto Rican small-scale commercial fleet landed about two million pounds of finfish and shellfish valued at $6 million. A 2008 census reported that there were 868 'active' fishermen, although there are likely many unlicensed and seasonal fishermen not captured under this. The lobster fishery is the most valuable commercial fishery in Puerto Rico yielding 265,518 pounds valued at U.S. $1,617,250 in 2008, with most landings on the West Coast.

The queen conch fishery is the second most important commercial fishery in Puerto Rico, yielding 208,676 pounds and U.S. $836,347 in 2008.

While commercial and recreational fishing provide important economic and cultural value to communities in Puerto Rico and the U.S. Virgin Islands, updated data quantifying this are lacking. NOAA's fisheries landing data and social vulnerability indicators are not inclusive of these communities, which is an important gap to address. Partnership with groups that manage fisheries or conduct outreach programs, such as Sea Grant Puerto Rico, could help address these gaps. The Puerto Rico Climate Change Council has suggested that certain demographic factors, such as the aging population, unemployment rate, poverty rate, and median income may all be important factors in considering the sensitivity of the island to ocean acidification and other aspects of climate change [102].

Aquaculture: There is a valuable shellfish aquaculture industry in the Southeast that is expanding. Oysters have been negatively impacted by acidification in lab experiments, and acidification has caused past production failures at hatcheries in the Pacific Northwest, indicating that the shellfish industry in other regions may be vulnerable as well. In South Carolina, the number of farmed oysters grew from 139,178 in 2014 to over 1.2 million in 2019, according to the South Carolina Department of Natural Resources. The South Carolina Sea Grant Program helped establish an in-state hatchery for oyster seed in 2014 and continues to provide technical assistance. North Carolina has 426 shellfish leases that cover a combined 2,197 acres. North Carolina is the only state in the Southeast to have launched a state Shellfish Initiative program based off of NOAA's National Shellfish Initiative. The North Carolina Shellfish Initiative brings together partners around the state to pursue the goals of job creation, protection of water quality, protection of shellfish health and sustainable management [103]. This also allows the state to receive more federal assistance in promoting oyster farming and habitat restoration. This could increase the state's adaptive capacity to respond to future threats to the shellfish industry, including ocean and coastal acidification. Additionally, the University of North Carolina Wilmington built and maintains a shellfish lease siting tool, which helps potential lessees to rapidly navigate the various layers involved in obtaining a lease, from the natural appropriateness of the site to the bureaucratic requirements. While not directly connected to acidification, tools like these serve to increase the overall resilience of growers.

There is also a growing queen conch aquaculture industry in Puerto Rico, focused on using farmed conch to restore the wild population and support a sustainable fishery. It would be valuable to understand if queen conch will be threatened by acidification, as this could affect restoration efforts.

Tourism: One study estimated the total value of reefs in Florida, Puerto Rico, and the U.S. Virgin Islands to be $1.45 billion in 2007 U.S. dollars [104]. Recent research examined the economic impacts of recreational fishing, snorkeling, and SCUBA diving in Florida's coral reefs. They found spending for reef-related recreational fishing trips in Southeast Florida supports approximately 3,787 jobs and generates economic output of $384 million; expenditures on reef-related diving and snorkeling in Southeast Florida support 8,668 jobs and generate about $902 million in total economic output yearly [105, 106]. Tourist spending in Puerto Rico is nearly $2 billion per year, resulting in nearly 30,000 jobs being sustained and $935 million in labor income [107]. Experiments have shown that acidification negatively impacts coral growth and structure (see section 3.2.2); more research is needed to determine if these negative effects on reefs will translate to economic losses to the tourism sector.

Coastal Resilience: A variety of habitats contribute to coastal resilience and other ecosystem services, including coral reefs, seagrass meadows, and mangroves. The U.S. Geological Survey led an effort to evaluate the role of U.S. coral reefs in hazard mitigation. Coral structures play a critical role in reducing flooding and erosion by dissipating shoreline wave energy, both in the Southeast and Caribbean. In Puerto Rico, corals provided annual protection to 4,221 people, $66,122,801 worth of buildings and $117,597,908 in economic activity annually, in 2010 U.S. dollars [108]. In the U.S. Virgin Islands, coral reefs annually protect 340 people, buildings worth $21,869,466, and $28,214,136 in economic activity, in 2010 U.S. dollars [108]. In Florida, coral reefs annually protect 5,663 people, buildings worth $355,960,998, and $281,052,199 in economic activity, in 2010 U.S. dollars [108]. More research is needed to couple these valuations with ecosystem forecasts that predict the effects of ocean and coastal acidification on coral reef structures, such as carbonate budget, reef framework persistence, and seafloor elevation modeling [110, 111]. Coupling these valuations with ocean and coastal acidification-specific forecasts for loss of coral reef structural integrity and rugosity may provide increased clarity for decision makers on the economic cost of ocean and coastal acidification-related reef degradation. Scenarios can also be updated to take into account sea level rise, population growth, economic change, and restoration [109]. This will be important for evaluating future impacts to coastal infrastructure and property, which could also affect blue economy sectors, such as coastal tourism and shipping. Most of the research in the Caribbean to date has focused on the value provided by coral reefs; more research is needed to understand how acidification may impact the ability of other blue carbon ecosystems to provide services such as storm buffering or erosion control.

Cultural Impacts from Ocean and Coastal Acidification

Some communities consume marine species vulnerable to ocean and coastal acidification (e.g., oysters, blue crab) for sustenance and as part of cultural traditions. These activities should be included in future socio-economic assessments of impacts from acidification; it is largely unknown how acidification might impact cultural resources or what factors could increase the vulnerability of communities to these changes. One community in the Southeast that is closely linked to vulnerable marine resources is the Gullah/Geechee Nation, who live in the area from Jacksonville, North Carolina to Jacksonville, Florida and the Sea Islands. Their culture is inextricably linked to the ocean, and they recognize that ocean and coastal acidification poses a threat to their way of life. They have traditionally been subsistence fishers, and rely on species such as oysters that are negatively impacted by acidification. In response, the Gullah/Geechee People joined the Ocean Acidification International Alliance and published an Ocean Action Plan. This plan centers around the goals of increasing scientific understanding of acidification, reducing the causes, protecting the environment and coastal communities from a changing ocean, expanding public awareness, and building sustained support. Many of these actions may increase the adaptive capacity of the Gullah/Geechee Nation and help to reduce the threat to their way of life. There may be other Indigenous Peoples in the Southeast who may be affected by ocean and coastal acidification, but more research is needed to identify these impacts.

In the Caribbean, fishing and coral reefs also contribute to community well-being, hold cultural significance, and contribute to food security. As mentioned previously, culture in the U.S. Virgin Islands remains deeply connected to the sea and fishing [97]. In Puerto Rico, coral reefs and associated fishing are deeply important socially as well. Surveys by the National Coral Reef Monitoring Program in Puerto Rico and the U.S. Virgin Islands found that it was not common for people to fish for the purpose of selling their fish. Respondents were more likely to fish for fun, for special occasions or cultural events, to give to extended family or friends, or to feed their household [112, 113]. 92% of respondents in the U.S. Virgin Islands agreed coral reefs were important to their culture, and 75% of respondents in Puerto Rico agreed coral reefs were important to their culture. Additional socioeconomic monitoring can help tease out the ways in which coral reefs and fishing contribute to community well-being. It is also possible that impacts to other ecosystems, such as estuaries, seagrass meadows, mangroves, and marshes may result in socio-cultural impacts as well.

Evaluating Sensitivity of Communities: Current Work and Research Gaps

It is largely unknown what factors are driving the sensitivity of communities to ocean and coastal acidification. An important component of assessing social vulnerability is first understanding the human connection to the ecosystem, addressing the interrelationship, the ecosystem services provided, and the community's perceived value of the ecosystem. This allows for a better assessment of the social and economic consequences of management policies, interventions, and activities.

There has been limited work to collect socioeconomic data related to ocean and coastal acidification in the Southeast and Caribbean, although the socioeconomic component of NOAA's National Coral Reef Monitoring Program includes survey questions on knowledge, perception, and awareness of key climate and ocean acidification related topics; see their socioeconomics homepage for more information about the information collected, as well as survey results and status reports. These surveys are done with household residents every 5-7 years in Florida, Puerto Rico, and the USVI. This information could be used to assess perception of reef health or awareness of ocean and coastal acidification in different areas, but additional questions related to acidification would be useful for future assessments. Surveys show that many residents are not familiar with ocean acidification and do not know whether it is a threat; while people may be vulnerable and may even be experiencing possible impacts, they may not really know the cause [114]. Additionally, NOAA's work to develop community social vulnerability indicators (see page 3) could inform creation of indicators specific to acidification. They have also compiled fishing community snapshots for states in the Southeast that provide recent data on these key indicators. The snapshots provide information on over 100 communities in the Southeast, and these data may serve as a starting point for identifying which communities are most reliant on marine resources.

There is a need to develop interdisciplinary tools that integrate socioeconomic data with ecological outcomes in order to assess and predict impacts to communities, such as mapping interdisciplinary indicators, like public perception of coral reef health, along with chemical and biological monitoring data [15, 115]. There may be an opportunity to use pre-existing tools and indicators that measure social vulnerability to climate change impacts, and to apply those techniques and institutional knowledge to ocean and coastal acidification for this region. Indicators should be spatially-explicit and able to be mapped, as this will make them a more informative communication tool for managers.

There is also a gap in being able to measure and predict the economic impact of ocean and coastal acidification in the region. Some work has been done to create economic valuations of various ecosystem services and fisheries; this should be coupled with ecosystem forecasts that include ocean and coastal acidification to estimate and predict economic impacts associated with increasing acidity. Understanding economic risk at smaller, local scales will allow communities to increase their adaptive capacity by informing their budget allocations, environmental mitigation, and research support.

To date, no assessments have been done of social vulnerability to ocean and coastal acidification specific to the Southeast. Ekstrom et al. identified North and South Carolina as having relatively high social vulnerability to ocean and coastal acidification as it relates to the shellfish industry [4].

Similarly, no formal ocean and coastal acidification vulnerability assessments have been done in the Caribbean. However, NOAA has funded a new project in Puerto Rico that will be designing a framework for a future vulnerability assessment through stakeholder interviews, science synthesis, and a regional workshop. There is a need to support additional vulnerability assessments in the Southeast and Caribbean.

Adaptive Capacity of Communities

Understanding a community's vulnerability and current capacity for resilience should be done with the aim of informing capacity-building initiatives that ensure a more resilient future for that community. It is important to understand which organizations, institutions, and policies may be able to help industries and communities respond to and prepare for increasing ocean change, including acidification.

Fisheries management organizations represent one area that may be able to adapt to acidification. The NOAA Fisheries Southeast Regional Office is responsible for the management and protection of marine resources within the U.S. economic exclusive zone (3-200 nm). They oversee management plans for a variety of species, including some that may be susceptible to acidification, such as the spiny lobster. Regulatory actions are recommended through the South Atlantic Fishery Management Council. Consideration of acidification in ecosystem-based management plans could be a potential avenue for responding to the impacts to fisheries. In the Caribbean, fisheries are overseen by the Caribbean Fishery Management Council, which has addressed ocean acidification as a concern in island-based fishery management plans for Puerto Rico, St. Croix, St. Thomas and St. John, acknowledging that proposed management actions will not directly address the impacts of ocean acidification (although they may increase resilience of ecosystems), but that ocean acidification monitoring should still be a priority in the region. It is also important to understand what affects the ability of fishermen to respond and prepare for acidification.

The Southeast Coastal Acidification Network (SOCAN) is one organization that plays an important role in engaging with stakeholders, in addition to increasing capacity for monitoring and research. The network is a collaboration between industry, scientists, research managers, and government representatives, and addresses acidification in North Carolina, South Carolina, Georgia, and Florida. Both SOCAN and the Gulf of Mexico Coastal Acidification Network (GCAN) work with communities on the West Coast of Florida; the organizations collaborate closely because of this overlap. Education and information-sharing with stakeholders could raise adaptive capacity, because stakeholders will be better informed about their risk and able to decide what mitigation actions are necessary. Learning and knowledge are key factors for social adaptation. Many stakeholders in the Southeast do not know if ocean and coastal acidification is progressing in their area, so they do not know if they are vulnerable and are not likely to perceive it as a threat [116]. During a SOCAN 2016 workshop, participants shared that they don't perceive ocean acidification to be a large threat to the shellfish industry in the Southeast. This could be because increases in acidification haven't been observed in the region, or because the industry is more concerned about other environmental threats, such as nutrient pollution or harmful algal blooms, which are more routinely monitored in the region.

Communities in the Caribbean are also concerned with other environmental threats, such as warming and coral disease. The Puerto Rico Climate Change Council is an organization that is working to assess the island's vulnerability to climate change and identify adaptation measures. They recognize ocean acidification as one threat to the island, and may be able to address it further in the future. Puerto Rico Sea Grant also engages with coastal communities to address climate change and impacts to fisheries; their relationships with the community make them poised to help address vulnerability to acidification as well.

3.2 Knowledge Informing Social Vulnerability

3.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

Monitoring is key for understanding the current levels and spatial and temporal variability in ocean and coastal acidification in the Southeast and Caribbean. Monitoring also contributes information on mechanistic drivers and co-stressors of acidification (i.e., river discharge, hypoxia, eutrophication, upwelling, atmospheric uptake of CO_2, biological consumption/production), and input parameters for predictive model algorithm development [82]. Monitoring in the region takes place through a variety of organizations and includes cruises (e.g., NOAA's East Coast Ocean Acidification Cruise), moorings (e.g., EPA's Indian River Lagoon National Estuary Program), and discrete sampling (e.g., NSF's Georgia Coastal Systems Long Term Ecological Research site). NOAA's National Coral Reef Monitoring Program collects important carbonate chemistry data at both fixed sites and through discrete sampling in coral reefs in South Florida, the Florida Keys, Puerto Rico, and the U.S. Virgin Islands; several sites have buoys that collect near real-time monitoring data. In the Florida Keys, they have conducted targeted quarterly cruises that capture large spatial coverage over the past decade, which is some of the most thorough monitoring in a shallow-water system. The following text describes the remaining gaps in ocean and coastal acidification monitoring for the regions.

Southeast: Open ocean monitoring in deep and shelf waters is limited because it generally relies on ships of opportunity. There are gaps in open-ocean monitoring during the winter season and in subsurface waters, both of which are needed to quantify seasonality in seawater chemistry for improved parameterization of ocean acidification within models. Deep-sea coral reefs are one habitat that is under-monitored but may be impacted by increasing acidification. Monitoring at key transition zones along climate and environmental gradients that affect ocean and coastal acidification will be valuable for model development. Additional monitoring is also needed to inform how different factors such as biological activity and river discharge affect variability in carbonate chemistry; this helps characterize the vulnerability to species and habitats of economic significance, such as shellfish hatcheries, oyster bed leases, public clam beds, and coral reefs [117]. Nearshore estuaries and coastal environments, such as wetlands, mangroves, and marshes that provide important ecosystem services (fisheries, tourism, recreation, essential fish habitat, coastal hazards protection), are currently under-sampled. Additional monitoring of ocean and coastal acidification and co-stressors, especially in areas impacted by human activities, will be valuable for informing the vulnerability of these habitats. Monitoring that captures variability and rate of change in these habitats is also important for informing biological research.

Caribbean: While acidification varies greatly across the Caribbean, current monitoring may not be sufficient to capture temporal and spatial variability of ecological relevance, especially at local scales [15]. There has not been a large-scale monitoring cruise to collect data of sufficient quality to detect long-term trends with a defined level of confide similar to the East Coast Ocean Acidification Cruise in the Caribbean; because it is a marginal sea, it receives lower priority for carbon inventory studies [15]. Surface sampling through the Ships of Opportunity Program is also limited. Increased frequency of carbonate chemistry measurements throughout the region is needed to capture regional events, such as mesoscale eddies, upwelling, or influence from the Orinoco River. The degree to which regional processes may begin to alter open ocean and coastal biogeochemistry need to be investigated. In coastal areas, there is a need to better understand diel and seasonal patterns in habitats of ecological and economic significance. Most efforts focus on understanding the exposure of coral reef ecosystems to acidification, but there is still a gap in monitoring at depth in these habitats. There is only one high-frequency carbonate chemistry monitoring station in the Caribbean, located in La Parguera, Puerto Rico; more high-frequency monitoring assets would increase the understanding of how biological processes modulate the natural carbon cycle at different spatial and temporal scales. Additionally, some ecosystems such as seagrass beds, mangroves, and soft-bottom sediment communities are not routinely monitored. Within all ecosystems, it is a priority to increase paired carbonate chemistry and biological monitoring to understand how acidification will affect ecosystem services. Monitoring should target species with known sensitivities, especially those that play an important role in ecosystem health, such as calcifiers and bioeroders. Monitoring programs should incorporate quantification of net community calcification and net community productivity, as these are important metrics.

In both the Southeast and Caribbean, there is good potential for additional partnership and collaboration among federal, state, and local agencies and institutions to leverage infrastructure and human capital to improve and expand acidification monitoring efforts. The Southeast Coastal Ocean Observing Regional Association (SECOORA) supports several moorings that could be leveraged to increase ocean and coastal acidification monitoring, including the stations NDBC 41004 in South Carolina, NDBC 41064 in North Carolina, and NDBC 41037 in North Carolina. The United States Caribbean Coastal Ocean Observing System (CARICOOS) may have existing monitoring assets that could be leveraged to expand spatial coverage of ocean and coastal acidification monitoring in the Caribbean. Additional monitoring assets that can be leveraged will be described in the IWG-OA's monitoring prioritization plan.

Ocean and Coastal Acidification Modeling

Models play an important role in characterizing the past, current, and future levels of acidification, often extrapolating information provided by monitoring assets to describe larger regions. Observing data in the region are used in existing modeling efforts, including the Ocean Acidification Product Suite developed for the Greater Caribbean region and now extended to include the East Coast. The Ocean Acidification Product Suite utilizes satellite data and a data-assimilative hybrid model to produce monthly maps of surface water carbonate system components [83].

Global data synthesis and process-based global models have also provided estimates for coastal U.S. regions, including the Southeast [118]. More recently, modeling efforts are being supported to address seasonal patterns of the carbon system [81]. Sustained support for modeling efforts is needed as they still show significant discrepancies in some regions [119-122]. The modeling portfolio for the region should be expanded to include nowcasts and forecasts, in addition to integrating ecosystem parameters and including robust validation. Acidification in nearshore environments is strongly influenced by benthic communities as they alter the carbonate chemistry of the overlying water column. Efforts are underway to understand these interactions by linking hydrodynamic flow and benthic community composition to local carbonate chemistry; this will lead to statistical models that better link projection models of oceanic carbonate systems to reef-scale acidification impacts. The application of this modeling framework in the Florida Keys is still in preliminary phases. There is also a need to develop new models to increase geographic coverage within the region. This will rely on down-scaling large scale models to accurately capture meso- to local-scale variability.

3.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

Shallow-water and coastal habitats in the Southeast and Caribbean include coral reefs, mangroves, seagrass beds, salt marshes, and carbonate sediments. Many of the species found within these ecosystems can also be found within the Gulf of Mexico; the ecological impacts of ocean and coastal acidification and research gaps are addressed in Chapter 4.

Coral Reefs: Ocean and coastal acidification is a significant threat for calcifier-dominated ecosystems such as coral reefs, which have been well-studied with regards to acidification compared to other habitats [123, 124]. Seven coral species in the Caribbean have been listed as threatened under the Endangered Species Act, underlying the importance of understanding the risk posed by acidification. It is well documented that ocean acidification decreases coral calcification rates [125-128]. Acidification can also negatively affect wound recovery, reproduction, and recruitment of corals, which can lead to impacts at the community or ecosystem scale [129-131]. However, it is also clear that responses are intra- and inter-specific. For example, the stony coral *Acropora cervicornis* exhibited reduced calcification under ocean acidification, but accelerated growth rates in more natural daily fluctuations, while some coral species may be able to mitigate adverse effects of ocean acidification by increasing feeding rate and lipid content [132, 133]. Ocean and coastal acidification enhances bioerosion of sponges and results in degradation to reef structure, in addition to causing physiological responses, such as changes in growth rate or skeletal density, in numerous coral reef species [110, 134, 135]. Caribbean and Atlantic coral reef degradation may occur more rapidly than previously predicted, with a shift towards increased sponge and macroalgal abundance [110, 136]. In contrast, a recent meta-analysis projected that coral calcification in the Caribbean Sea will decrease under ocean warming, but not ocean acidification [137]. Research also suggests that octocorals may be resilient to acidification and be able to persist under future ocean and coastal acidification in the Caribbean [135].

Along the Florida Reef Tract, despite showing overall net carbonate production, reef calcification is 10% of historical rates and those reefs farthest north are eroding faster than they are being built [111, 138]. Observations from the La Parguera, Puerto Rico and Cheeca Rocks, Florida Keys CO_2 time series demonstrate that dissolution processes dominate calcification throughout the year, with higher rates during late summer and fall, when a combination of stressors (high temperature and acidity) co-occur with more frequency. Since 2009, coastal reef areas in the southwest of Puerto Rico have experienced a decadal increase of 3% in seawater CO_2 concentration and 2% in acidity. Conditions favorable for coral reef carbonate sediment dissolution have continued to increase since 2009 and persist by as much as 90% of the year. Moreover, the concentration of calcium carbonate minerals has decreased by about 1.7% in the last decade, making calcification more difficult for marine organisms (e.g., corals) and weakening marine carbonate structures [87].

Deep-water Coral Communities: At depth, cold water coral habitats are found in the Southeast, such as Oculina Banks (*Oculina varicosa*) off the east coast of central Florida and *Lophelia pertusa* and *Enallopsammia profunda* reefs off North Carolina and on the Blake Plateau off South Carolina through the Straits of Florida [139]. These habitats provide nursery grounds and habitat for economically important fish species and are also vulnerable to ocean and coastal acidification. Hydrographic cruise data provides evidence that low aragonite saturation waters are already impinging on those habitats [38]. *Lophelia pertusa* in the Gulf of Mexico have shown intraspecific variation in calcification under experimentally low pH, but survive under aragonite saturation of 1.3, *in situ* [140-142]. However, these studies did not investigate the impact of dissolution on reef frameworks, and no studies have been conducted into the effect of ocean acidification on cold-water corals in the South Atlantic Bight.

Crustaceans: Ocean and coastal acidification alters the ability of **Caribbean spiny lobster** to use chemosensory cues to find suitable shelter, potentially reducing survivorship, and can disrupt the orientation of postlarval individuals, increasing post-settlement mortality [143, 144]. Under ocean and coastal acidification, the size and survival of **Atlantic blue crab** larvae have been shown to decrease, while **stone crab** embryonic development, hatching success, larval vertical swimming, and larval survivorship is reduced, limiting population growth and dispersal [145-148].

Mollusks: **Queen Conch** are expected to be vulnerable to ocean acidification due to the composition of its shell, which is 99% aragonite; preliminary data suggests warming and ocean acidification will impact larval survival and calcification, changing dispersal and settlement patterns [149-151]. Under experimentally elevated CO_2, larval **hard clams** exhibit decreased survivorship, delayed metamorphosis, and reduced size, especially under the high CO_2 levels that can occur in southeastern estuaries [63]. Similarly, juvenile hard clams have been shown to reduce shell micro-hardness and fracture toughness under elevated CO_2 [152]. Ocean and coastal acidification has been shown to have effects on early life stages of **oysters** in lab experiments, raising concerns about bottleneck effects to populations.

Fishes: Significant effects have been shown to fish, but these impacts vary among taxa and life stages (e.g., summer flounder has shown sensitivity). Under ocean acidification, larval **Cobia** are impacted through alteration of otolith (ear stone) size, density, and mass, directly impacting its mechanics and sensory function, which will likely impact survival, dispersal, and recruitment [153, 154].

Needed Research on Economically Important Species

In the Southeast and Caribbean, crustaceans, mollusks, fish, and corals are economically important organisms which are especially vulnerable to ocean and coastal acidification. However, for most of the economically important species in the region, more research is needed to fully understand how populations will be impacted, which will inform how fisheries will be financially impacted. Other regional commercial fisheries besides Cobia have not been studied (i.e., **flounders, groupers, king mackerels, snappers, swordfish, and tunas**), and further study is needed to understand the impacts of ocean and coastal acidification on the physiology of these species at multiple life stages. There is also a need to consider how their prey will be impacted by acidification. Most studies on mollusks have focused on a single life stage, without considering the synergistic effects of other stressors (water quality such as temperature, food availability) or the potential for adaptation or acclimation [155]. Multi-generational and multi-stressor experiments on species from geographically distinct locations in the Southeast and Caribbean will better elucidate the expected impacts to commercial mollusk species.

Additional research into genes or molecular mechanisms that give higher resilience would be beneficial for commercial species; this intraspecific variability in adaptability could be leveraged by managers through selective breeding of corals, for example. Studies should incorporate genotype into ocean and coastal acidification response experiments across taxa, assess how the transcriptomes and proteomes of key taxa are influenced by ocean acidification (for resilient vs. sensitive individuals), and identify genomes and gene expression of taxa existing in ocean acidification hotspots [15]. There is also a need for further research into how exposure to variability in carbonate chemistry will affect future resilience. For some Caribbean corals, acclimatization to highly variable environments did not increase resilience to future high-pH conditions [156].

Current and Needed Research on Impacts to Populations and Ecosystems

Within the Southeast and Caribbean, research must consider broader ecological complexity when evaluating ocean and coastal acidification's impacts on ecosystems (i.e., consider multi-species community response and species interactions). Research efforts must move from micro- to meso- and macro-scales to include effects at multiple trophic levels, shifts in community structure and function, population dynamics, and biogeochemical cycles and feedback mechanisms [82].

There is also a need to develop habitat persistence models (e.g., carbonate budgets) that forecast reef habitat permanence under future ocean and coastal acidification, taking into account the sensitivity of calcifiers and bioeroders [110]. Additional research on the influence of ocean and coastal acidification on bioeroding taxa is needed, as the balance between these and calcifiers determines the status of coral reefs. Previous experiments suggest ocean acidification will accelerate chemical dissolution by these taxa, and the relative impact of bioeroders may increase as coral cover declines, making bioerosion the driver of reef carbon budgets. Other environmental stressors such as warming will likely impact this dynamic. Spatiotemporal information could also be applied to carbonate budget models to identify additional hotspots and refugia within the region, where species may have developed increased resilience.

The importance of biogeochemistry within sediment pore waters and effects of acidification on carbonate sediment dissolution should be evaluated to improve understanding of how this relates to ecosystem function, seafloor structure and elevation, and services provided such as coastal protection, particularly for coral reefs and other carbonate environments [109, 111, 157-169]. Carbon stores in coastal sediments need to be estimated, as sediments release both inorganic and organic CO_2, decreasing pH locally; this is particularly important in South Carolina and Georgia marshes.

While many researchers have focused on coral reef ecosystems, blue carbon ecosystems have not been as well studied and still hold important economic value for the region. Additional research is needed on seagrass, mangrove, and salt marsh habitats, including how organic sources in these environments affect the ecosystem. Preliminary results show that seawater $p\mathrm{CO}_2$ values in mangrove and inshore channels in La Parguera are very high [160]. Also, more research is also needed on microbial communities to translate to ecosystem level effects, especially on micro-zooplankton grazers, who affect energy and carbon transfer to higher trophic levels [98]. The taxonomic and functional diversity may give the group resilience to ocean and coastal acidification, but the shifts in community could have important effects.

Naturally acidified ecosystems, such as volcanic CO_2 vents, provide a means of investigating complex ecosystem-level responses to acidification, where long-term exposure (decades to centuries) can reveal the implications of subtle responses, as well as acclimatization. Those in the Caribbean are currently understudied, and should be leveraged to conduct *in situ* ocean acidification observations and experiments [161].

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

In the region, and especially in the Florida Keys, Puerto Rico, and the U.S. Virgin Islands, coastal ecosystems such as mangroves, seagrasses, and coral reefs (along with their associated ecosystem services) are of significant importance to local communities and their livelihoods [84, 162, 163]. However, in the case of coral reef ecosystems, the evaluation of long-term impacts of ocean and coastal acidification will become even more challenging because over the last several decades these ecosystems have been subject to degradation due to overfishing, disease, and degrading water quality, in addition to rapid ocean warming, sea level rise, and storm damage resulting from climate change [84, 111, 163-165]. Further research is needed to better understand the effects of multiple stressors, which may result in unforeseen nonlinear responses in Southeast and Caribbean ecosystems; this should integrate spatial and temporal human use.

Previous studies of co-stressors have determined that coexisting species can respond differently to ocean and coastal acidification [166-168]. Therefore, additional research of the differential effects of ocean and coastal acidification on coexisting species with regards to variability in co-stressor conditions is needed. Ocean and coastal acidification alone does not induce the same response in single plankton or microbe species or complex assemblages as do conditions where temperature and/or nutrients are also manipulated [166, 169]. For example, performance (fatigue behavior and mate-guarding behavior) of adult Atlantic blue crab declined in moderate hypoxia (50% air saturation), but improved when seawater pCO_2 was elevated to an extreme under the same hypoxic conditions [170]. Other studies showed the magnitude of response varied among taxonomic groups and life stages, and sensitivity to acidification increased when taxa were concurrently exposed to elevated temperature, highlighting the importance of considering the effect of co-stressors [167].

Ocean and coastal acidification may result in a shift in plankton assemblages towards an increase in harmful algal blooms, such as Florida red tide (*Karenia brevis*) which affects human health, the survival of marine organisms, and can ultimately disrupt coastal economies [171, 172]. Some harmful algal blooms will grow faster or become more toxic in acidified waters, although this is not uniform across genera, species, and strains. Harmful algal blooms can cause coastal acidification and hypoxia through their decomposition. The co-effects of harmful algal blooms, ocean and coastal acidification, and hypoxia on aquatic life are largely unexplored, with few studies to date, but it is likely that the co-occurrence of these stressors will become more common in the future [12, 95, 173, 174].

Additionally, research is needed into the effects of ocean and coastal acidification on macro-algae, specifically *Sargassum*. Over recent decades, the occurrence of *Sargassum* strandings on beaches in the Caribbean has increased, likely due to eutrophication and warming. However, these strandings can cause economic impacts from fish kills and reduced water quality. Therefore, it will be important to understand whether this threat will be exacerbated by ocean and coastal acidification; researchers should build the capacity to monitor hypoxia and acidification during *Sargassum* inundation events in the Caribbean near-shore.

4.0 Gulf of Mexico Region

Key Points

- Gulf of Mexico carbonate chemistry is highly complex but remains relatively under-observed with respect to ocean acidification and poses critical knowledge, research, and monitoring gaps that limit our current understanding of environmental, ecological, and socioeconomic impacts.
- Many industry stakeholders in the Gulf of Mexico are more concerned with hypoxia or harmful algal blooms than ocean and coastal acidification. However, these stressors often interact, and little research has been conducted to evaluate these co-stressors.
- International collaboration with Mexico and Cuba is key to understanding the influence of basin-scale ocean acidification drivers and dynamics in the Gulf of Mexico; however, modeling approaches paired with the limited available observations is a valuable strategy for filling monitoring gaps in the Gulf of Mexico.

The Gulf of Mexico spans more than 1,500 miles of U.S. coastline along the states of Texas, Louisiana, Mississippi, Alabama, and Florida, and includes coastal zones of Mexico and Cuba, making international coordination and collaboration key to understanding ocean and coastal acidification throughout the entire region. The Gulf of Mexico is home to highly diverse marine, coastal, and estuarine environments that store and cycle blue carbon and ecosystems that contribute significantly to the U.S. Blue Economy [1, 175-179]. These systems contain several habitats and species including shellfish, coral reefs, and carbonate seafloor that are vulnerable to acidification. Various processes in the region contribute to ocean and coastal acidification, which affects these diverse ecosystems and communities.

Ocean and coastal acidification has been documented across much of the Gulf of Mexico, although conditions are highly variable and long-term sustained observations are limited, particularly in the open ocean. Regional field studies and Gulf-wide observing campaigns have demonstrated considerable carbonate chemistry variability across the Gulf region over time [38, 39, 42, 180-185]. Both model simulations and field studies suggest a significant decline in pH across the Gulf of Mexico due to anthropogenic ocean acidification during recent decades [186]. While the region has higher carbonate mineral saturation states compared to northern regions, pH and saturation state are decreasing rapidly in the region, making it one of the faster changing environments due to ocean acidification [84].

In addition to the absorption of anthropogenic CO_2, acidification in the region is influenced by a complex interplay of processes and stressors including increasing water temperature, ocean circulation, riverine influence, eutrophication, harmful algal blooms (HABs) and hypoxia [186, 187]. The Mississippi-Atchafalaya River Basin drains a watershed of over 1,245,000 square miles into the Gulf of Mexico, leading to relatively high alkalinity in the central Gulf [188]. Within the Gulf region, vulnerability to ocean and coastal acidification is largely unknown, due to the limited acidification-related datasets and small number of Gulf-specific biological sensitivity studies. Continued advancements in monitoring, modeling, and further Gulf of Mexico dedicated biological research have the potential to fill this existing knowledge gap, helping researchers to understand the impact of ocean and coastal acidification on ecosystems and society.

4.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

Federal, state, and local governments in the Gulf of Mexico are concerned with knowing how ocean and coastal acidification may affect coastal communities, but there are challenges in understanding the socioeconomic and cultural impacts. More work is needed to understand the economic and social value marine resources hold for communities across the Gulf. Additionally, the region represents diverse cultures, interests, and needs across commercial and recreational sectors, resource management, Tribal heritage, and subsistence communities. This section examines the potential impacts to communities from ocean and coastal acidification and the gaps in understanding social vulnerability.

Economic Impacts from Ocean and Coastal Acidification

Commercial and Recreational Fisheries: The seafood industry in the Gulf of Mexico generated nearly $6 billion of income in 2019 and supported over 160,000 jobs. The region also has a high amount of recreational fishing activity, which generated over $1 billion in income in 2019 and supported over 40,000 jobs [13]. Tables 7 and 8 describe the economic importance of commercial and recreational fisheries for each state in the region.

Table 7: The economic impact of the seafood industry in 2019 by state in the Gulf of Mexico region, including imports [13]. Landings revenue is the price fishermen are paid for their catch, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars. Data for Florida are for the entire state, although this chapter focuses primarily on the west coast of Florida.

	Landings Revenue	Jobs	Sales	Income
TEXAS	$209,279,000	39,384	$5,415,475,000	$1,322,455,000
LOUISIANA	$317,319,000	27,686	$1,708,923,000	$628,327,000
MISSISSIPPI	$58,661,000	7,506	$399,975,000	$157,334,000
ALABAMA	$57,662,000	10,058	$495,606,000	$194,938,000
FLORIDA	$237,631,000	81,647	$19,373,993,000	$3,619,588,000

Some of the most important species for commercial fisheries include **blue crab, shrimp, oysters, tuna, red snapper, spiny lobster, menhaden, mullet, and grouper**. Species of importance for recreational fisheries include **Atlantic croaker, Gulf and Southern kingfish, sand and silver seatrout, sheepshead, red snapper, southern mackerel, and striped mullet**. Shellfish accounted for 75% of landings revenue for commercial species in 2018 and are expected to be some of the most sensitive species to ocean and coastal acidification.

While finfish may not be as sensitive to acidification as shellfish in terms of direct physiological impacts, they may be negatively impacted indirectly by changes to their prey. However, gaps remain in our understanding of ocean and coastal acidification dynamics, species and ecosystem impacts, and our ability to directly link species response to ocean and coastal acidification, which complicates estimating how commercial and recreational stocks will respond and the resulting economic impacts. As species and ecosystem models are improved to account for the impacts of ocean and coastal acidification, these results should be linked to economic models as well.

Table 8: The economic impact of recreational fishing expenditures 2019 by state in the Gulf of Mexico region [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
TEXAS	3,996	$507,678,000	$164,258,000
LOUISIANA	5,333	$590,834,000	$187,285,000
MISSISSIPPI	1,399	$120,974,000	$40,061,000
ALABAMA	8,198	$794,233,161	$233,153,000
WEST FLORIDA	23,301	$2,497,490,000	$849,282,000

Ecosystem Services: The level of ecosystem services provided by marine ecosystems, as well as the level of economic activity that they support, depends on both the health of the resources (which is influenced by environmental stressors, including acidification) and the demographic and socioeconomic conditions in affected Gulf of Mexico communities. It is more challenging to monetize ecosystem services than commercial fisheries landings or marine-related tourism, but valuation of ecosystem services illustrates the importance of marine ecosystems. In one single estuary in south Texas, oysters were estimated to remove more than 750 kg of nitrogen annually; that single ecosystem service was valued at nearly $294,000 annually based on the replacement cost of a biological nitrogen removal process during wastewater treatment [189]. Thus, the deterioration of healthy natural environments from acidification (and other environmental stressors) could lead to substantial environmental engineering expenses.

The total economic value of services provided by U.S. coral reefs is estimated at $3.4 billion per year [104]. Gulf of Mexico coral reefs provide protection to coastal communities from hazards such as storms, waves, and erosion and serve as habitat and nurseries for many economically important species. Some reefs are already experiencing net dissolution due to ocean and coastal acidification that contributes to seafloor elevation loss [111, 190]. One study estimated that the coastal protection lost due to projected coral reef degradation would increase flooding, affecting over 7,300 people annually and leading to direct damages to buildings of over $385 million and indirect damages of lost economic activity of over $438 million, all in 2020 U.S. dollars [109].

Cultural Impacts from Ocean and Coastal Acidification

There are gaps in assessing how ocean and coastal acidification will affect marine resources that hold social or cultural values. Marine species and habitats may contribute to community well-being, hold spiritual or cultural value, or contribute to other related non-economic values. Communities may also rely on harvesting marine species for food security. Although it is more difficult to assess this type of value, this should be considered in future vulnerability assessments for the region.

Evaluating Sensitivity of Communities: Current Work and Research Gaps

There is a need for detailed vulnerability assessments specific to ocean and coastal acidification in the Gulf of Mexico. There are currently no non-coral studies in the Gulf of Mexico that describe potential socioeconomic impacts from ocean and coastal acidification, and there are currently no socioeconomic studies specific to the Gulf of Mexico that describe potential impacts of ocean and coastal acidification or resulting social vulnerability impacts on nearby and regionally-dependent populations.

Economic and acidification data at smaller geographic scales (e.g., county or community level) will allow for more detailed vulnerability assessments. Coastal acidification can vary at small scales due to localized drivers, which could lead to spatial variability in socioeconomic impacts within the Gulf of Mexico. It is also important to understand what increases the sensitivity of communities to economic declines in fisheries driven by ocean and coastal acidification. The Gulf has multiple environmental stressors that negatively impact coastal communities and could make them more vulnerable to stress from acidification, including hypoxia, harmful algal blooms, heatwaves, sea level rise, and tropical storms. Communities may also be under stress from non-environmental issues such as the COVID-19 pandemic, increasing gentrification pressure, or poverty. It is unknown how these compounding stressors could increase a community's vulnerability to acidification.

Synthesis of socioeconomic data on potentially impacted species, ecosystems, industries, and resources is needed to begin developing vulnerability assessments at the regional and sub-regional scales. It may be valuable to develop social indicators specific to acidification to evaluate the vulnerability of coastal communities. This could be informed by existing social indicator frameworks, such as the community social vulnerability indicators developed by NOAA Fisheries (see page 3).

Adaptive Capacity of Communities

In addition to evaluating the economic and social impacts of ocean and coastal acidification and how sensitive communities are to these impacts, future vulnerability assessments should also consider the ability of communities to respond and adapt to acidification. Communities may have resources to manage other environmental stressors, such as nutrients, and for habitat restoration activities that may help mitigate impacts from ocean and coastal acidification. Organizations may be able to take adaptive actions either through resource management actions or by educating and involving industry and other community members in addressing acidification. One key organization is the Gulf of Mexico Coastal Acidification Network, which works directly with scientists, resource managers, stakeholders, and educators to facilitate, synthesize and communicate the state of ocean and coastal acidification science in the region. NOAA Sea Grant Programs play a key role in supporting coastal research, education, and outreach. They are also well poised to help communities identify needed adaptation measures.

State governments can increase adaptive capacity to ocean and coastal acidification through management actions. Following the establishment of dedicated U.S. federal support for ocean and coastal acidification science, a number of states across the United States passed legislation with direct mentions of ocean or coastal acidification. However, the states along the Gulf of Mexico (Florida, Mississippi, Louisiana, and Texas) have yet to pass legislation that recognizes acidification, though Mississippi has proposed legislation twice. Despite this legislative inaction, state-funded agencies in the Gulf have made meaningful contributions to ocean and coastal acidification monitoring. For example, the Texas Commission on Environmental Quality and Florida Department of Agriculture and Consumer Services collect and maintain estuarine water quality data and have made complementary measurements of pH and total alkalinity (since 1969 and 1980, respectively). While data have been invaluable for understanding long-term trends in estuarine carbonate chemistry, their coverage across the highly dynamic estuarine environments along the U.S. Gulf of Mexico coastline is limited; furthermore, the vast non-U.S. regions of the Gulf of Mexico lack such historical, estuarine carbonate chemistry measurements [78, 182, 191].

4.2 Knowledge Informing Social Vulnerability

4.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

Current U.S.-led ocean and coastal acidification monitoring efforts in the Gulf of Mexico region include fixed mooring sites, research cruises, autonomous observing floats, underway CO_2 systems outfitted on ships of opportunity, and satellite data. Only four fixed monitoring locations are currently located within the Gulf of Mexico, including Tampa Bay, Florida, a reef region in the Florida Straits, the coastal zone of Louisiana, and at the entrance to the Mission/Aransas and Corpus Christi Bay systems, Texas [192-194]. Four Gulf of Mexico-wide ocean acidification synoptic carbonate chemistry surveys were conducted between 2007 and 2021 on 4-to-5 year intervals during the Gulf of Mexico Ecosystems and Carbon Cycle Cruise (GOMECC), formerly known as the Gulf of Mexico and East Coast Carbon Cruise [38, 39, 195]. These cruises provide a long-term, albeit temporally sparse, dataset for Gulf ocean acidification by routinely collecting physical and chemical data, with biological monitoring (incorporated in 2017) to support investigations of how acidification impacts ecosystems.

Other smaller-scale ocean and coastal acidification and water quality observing cruises carried out by federal and state agencies (e.g., NOAA, United States Geological Service (USGS), EPA, Florida Fish and Wildlife Conservation Commission (FWC)'s Fish and Wildlife Research Institute (FWRI), and Florida Department of Agriculture and Consumer Services (FDACS), Texas Commission on Environmental Quality), NGO and academic researchers (often supported by NSF) have been instrumental in observing ocean and coastal acidification within many U.S. Gulf coastal regions. However, many of these cruises were limited in geographic scope and/or not repeated to acquire time series data. In 2021, for the first time, five-sensor biogeochemical-Argo (BGC-Argo) floats were deployed, returning near real-time pH data across the upper 2,000 m of the open Gulf of Mexico. Autonomous observing technologies including BGC-Argo floats and surface vessels such as Saildrones offer great potential for closing critical ocean acidification observing gaps in characterizing water column and surface carbonate chemistry in the Gulf [196-198]. Earth observing satellites also provide surface measurements (<1 m) of carbonate chemistry and enable broader spatial and temporal coverage that is complementary to *in situ* surface measurements [199-201].

Sustained and additional monitoring is needed in the Gulf of Mexico to track the progression and understand the dynamics of acidification across the region due to the diversity of environments and high degree of spatial and temporal variability in carbonate chemistry, especially in subsurface environments. Due to limited observational data, impacts of ocean and coastal acidification on coastal and seafloor habitats and species are poorly understood in the Gulf of Mexico. Monitoring in the open ocean, particularly subsurface waters, is needed both to improve parameterization of ocean biogeochemical models and to better characterize the interactions between open ocean and coastal zone water in studies of acidification processes. Seasonal variability has not been well-characterized in the Gulf due to limited collection of data during winter and fall seasons. Targeted subsurface observations are critical for supporting research to understand vulnerable seafloor communities which are already exposed to more acidic waters, such as deep, cold-water coral habitats of Flower Garden Banks National Marine Sanctuary [142, 185, 202].

Building out coastal acidification time-series monitoring networks is central to better characterizing ocean and coastal acidification in highly variable regions rich in marine resources and essential fish habitats. Estuaries, seagrass meadows, mangroves, marshes, and oyster reefs in the Gulf of Mexico are undersampled for acidification data, but are important for commercial and recreational purposes (e.g., oyster bed leases, public clam beds, shellfish hatcheries). Additional sustained ocean and coastal acidification moorings are needed in critical areas such as the West Florida Shelf, the Mississippi Sound, and south Texas shelf. Only three of over 200 estuaries in the Gulf of Mexico region have sustained time-series observations (Tampa Bay, Florida; Mission-Aransas Estuary, Texas; and coastal Louisiana), and conditions often cannot be extrapolated from one location to another. Expanded monitoring will help characterize variability in these dynamic environments and identify acidification drivers, particularly in freshwater systems facing co-stressors for coastal acidification and eutrophication that have high levels of human activities and that strongly influence coastal oceans.

The Gulf of Mexico region is influenced by exchange of water masses with the Caribbean Sea through the Yucatan Channel and loop currents that create substantial chemical, biological, and socioeconomic connectivity among U.S., Mexican, and Cuban sub-regions. Ocean acidification monitoring within the Yucatan Channel is limited yet critical to understanding how these exchanges and loop current dynamics affect ocean acidification parameters in Gulf waters. This emphasizes the fundamental need to facilitate and enhance international collaboration between the U.S., Mexico, and Cuba for a comprehensive acidification monitoring system in the region. This collaboration should also extend to enabling concurrent biological observations relevant to understanding the impacts of acidification, ideally following common standards and best practices.

Efficient, cost-effective expansion and improvement of Gulf of Mexico acidification observations in both time and space require development of new surface and profiling sensor capabilities for ocean acidification observing and build-out of an integrated network of gliders, floats, moorings, autonomous surface vehicles, and other autonomous platforms [203]. Coordination among technology development research groups is needed to expedite sensor development, integration into observing platforms, field testing, and establishment of best practices for use in diverse Gulf of Mexico environments. Inclusion of sensors on observing platforms for measurement of additional variables besides pH (such as total alkalinity, dissolved inorganic carbon, oxygen, nutrients, carbonate concentration, chlorophyll, and others) is important for characterization of Gulf of Mexico water that is highly influenced by terrestrial and riverine inputs.

Ocean and Coastal Acidification Modeling

Given the limited observational time-series data available to understand the progression and net change in surface and water column pH across the Gulf, numerical model simulations and paleoclimate studies are important to understanding Gulf ocean acidification in a historical context. Regional, three-dimensional, high-resolution, ocean-biogeochemical models can help fill observational gaps, providing a framework to better understand underlying drivers of carbon system variability. In addition, regional ocean-biogeochemical models can be used to downscale future scenarios from the CMIP6 Global Circulation Models, providing plausible trajectories in ocean circulation and ocean biogeochemistry, which are relevant to evaluate regional ecosystem vulnerability to future ocean acidification disturbances.

The NOAA Ocean Acidification Product Suite utilizes satellite data and a data-assimilative hybrid model to map the components of the carbonate system of surface water and provide monthly surface estimates of ocean acidification parameters in the eastern half of the Gulf (https://www.coral.noaa.gov/accrete/oaps.html). In addition, several ocean-biogeochemical modeling efforts were conducted to study carbon system variability in the region. These efforts examined bottom acidification patterns near the Mississippi Delta, Gulf of Mexico-wide variability in surface pressure of CO_2 and air-sea CO_2 fluxes, and spatial variability in ocean acidification progression [119, 120, 186, 204].

Most of the current models are either Gulf-wide and do not incorporate local drivers of high variabilities, or they focus on limited geographic regions (i.e. the northern Gulf). In particular, the southern Gulf, upwelling-prone regions (e.g., the western and southern shelves), and the broader Louisiana and Texas shelf all need more extensive modeling effort to investigate carbonate variability with changing hydrodynamics and freshwater and nutrient discharge. There are also limitations in how well models represent the impact of the Mississippi-Atchafalaya River Basin on surface carbonate chemistry. There is also a gap in models that look at sub-surface carbonate chemistry.

A rigorous synthesis of existing historical and modern data relevant to ocean acidification observations and research has not been conducted in the Gulf of Mexico. This type of data synthesis is needed for examining 'time of emergence and detection' of acidification to aid decision making for monitoring areas of interest; for informing restoration and mitigation strategies; for improving ocean biogeochemical models that can also inform sampling strategies and observing system design through Observing System Simulation Experiments; and for modeling past and future changes in ocean acidification [205]. Collaboration among the Gulf of Mexico states and nations is needed to enhance data sharing and collaborative, integrated modeling activities.

4.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

The Gulf of Mexico and its adjacent bays and estuaries are home to a range of marine habitats, including salt marshes, seagrass beds, mangroves, oyster reefs, and coral reefs that host economically, ecologically, and recreationally important marine species that are vulnerable to acidification. However, studies on impacts of ocean and coastal acidification in the Gulf of Mexico have been limited and mostly focused on a few economically important Gulf of Mexico shellfish species (including **Eastern oysters, Bay scallops, Hard clams, Queen conch, Gulf shrimp, and Florida stone crab**) [187]. These studies have indicated that responses to acidification can vary both between species and within species [4]. Shellfish are particularly vulnerable to low pH and aragonite saturation state, which can hinder the formation of calcium carbonate shells and can negatively impact larval growth and survival. This can have cascading effects on shellfish, reducing their tolerance and increasing their vulnerability to other stressors like changes in temperature or salinity. While the Gulf of Mexico has over 1,443 finfish species, studies of acidification impacts on fish are also limited to only a few species, and these studies have shown that ocean and coastal acidification results in diminished growth, size, survival and fertilization rates, embryonic and larval development, and behavioral changes [154, 206-208].

Coral reefs are vulnerable to acidification, which slows growth rates of corals and other reef calcifiers and increases dissolution of carbonate shells and seafloor sediments through chemical erosion, resulting in decreasing rates of reef accretion [111, 190]. Some deepwater corals can adapt to more acidified conditions; however, acidification can sharply reduce their growth rates. Tropical corals at the Flower Garden Banks National Marine Sanctuary have shown increased calcification in response to warming temperatures, but these coral populations have also experienced localized mortality events in response to river- and upwelling-induced hypoxia and acidification [209-212].

Conversely, increased CO_2 has the potential to increase the growth of aquatic vegetation such as seagrass, salt marsh, and mangroves, allowing these species to locally buffer the impacts of acidification as they consume CO_2 and elevate pH through photosynthetic processes, although the presence of seagrass may also increase short-term extremes in carbonate chemistry [93, 94, 213]. Habitat restoration for ocean and coastal acidification mitigation and for storing blue carbon is an area of growing interest among federal, state, local agencies, and commercial sectors dependent on coastal and ocean resources [175, 214].

Needed Research on Economically Important Species

Focused ocean and coastal acidification exposure studies in both laboratory and field settings using Gulf of Mexico species (particularly the economically important Eastern oysters, Bay scallops, Hard clams, Queen conch, Gulf shrimp, and Florida stone crab) are needed to better understand species response and multi-stressor interactions. Additionally, a comprehensive set of life stages for each of these species should be studied to better inform species vulnerability assessments, particularly for lower trophic levels, including phytoplankton and calcifying zooplankton, to understand the cascading indirect impacts of ocean and coastal acidification across the marine food web.

Estuarine, coastal, and open marine habitats in the Gulf of Mexico provide a variety of ecosystem services that support food security, recreation, tourism, industry, coastal resilience, and coastal hazards protection. Focused long-term studies on salt marsh, seagrass, mangrove, oyster reef, coral reef, and other carbonate ecosystems are needed to understand ocean and coastal acidification impacts on ecosystem resources and services that provide benefits to coastal communities. These long-term studies should include focused field and laboratory analyses, as well as model studies, to estimate ecosystem range shifts and changes in seafloor structure and marine habitats under future elevated pCO_2 conditions. Additional knowledge gaps include: 1) assessing the impacts of biogenic carbonate dissolution caused by ocean and coastal acidification on seafloor chemical erosion, elevation loss, and related sea level rise and coastal hazards; 2) identifying resilience mechanisms and independently resilient ecosystems; 3) conducting research to inform and develop mitigation strategies for acidification; and 4) monitoring downflow consequences of multi-stressor impacts on marine species and ecosystem function and services (e.g., ocean and coastal acidification's impacts on HAB toxicity and consequently food security).

Current and Needed Research on Impacts to Populations and Ecosystems

Ocean and coastal acidification not only impacts specific habitats and individual species in the Gulf of Mexico, but also has consequences on food webs and entire ecosystems. Species that are critically important to marine food webs may be impacted by changes to their prey or ecosystem productivity rather than by direct impacts from changing water chemistry, which is also relevant for predicting and understanding the impacts of ocean and coastal acidification on finfish and other commercially and economically important species.

A foundational step in understanding ecosystem impacts of ocean and coastal acidification is characterizing the impacts of increasing acidification on phytoplankton, which form the base of the marine food web, impact ecosystem function and energy flow, and play a critical role in biogeochemical and elemental cycling. The impacts of ocean and coastal acidification on calcifying plankton, such as foraminifera species, are not well-understood, particularly in the Gulf of Mexico. Studies conducted in other regions show decreased calcification, growth malformation, and dissolution of coccolithophores and pteropods under ocean and coastal acidification [215]. NOAA's last two GOMECC cruises have measured phytoplankton and zooplankton abundance to characterize food web structure, but further characterization of plankton communities along and across acidification gradients is needed to better separate the impacts of ocean and coastal acidification and seasonal or episodic drivers. Continuation of plankton and neuston net tows, along with genetics analysis, on ocean and coastal acidification cruises will enable identification of regions where shifts in carbonate chemistry led to shifts in plankton community structure and function. Sustained carbonate chemistry measurements must be an essential component for ongoing and future ecosystem monitoring efforts to assess the impacts of acidification on marine food webs. Additionally, research is needed to identify indicator species (i.e., species that are sensitive to acidification and serve as a harbinger of larger ecosystem impacts).

Additional experiments are needed to study the impacts of acidification on primary productivity and zooplankton grazing rates, particularly analyzing the effects of eutrophication, harmful algal blooms, and hypoxia. These types of studies are important to assess the rate of and impacts on carbon flow to higher trophic levels, which is necessary to better parameterize ecosystem models and to understand how acidification will affect food webs and carbon transfer. Species sensitivity studies must account for multiple stressors and incorporate ocean and coastal acidification and biogeochemistry to better understand changes to primary production and predator species populations through predictive ecosystem models, which can further elucidate how these factors impact commercially and economically important aquatic and marine species.

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

The Gulf of Mexico experiences many environmental stressors in addition to ocean and coastal acidification, including hypoxia, eutrophication, warming, HABs, episodic storm events, and oil seeps and spills. As an example, in 2016, intense precipitation and coastal flooding led to nutrient-rich freshwater runoff, local hypoxia, and acidified water that, combined with record high surface and bottom water temperatures, led to an unprecedented coral die-off in the Flower Gardens Bank National Marine Sanctuary [210, 211]. While all these stressors could have negative impacts on marine species individually, little is known about how they interact with each other and with background ocean acidification. Interdisciplinary research, incorporating a multi-stressor framework, is needed to understand how these and other stressors like increased nutrients or rising water temperatures will interact with ocean and coastal acidification and consequently affect species and their vulnerability to acidification [216, 217].

Hypoxia and respiration-driven acidification often co-occur as they are both driven by eutrophication. Both processes have been observed near the Mississippi River Delta, along the Louisiana shelf, and in the bottom waters along the Texas coast, Mobile Bay, and their adjacent continental shelves [42, 218]. These regions may also be subject to additional stressors such as seasonal acidification and hypoxia. Research is needed to better understand the threat that co-occurring hypoxia and acidification present to key aquatic species in these regions of the Gulf of Mexico.

HAB events are also prevalent in the Gulf of Mexico, resulting in public health issues, commercial fishery closures, and reduced recreational tourism [219]. A particularly severe 2017–2019 bloom along the Florida Gulf Coast contributed to an estimated $1 billion dollars in total losses across several economic sectors [220]. Florida and other states experience wide-scale fish die-offs and neurotoxic shellfish poisoning from *Karenia brevis* and other HAB species [172, 219]. Harmful cyanobacteria and their toxins have also been detected in low-salinity estuaries in Louisiana and Florida and have been shown to bioaccumulate in commercially-important consumer species (e.g., blue crab) [221-223]. Further research is needed to understand how increasing acidification will affect HAB occurrence, growth, and toxicity, and to understand how HABs and ocean and coastal acidification act as co-stressors to other species as well (i.e., are the effects additive or synergistic?). While there has been some research on these topics in other regions, those studies have not been shown to be comparable to the unique biodiversity and ecology of the Gulf of Mexico, with few studies focused on species that live in the Gulf of Mexico. Isolation- and cultivation-based laboratory experimentation on local HAB-causing species should be done to examine species-level and community responses to carbonate chemistry conditions, and HABs should be monitored in conjunction with ocean and coastal acidification.

An abundance of carbon from petroleum sources enters the Gulf of Mexico waters, but monitoring of carbonate chemistry dynamics associated with oil spills and oil/gas seeps is limited. Monitoring of both petroleum and water chemistry (e.g., carbonate parameters, dissolved oxygen, etc.) along with isotopic tracers (i.e., stable carbon isotopes) are needed to assess the impact of this carbon on the marine environment and in the context of ocean and coastal acidification for the Gulf of Mexico.

5.0 Alaska Region

Key Points

- Ocean acidification is progressing more rapidly in the cold waters of Alaska compared to other regions, potentially increasing the vulnerability of species and communities.
- Alaska has significant commercial and subsistence fisheries that are expected to be vulnerable to ocean and coastal acidification. A relatively large proportion of the state is reliant on subsistence fishing.
- Engagement with Tribes has led to community-led monitoring efforts of ocean and coastal acidification, but challenges remain in monitoring.

The state of Alaska is surrounded by the Gulf of Alaska, Bering Sea, Chukchi Sea, and Beaufort Sea, with extensive ocean-dependent coastal communities and a large portion of the state's economy being supported by fisheries. The cold temperatures of Alaskan waters increase the solubility of CO_2, leading to more CO_2 being absorbed from the atmosphere and a higher rate of ocean acidification relative to other regions [224, 225]. This also means that future absorption of CO_2 could lead to relatively large increases in ocean acidification [226]. Offshore of northern Alaska, as well as in the coastal regions, persistently corrosive waters have already emerged and expanded over the past few decades [224, 227, 228]. Other regional processes can contribute to large variations in carbonate chemistry, including transport of ocean water, riverine discharge of organic and inorganic carbon, sea ice melt pulses that dilute alkalinity and lower buffering capacity, upwelling, and seasonal productivity [229-231]. It is worth noting that many of these processes themselves are changing, driven by warming and other climatic changes [232].

Alaskan coastal communities are highly reliant on marine resources for subsistence, livelihood and economic benefits, and cultural and spiritual well-being. Alaska Natives who have lived in the region for thousands of years participate in the harvest of fish, shellfish, marine mammals, and seabirds through customary and traditional practices. Although the connectivity between the marine ecosystem and resident well-being resonates across all of Alaska's coastal communities, there are substantial differences in how residents participate in and derive well-being from their local ecosystems across the broad ecosystem regions — Gulf of Alaska, Bering Sea and Aleutian Islands, and Arctic.

5.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

Communities within the Gulf of Alaska participate across the spectrum of diverse state and federal commercial fisheries, harvest fisheries and shellfish resources for subsistence, generate income from charter fishing operations, and enjoy participating in fishing as recreation. In the Bering Sea and Aleutian Islands, most commercial fishing by local residents takes place in nearshore state fisheries, although many communities in the region derive indirect benefits from large-scale groundfish fisheries off their shores through the Community Development Quota program. Residents of the Bering Sea and Aleutian Islands also have deeply rooted subsistence and traditional ties to their local marine resources. In the Arctic, commercial fishing is prohibited under the Arctic Fisheries Management Plan, but the Alaska Native people who reside in these coastal communities have a profound reliance on their local marine resources including fish, marine mammals and seabirds for subsistence and traditional practices. Additionally, Alaska marine species are important for fishing communities beyond the immediate area. Fishing communities in Washington and Oregon are also connected to and dependent on Alaska's Bering Sea crab fisheries, valued over $160 million.

Economic Impacts from Ocean and Coastal Acidification

Commercial Fisheries: The commercial seafood industry is a critical component of the Alaska economy and the nation's food system with over half of the seafood harvested in the United States coming from Alaska's waters. The Alaska seafood industry includes commercial harvesters, seafood processors and dealers, wholesalers and distributors, and retail; altogether the industry supports over 50,000 jobs and a significant amount of revenue (Table 9). High-profile fisheries include those for **salmon, crab, pollock, cod, and halibut**. The productivity and profitability of Alaska fisheries are

Table 9: The economic impact of the Alaskan seafood industry in 2019, including imports [13]. Landings revenue is the price fishermen are paid for their catch, jobs include full-time and part-time jobs supported directly or indirectly by the sales of seafood or purchases of inputs to commercial fishing, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Landings Revenue	Jobs	Sales	Income
ALASKA	$1,754,000,000	52,702	$4,321,384,000	$1,930,355,000

vulnerable to climate drivers. Recent high temperature events appear to have had significant negative effects on multiple fisheries including Pacific cod, crab species, and pink salmon [233].

Along with these temperature changes, acidification is occurring and may play a role in the longer-term future of these and other fisheries by limiting recovery or potential production. In 2015, Seung et al. estimated the potential impacts of ocean acidification to the Bristol Bay **red king crab** fishery could exceed one billion dollars [234]. While higher temperatures may stimulate production in some species, the negative effects of ocean acidification could constrain the increased production [235]. Furthermore, while experimental work to date has suggested a general resilience of **walleye pollock** to acidification conditions, those assessments did not take into consideration potential changes in the availability of pollock's more sensitive invertebrate prey [236, 237]. Additional work is needed to evaluate the risks to other critical fisheries and broaden those assessments to include all aspects of ocean acidification influences and the interactions with other stressors on fishery production.

Non-commercial Fisheries: Non-commercial fisheries in Alaska occur across a spectrum from recreational fishing, to personal use, and subsistence harvest. These categories are not necessarily exclusive, as many Alaskans harvest food to meet their nutritional needs through techniques often associated with sport fishing. In addition, charter sport-fishing operations (mainly for **salmon and halibut**) that cater to non-resident visitors represent a blending of the commercial and recreational fishing sectors. Table 10 describes the economic impacts of recreational fishing expenditures in Alaska. Salmon represent the largest contribution to wild foods harvested by Alaskans with other fishes, shellfish, and marine mammals also being harvested. Although the total amount of subsistence harvests is much smaller than that taken in commercial fisheries, they are critical to meeting the nutritional needs of Alaskans, especially in the western and Arctic regions. The availability of these foods is subject to the same types of climate controls as those taken by the commercial fisheries. The risk from ocean acidification to food security of rural Alaskans remains a significant concern as many of the harvested species, in particular salmonids and nearshore shellfishes, have yet to be evaluated for how acidification affects species sensitivity or predator-prey interactions.

Table 10: The economic impact of recreational fishing expenditures in Alaska in 2019 [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
ALASKA	3,910	$456,117,000	$152,172,000

Mariculture: Mariculture in Alaska has historically been a minor industry, focused on the culture of oysters and mussels. While the culture of finfishes remains prohibited in Alaska, there is active engagement in expanding the mariculture of a broader range of shellfish and macroalgae (kelp). This interest is highlighted by the Mariculture Task Force established by Alaska Governor Walker in 2016. The resulting statewide plan for mariculture development indicates the potential for expansion of the mariculture industry to grow to $100 million in the next 20 years [238]. Similar to wild-capture fisheries, the success of mariculture operations will be in part dependent upon climate conditions being favorable to the production of target species. Industry experience and research in other parts of the United States have demonstrated the risks that ocean acidification poses to coastal invertebrate mariculture, which may pose a similar risk to the expanding industry in Alaska [239]. In contrast, culture of macroalgae may not only be less susceptible to acidification influences, but may even serve as a mitigating factor in the co-production of bivalves [240]. Considerable research effort is needed to evaluate the long-term risks of ocean acidification to bivalve culture in Alaska and the opportunities and limitations of algae-bivalve co-culture. For example, there is a need to test Alaska-grown oyster seed against seed imported from the lower 48 states to assess differences in resilience. In addition to ocean acidification, mariculture of bivalves is also strongly threatened by harmful algal blooms (HABs) [238]. Previous bloom events have resulted in human illness from harvested shellfish, and detection of HABs can lead to shellfish harvest being prohibited, causing economic loss to farmers [241].

Cultural Impacts from Ocean and Coastal Acidification

Ocean acidification has the potential to affect commercial, subsistence, and cultural resources that are critical to the well-being of Alaskan coastal communities. Communities that have the strongest reliance on subsistence harvest of crabs and other invertebrates and those whose economies rely the most on commercial fishing are expected to be most strongly impacted [242]. However, communities throughout Alaska rely on a mix of subsistence, commercial, and recreational fisheries and marine mammal harvests that may be impacted by adverse implications of ocean acidification across the marine food web. In the Arctic, where subsistence and cultural practices include the harvest and community sharing of marine mammals, ocean acidification will interact with other climatic stressors, including sea-level rise and permafrost thaw, that are already threatening communities' access to marine resources and their very existence. The highest exposure to acidification may be in areas that support critical populations of seabirds, walruses, seals, and bowhead whales [227].

Evaluating Sensitivity of Communities: Current Work and Research Gaps

Much of the research around community vulnerability to ocean acidification and other climate stressors for Alaskan coastal communities focuses on economic vulnerability. This is in part because of the tremendous economic value of fisheries in the region, worth over $1 billion USD, employing 15,000 full time-workers, and contributing tax revenues throughout the region [243]. Despite recognition that fisheries and other marine resources are critical to the overall well-being of Alaskan coastal communities, social scientists in the region are limited in their capacity to readily make these linkages because of underlying data gaps. Many of the datasets that cover these non-economic linkages between Alaskan coastal residents and their marine resources are voluntary in nature and therefore not comprehensive and often have substantial temporal gaps. Social science data gathering, which is necessary to understand the nuances of how participation in fisheries and marine mammal and shellfish harvest affect coastal resident well-being, is time and resource intensive, often necessitating years of interaction to develop trusting relationships.

NOAA and university researchers are developing coupled socio-ecological models to examine the impacts of climate stressors on fisheries systems in Alaska (e.g., the Alaska and Gulf of Alaska Climate Integrated Modeling Projects) [244]. Similarly, scientists in the region recognize the need to develop integrated climate-biological-socioeconomic models that link the physiology, growth, behavior, and distribution of species to spatial and temporal patterns of corrosive water exposure, which will allow for evaluation of direct and cascading effects of acidification on the social-ecological system. In addition to these large-scale efforts, researchers should develop community-specific socio-ecological models that holistically consider multiple climate stressors, various marine resource user groups and maritime industries, and economic and non-economic components of well-being. Such integrated modeling can help reveal cumulative impacts on coastal communities and potential trade-offs between users, sectors, and well-being components. There is also recognition that ocean acidification assessments need to be expanded to consider the sensitivity of communities to impacts on nutritional and cultural resource species and the impacts of acidification-induced food web changes that could affect harvest of these species, including large marine mammals. Researchers need to work with communities to identify these locally important species and to create community-relevant mechanisms for knowledge exchange around the impacts of ocean acidification and other climate stressors. Including traditional ecological knowledge will be key in characterizing vulnerability as well.

Some coastal communities throughout Alaska have been developing climate adaptation plans or integrating climate adaptation planning within broader hazard mitigation plans. Tribes throughout the region have also been conducting separate risk assessment and adaptation planning processes. However, most often the climate planning that does exist does not focus specifically on fisheries or marine mammal resources, nor do they substantially focus on ocean acidification. This is despite the broad recognition of potentially severe climate impacts on these resources, as well as specific acknowledgement of the detrimental effects of ocean acidification.

Federal agencies and researchers working in coastal Alaska are developing vulnerability assessments and updating critical data infrastructure to help communities in their planning processes. The National Marine Fisheries Service conducted a vulnerability assessment of Bering Sea and Aleutian Islands fisheries, examining how critical species in the region may respond to various climate stressors; a similar assessment is underway in the Gulf of Alaska [245]. The Alaska Mapping Executive Committee (AMEC), a federal-state partnership, recently developed the Alaska Coastal Mapping Strategy (ACMS) Implementation Plan to update maps of Alaska's shoreline which will be critical in planning for coastal impacts from climate stressors [246]. Future work needs to continue incorporating biological sensitivity data into modified stock assessment models to help inform adaptation strategies for fisheries, subsistence users, and local communities.

A new regional vulnerability assessment is examining the vulnerability of traditional and emerging coastal Alaska industries to ocean acidification. The project is working to understand the threat of ocean acidification in south-central and southeast Alaska and involves the development of decision-support tools incorporating ocean acidification risks into localized socio-ecological systems. The tools are based on a network of models representing ocean acidification hazards, bio-ecological systems, and socioeconomic systems linked to adaptive actions. This will lead to an exchange of knowledge between scientists, policy-makers, and community stakeholders. The network of models creates decision-support tools that are responsive to stakeholder concerns, reflect regional variation in the priorities of communities and their ecological, social, and management context, and synthesize the best-available science to determine the risks posed by ocean and coastal acidification.

Adaptive Capacity of Communities

Alaskan communities' reliance on marine resources, geographic isolation, and lack of economic diversity make many of its communities highly susceptible to the impacts of climate change, including ocean acidification [247]. However, communities in the Bering Sea, Aleutian Islands, and Arctic are likely to be the most vulnerable due to the co-occurrence of multiple climate-related stressors, as well as underlying socioeconomic vulnerability associated with limited economic diversity, higher poverty rates, and lower education levels [248]. Historically, these communities have been very self-reliant, resilient, and adaptable, but the magnitude of current and expected changes are making the utilization of previous approaches difficult. Already, communities in the region are facing coastal erosion, sea level rise, and permafrost thaw that are necessitating relocation, or "managed retreat." While the community of Newtok is actively relocating, this necessitates tremendous financial support. Even for those communities that are able to relocate, the cultural loss and degradation of other dimensions of well-being tied to place and traditional practices may never be replaced. Across the region, multiple stressors on marine resources and changes to the capacity to continue traditional harvesting practices due to environmental changes like sea ice loss will jeopardize basic food security [249].

Additional work is needed to understand what actions or approaches will be most effective in increasing adaptability and resilience to ocean and coastal acidification. There are a number of organizations that may have the capacity to help communities adapt to increasing acidification. The Alaska Ocean Acidification Network engages with scientists and stakeholders to expand the understanding of ocean acidification processes and consequences, as well as potential adaptation strategies. Alaska Sea Grant is actively engaged in ocean acidification outreach, education, and research through working with Alaska Tribes and other partners; they also work with communities on a number of other topics, including supporting aquaculture and fisheries. Additionally, fisheries in the state are managed by the North Pacific Fishery Management Council, which may be able to consider ocean and coastal acidification in future management actions.

5.2 Knowledge Informing Social Vulnerability

5.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

Monitoring in Alaska presents unique challenges given the vast area, remoteness, harsh environment, and other factors such as seasonal ice cover. Characterizing the exposure of commercially and culturally significant habitats is needed, in order to deliver information that is relevant to communities and managers [242, 249, 250].

Monitoring increases understanding of how chemical, physical, and biological processes interact and contribute to ocean acidification, in addition to determining the spatial and temporal variability in the carbonate system. Ocean and coastal acidification monitoring provides important context to species response studies, economic forecasts, and strategies for building resilience. The current Alaska ocean and coastal acidification monitoring network includes moored sensors, ship-based monitoring, shore-based stations, autonomous vehicles, and community sampling.

Improving ocean and coastal acidification monitoring in biologically important regions can support species response studies. These observations are necessary to understand the magnitude, duration, and frequency of ocean and coastal acidification events that species are exposed to across various life stages. From the magnitude and duration, a severity ocean acidification index can be derived that can be linked to biological response interpretation [251]. Currently, only two fixed mooring sites exist in Alaskan waters (one in the Gulf of Alaska and one in the Bering Sea), and these provide information about the variation in ocean acidification in these important biological habitats. Given the vast expanse of Alaskan waters and varying ocean and coastal acidification dynamics, additional moorings are needed to understand ocean acidification across the Alaska region. In the Gulf of Alaska, observational data are largely constrained to the Seward Line (collected through NSF's Northern Gulf of Alaska Long Term Ecological Research Site), leaving large spatial-temporal data gaps (particularly across the coastal shelf) that limit model skill assessment.

Additionally, important fish habitats including Bristol Bay and Southeast Alaska lack long-term monitoring sites and represent target areas of expansion of the ocean acidification observing network. Repeated dedicated ship-based surveys of carbonate parameters in fisheries habitats can provide more extensive observation of temporal and spatial variability of ocean acidification in these areas [15]. Ideally, such cruises should be coordinated with existing fisheries population surveys to allow for research on the potential connections between ocean acidification and fisheries population changes [249, 250]. Increasing the use of autonomous observing platforms offers the potential to expand observations in areas where other platforms cannot feasibly reach at certain times of the year (e.g. Chukchi/Beaufort Seas) [252, 253]. These could also be utilized to provide an early warning data stream for shellfish growers [254].

Expanding the spatial coverage of ocean acidification monitoring in Alaska is critically important, as the impacts to many communities will depend on very localized effects on subsistence harvest fisheries or community-scale mariculture [255]. Many communities in Alaska are geographically isolated and don't have the local monitoring in place to understand the current state of ocean acidification in their area. Utilizing existing community observing and citizen science efforts offers some opportunity to address this observing gap. There is currently an ongoing effort led by Tribes to coordinate community sampling of ocean acidification and HABs, with over 20 communities involved in water sampling since 2018. However, ocean acidification sampling requires consistency of sampling and processing. There is also a continued need to provide training and support for community sampling efforts, and to develop information networks and data management procedures to ensure that the data collected are shared in a relevant and timely fashion. Efforts to work with new communities, local shellfish growers, and ocean ranchers to identify their local monitoring needs and regions of interest will be central to determining where additional monitoring sites should be established.

Other existing monitoring networks can be leveraged to expand ocean acidification monitoring in the region. Partnerships with existing monitoring initiatives have already helped to advance acidification monitoring in the region. In 2010, NOAA created a long-term monitoring initiative in the Pacific Arctic called the Distributed Biological Observatory, with some time-series in the region dating back decades. This project is supported by BOEM, NASA, and NSF and collects biological, physical, and chemical data from the Bering to Beaufort Seas to make linkages between environmental change and biological observations. Ocean acidification observations were added to the network in 2017, with some regional measurements starting in 2015. Further, the NOAA Ocean Acidification Program has also funded ocean acidification measurements on fisheries population survey cruises in the Bering Sea and the Gulf of Alaska, with this annual program beginning in 2022. The IWG-OA monitoring prioritization plan will expand upon additional opportunities for partnerships to increase ocean and coastal acidification data collection.

Ocean and Coastal Acidification Modeling

Long-term model projections and short-term forecasts are important tools in studying the current and future state of ocean acidification in Alaskan waters and predicting impacts to communities. Simulations of ocean acidification are particularly important given the broad spatial scale and the financial and logistical limits of increasing monitoring observations. Global-scale Earth System Models are typically too spatially coarse to resolve the coastal shelf region, along with coastal physical-biogeochemical dynamics. Regional ocean models with carbonate chemistry have been developed and validated for both the Bering Sea and the Gulf of Alaska [256-258]. These model results highlight the importance of coastal processes such as freshwater runoff from rivers and glaciers, as well as climate variability on interannual to decadal timeframes, in modifying ocean acidification trends, and are informative of long-term trends impacting biological responses [228]. Ocean acidification output from the Bering Sea model is also used to inform fisheries management through a recently developed ecological indicator reported in the annual NOAA Eastern Bering Sea Ecosystem Status Report [259].

Ship-based process studies are also needed to improve understanding of ocean acidification drivers (e.g., freshwater riverine and glacial discharge, coastal advective transport, rates of planktonic and benthic productivity and respiration); these studies improve evaluation of different rates and fluxes and are critical to reducing uncertainty in models and informing targeted model improvements. Validation of ocean regional models is currently conducted using observational data that is limited in space and time. In Arctic regions, seasonal sea ice greatly inhibits the collection of year-round data. Furthermore, the formation of corrosive water conditions often occurs in deeper bottom waters due to biological respiration processes. These bottom water conditions are more challenging to sample, outside of costly ship-based measurements. Coordinating sampling efforts with fisheries surveys may help identify regional spatial and temporal vulnerability across important habitats [228]. This is especially important with regards to the fisheries, where such inputs can help elucidate important statistical and mechanistic relationships between carbonate chemistry variables and fisheries population data.

5.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

Over the last decade, research has primarily focused on determining sensitivity of commercially important Alaska crab and groundfish species of the Gulf of Alaska and Bering Sea, although limited work has been done on other ecologically important species. These results have demonstrated important differences in sensitivity between species and among life stages within species. They have also demonstrated variation in the primary mechanisms by which ocean acidification will affect the productivity of specific fishery species.

Crab species in Alaska appear to be highly vulnerable to ocean acidification based on lab studies to date. Embryos of **red king crab** and **Tanner crab** both show altered development under acidification conditions, with Tanner crab embryos experiencing substantial mortality [260, 261]. Larval red king crab, Tanner crab, and **Dungeness crab** all show sensitivity to ocean acidification [260, 262-264]. Juveniles appear to be the most consistently sensitive to ocean acidification, with red, **blue**, and **golden king crab** and Tanner crab all exhibiting higher mortality and reduced growth, with many species also showing reduced hardness in their exoskeletons [265-268]. Adult crabs can suffer higher mortality, both internal and external shell erosion, and increased hemocyte mortality [261, 269, 270]. Of the species tested so far, **snow crab** is the only one with marked resistance to ocean acidification [271, 272]. Research on other shellfish species, including **littleneck, butter, and razor clams** is ongoing.

Among groundfishes, experimental work on larval and juvenile **walleye pollock** has indicated a general resiliency of growth and survival rates to elevated CO_2 levels [236, 273]. However, researchers have also documented sub-lethal effects in larvae that may have negative carry-over effects to later life stages [237]. In contrast, a direct effect of elevated CO_2 was observed in **northern rock sole** with larvae exhibiting lower survival rates at higher CO_2 levels [206]. A complex set of responses were observed in larval **Pacific cod** reared at elevated CO_2 levels with lower growth rates right after hatch, but higher growth rates in older larvae [274]. In addition, exposure to ocean acidification altered the behavior of larvae that may be related to the observed growth changes [274]. The most sensitive finfish tested to date is **pink salmon** whose embryos and larvae showed decreased growth and altered behavior (larvae only) in elevated pCO_2 [275].

Limited work has been done on other species that are native to Alaska, but most of these studies have been done on populations outside of Alaska and there could be differences in response. **Pteropods** are highly sensitive to OA, showing a decrease in growth and calcification and increase in shell damage in both field and laboratory settings [228, 276-278]. **Northern shrimp** larvae and adults are reasonably tolerant of acidification with larvae showing a slight decrease in growth and adults able to regulate their hemolymph even under extreme conditions [279, 280]. Similarly, larvae and juvenile **Baltic clams** are not strongly impacted by ocean acidification [281, 282]. The **common cockle**, on the other hand, grows more slowly in acidification conditions [283].

Needed Research on Economically Important Species

Intra- and interspecific variability in organism response to ocean acidification points to the potential for species to acclimate or to become more resilient to gradually increasing acidification [260, 266, 284]. Laboratory ocean acidification experiments generally expose species to conditions expected to occur in the next 50-200 years. Most experiments cannot take acclimation or adaptation into account and are thus likely overestimating the future effects on most species. Longer-term studies and studies examining individuals over multiple life history stages are necessary to understand carry-over effects [285, 286]. Maternal, or transgenerational, effects can also be a means of acclimation and should be investigated [287]. Finally, evolutionary potential needs to be assessed [288]. A more mechanistic understanding of the physiological responses to ocean acidification and their genetic underpinnings will help in estimating evolutionary potential. Other approaches, some of which may be unfeasible for longer-lived species, include multigenerational experiments, targeted breeding, and selection experiments.

Although advances have been achieved in quantifying the responses of Alaska marine species to ocean acidification, more work must be done to predict how ocean acidification will alter marine ecosystems. To date, most of the research has focused on commercial crab and selected groundfish species; there are many species that have not been investigated. In particular, **salmon** are critical in Alaska as fisheries species, but research on their sensitivity to acidification is still in the early stages and is awaiting publication. Although bivalves are generally sensitive to acidification, there are many harvested bivalve species, including **weathervane scallops, razor clams, geoduck, and littleneck clams,** that need to be investigated [167]. Recently, efforts to evaluate the sensitivity of salmon and bivalves have begun in partnership with Alutiiq Pride Marine Institute and universities.

Ocean acidification is also expected to impact lower trophic-level species, but more research needs to be done on Alaskan species. The most important lower trophic-level species are food web "bottlenecks," critical prey species that funnel energy from phytoplankton to larger organisms. Impacts on these bottleneck species will spread throughout the food web, potentially disrupting population productivity of commercially important fish and crabs, as well as protected and culturally important species. In the Gulf of Alaska and Bering Sea these include many planktonic species, such as **krill, pteropods, and copepods**.

In the Arctic Ocean (i.e., north of the Bering Strait), which is a benthic-dominated system, **brittle stars, lyre crab, and clams** are the most critical lower trophic levels species; however, planktonic organisms, particularly **copepods species, euphausiids, and pteropods** are also ecologically important [289, 290]. In addition, acidification is likely to alter predator-prey dynamics and other interspecific interactions. Food web disruptions are expected to be the primary mechanism of ocean acidification effects on marine mammals, some of which are endangered, and some fish species. Therefore, understanding the sensitivity to ocean acidification of key lower trophic level species and the effect of acidification on interspecific interactions is critical to predict the consequences of acidification to the Alaskan economy and communities.

Current and Needed Research on Impacts to Populations and Ecosystems

Headway has been made in incorporating the results of single-species exposure experiments into population, stock assessment, and fisheries models. In Alaska, ocean acidification effects on fisheries will likely be the single most important aspect in driving community vulnerability, both from an economic (i.e., commercial fisheries) and a food security (i.e., personal and subsistence fisheries) perspective. Single-species models provide critical information to managers about the predicted magnitude of effects and the timeframe over which they are expected to manifest. Currently, there are larger and earlier negative effects in sensitive species, and later or no effects on more resilient ones [235, 291, 292]. These efforts need to continue both by making new models for species and by refining existing models to incorporate new data from experiments or observations and adding complexity by incorporating spatial dynamics or multiple stressors [293].

Increasing research focus on the ecosystem-wide effects of ocean acidification will enhance understanding of the cumulative effects on ecosystems and fisheries. In the region, this will be critical to informing protection and management of fisheries, protected species, and ecosystems and to identify risk and evaluate adaptation measures. Identification and monitoring of an indicator species could help track potential ecosystem effects. Pteropods could be an effective indicator because of their sensitivity to ocean acidification conditions; further work could develop the necessary methods to detect biological effects *in situ* during survey operations [228]. New and existing food-web models can be modified to include climate and acidification drivers. Recent advances in climate-informed modeling include ongoing efforts to couple food web models (e.g., climate enhanced size spectrum), climate-enhanced groundfish assessment models and individual based models for snow crab to environmental indices derived from high resolution regional ocean model system nutrient-phytoplankton-zooplankton (ROMS-NPZ) models [294, 295]. Inclusion of mechanistic ocean acidification linkages are now possible through the incorporation of carbonate dynamics in ROMS models which reveal distinct seasonal and spatial patterns in ocean acidification, and which can be projected to evaluate past and future changes in acidification-related exposure across space and time [256, 296]. Such projections, linked statistically or deterministically to key processes in biological models (e.g., physiology, predation, behavior, distribution, and growth) could help reveal sensitive species and interactions, emergent, non-intuitive outcomes of cascading impacts, and potential attenuation/amplification of cumulative effects of multiple stressors (e.g., warming, ocean acidification, and fishing) [228]. Management strategy evaluations that determine the degree to which spatial and harvest management tools can counter ocean acidification and climate-driven impacts will further help reveal inherent tipping points and thresholds under various adaptation goals and provide climate-informed scientific advice for decision making [297-299].

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

Declining ocean pH is co-occurring with large-scale changes in temperatures, oceanic oxygen levels, sea ice cover, and freshwater inputs, in addition to localized habitat modification. Very little work has been done on the interaction between ocean acidification and these stressors. These interactions can be complex; for example, in one of the few multi-stressor studies on an Alaskan species, a 2°C increase in temperature ameliorated the negative effects of acidification on red king crab juveniles, while a 4°C increase made the effects much worse [300]. Current and funded research will continue to examine the interactions of ocean acidification and warming on commercial crab and finfish species. Research on the combined effect of acidification and temperature on pteropod calcification shows that both parameters are important for this species as well [228, 278]. Although temperature change is the most universally important co-stressor for Alaskan and Arctic species, future work should focus on identifying which other stressors are most likely to simultaneously affect key species and performing appropriate experiments. This research can be complex, as experimental designs accounting for multiple stressors can result in an unwieldy number of treatments. Reduced experimental designs focusing on ecologically-relevant combinations of stressors may simplify such studies while answering these important questions.

6.0 West Coast Region

Key Points

- Coastal waters and habitats on the West Coast are exposed to carbonate chemistry conditions that currently or will soon pass biologically significant thresholds.
- The West Coast has a rich history of ocean acidification policy planning at the state level.
- Aquaculture has significant value on the West Coast and was the first industry to be economically impacted by acidification, when corrosive waters led to production failures at shellfish hatcheries in the Pacific Northwest. The industry currently engages in adaptation practices to mitigate the impacts of ocean acidification today and in the future.
- Indigenous communities on the West Coast have strong cultural, spiritual, and economic ties to marine species, and many are co-managers of marine natural resources. For these reasons and likely more that are unforeseen, Tribes are potentially vulnerable to ocean and coastal acidification; many have taken steps to adapt to or mitigate the impacts of ocean acidification and other environmental changes.

The West Coast region includes California, Oregon, and Washington, and is home to many communities and Indigenous Peoples who are inextricably linked to the ocean. The continental shelf waters off the western United States and Mexico, from the northwestern tip of Washington State to Baja California, comprise an upwelling region known as the California Current Large Marine Ecosystem. On the West Coast, various processes, including enhanced upwelling and eutrophication, combine to increase concentrations of anthropogenic CO_2 and drive a rapid rate of acidification compared to other regions [301-307]. The West Coast generally has lower pH conditions compared to other regions in the country; coastal waters and habitats are exposed to carbonate chemistry conditions that currently or will soon pass biologically significant thresholds [4, 53, 308-310]. The region experiences strong seasonal upwelling from early spring to early fall, which brings nutrient- and CO_2-rich, low-pH, deep waters onto the continental shelf [301, 302, 305, 308, 311-313]. These waters are high in CO_2 because of both oceanic uptake of anthropogenic CO_2 and a natural increase in CO_2 at depth from biological respiration. Ocean acidification is already affecting coastal waters and communities, with frequent observations of corrosive waters documented in the region (see real-time data from the Northwest Association of Networked Ocean Observing Systems (NANOOS) Visualization System) [302, 309, 314]. Models project that 50% of shelf waters in the central area of West Coast will experience year-long aragonite undersaturation by 2050 [305, 308, 313]. Additionally, Puget Sound is predicted to have a dramatic decrease in aragonite saturation state and pH, with future projections showing aragonite saturation states below thresholds that impact calcifiers year-round by 2050 [264, 315]. These projected declines in pH could have significant consequences for species that communities depend on.

Other coastal processes are important drivers of ocean acidification and affect its spatial variability [316]. The northern part of the West Coast experiences strong freshwater influence associated with large outflows from the Salish Sea, Columbia River, and San Francisco Bay, as well as numerous smaller rivers with more episodic discharge from mountainous regions. This riverine input leads to both lower buffering capacity and increased nutrient loading in coastal and estuarine waters. Coastal eutrophication symptoms are generally less common in western coastal systems when compared to the rest of the U.S., though land-based nutrient loading from wastewater does have an impact in some regions such as Southern California and Puget Sound [317, 319]. Eutrophication, driven in part by wastewater, in the Salish Sea has been shown to combine with naturally high-CO_2 oceanic waters and exacerbate acidification [315, 318-321].

6.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

West Coast communities are intrinsically connected to the ocean and marine resources, making it likely that ocean acidification will have social, cultural, and economic impacts in the region, as pH is projected to decline dramatically over the next century [315]. Robust projections of ocean acidification and resulting ecological impacts will help communities understand expected changes to the marine resources on which they depend. A parallel effort is needed to understand what factors impact the socioeconomic risk and vulnerability of fishing and coastal communities to inform how people will be impacted by ocean acidification and what local adaptation strategies could reduce their risk [4]. It is also necessary to understand how dependencies on different marine resources vary across communities and which people are most reliant on the ocean for their wellbeing. This information will be invaluable to decision makers at local-to-regional scales.

Economic Impacts from Ocean and Coastal Acidification

The West Coast has already faced economic challenges resulting from ocean acidification. Between 2005 and 2009, several major commercial oyster hatcheries in Oregon and Washington that supply seed for oyster farmers along the West Coast experienced unexplained production failures. Research identified that ocean acidification was responsible for the mass mortality of oyster larvae, leading to the first large-scale economic impacts from acidification [314]. There are a variety of sectors, largely related to seafood, that continue to face threats from ocean acidification; it is important to understand the economic value they provide to communities and how they may respond to increasing acidification. It is possible that other sectors, such as tourism and real estate, could be affected. Potential future economic disruptions from continued acidification are difficult to predict from current data.

Commercial Fisheries: Commercial fisheries on the West Coast brought in over $637 million worth of landings in 2019. Table 11 details the economic value of fisheries for each state in the the region. Some of the economically important species in the region include **Dungeness crab, sardine, Pacific hake, shrimp, market squid, mackerel, anchovy,** and **nearshore urchins,** some of which have demonstrated sensitivity to acidification in lab experiments (see section 6.2.2 for biological impacts). Predicting economic impacts of ocean and coastal acidification remains difficult due to uncertainties around the severity of acidification that species will be exposed to across different life stages, and the direct and indirect biological impacts of this acidification. Furthering efforts to couple ecological and economic models will advance our understanding of expected changes in income, employment, and economic value of fisheries due to acidification. Economic models may need to account for confounding socioeconomic dynamics, such as changes in fisheries management response or fishing behavior, but designing the models to do so is challenging [322].

Understanding of the impacts of ocean acidification on human communities would be advanced by evaluations at local or sub-regional scales, such as at the port or county level. One study that coupled an ecosystem and economic model estimated the economic responses to acidification at 17 ports along the West Coast. While the models predicted species biomass would decline most in the southern region, the largest economic impacts on revenue, employment, and income occurred from northern California through Washington, primarily driven by declines in Dungeness crab due to loss of prey [322].

Table 11: The economic impact of the seafood industry in 2019 by state in the West Coast region, including imports [13]. Landings revenue is the price fishermen are paid for their catch, sales represents the gross value of both direct sales of fish landed and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Landings Revenue	Jobs	Sales	Income
WASHINGTON	$351,232,000	63,422	$9,242,566,000	$2,460,734,000
OREGON	$165,020,000	13,408	$1,060,827,000	$371,817,000
CALIFORNIA	$163,986,000	135,340	$26,881,300,000	$5,702,759,000

Recreational Fishing: Recreational fisheries also stand to be impacted from acidification. Similar techniques should be used to model the expected economic impacts as those used to assess impacts to commercial fisheries. Species of importance include **black rockfish, mackerels, salmon, tunas, lingcod, and bocaccio**. Table 12 describes the economic value of recreational fisheries to individual states.

Table 12: The economic impact of recreational fishing expenditures 2019 by state in the West Coast region [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
WASHINGTON	1,783	$245,362,000	$81,171,000
OREGON	715	$72,185,000	$27,429,000
CALIFORNIA	8,413	$1,153,869,000	$295,059,000

Aquaculture: Aquaculture also has significant value on the West Coast and was the first industry to be economically impacted by acidification, when corrosive waters led to production failures at shellfish hatcheries in the Pacific Northwest. Given these hatcheries supplied seed to many operations along the West Coast, the subsequent bottleneck in shellfish seed availability impacted growers across the region and heightened concern for its future impacts to the industry [314]. Along the West Coast, many shellfish farms are small, long-established farms, often family owned and operated. There is concern that without adaptation, these farms and shellfish aquaculture communities will be negatively impacted in the future, as shellfish at all life stages can express vulnerability to acidification. Shellfish hatcheries in the Pacific Northwest have already adapted to current ocean conditions by modifying intake water chemistry to lessen acidification, changing the timing of water intake to avoid low-pH waters, and moving hatcheries to Hawaii, where ocean conditions are more amenable to hatchery operations. Further research is needed, as limited monitoring makes attribution of reduced growth and survival to acidification challenging [323]. However, acidification is one of many stressors, and, in many cases, other factors, such as policies, regulations, environmental stress, or marine disease, are of bigger concern [324]. Up-to-date, comprehensive, state-specific data on the economic value of aquaculture are lacking, making it difficult to assess the jobs and income in this sector that could be threatened by ocean acidification. Additionally, while macroalgae are not currently harvested to a significant extent, kelp may soon be an important sector of the aquaculture industry and is expected to respond positively to acidification.

Cultural Impacts from Ocean and Coastal Acidification

Healthy marine ecosystems support human communities in a variety of ways outside of providing economic benefits, such as supporting nutritional needs and health, providing recreational benefits, having spiritual or intrinsic value, and by being a part of their cultural heritage. However, the full extent to which marine ecosystems provide cultural value to various communities is not always well-characterized, making it difficult to predict how these benefits may be threatened by acidification and other environmental stressors [325, 326]. Characterizing these values would allow for social and cultural impacts from acidification to be included in social vulnerability assessments.

Indigenous communities on the West Coast have strong cultural and spiritual ties to marine species based on thousands of years of use for Tribal religious and cultural ceremonies, subsistence, and commerce. Additionally, many Tribes also participate in recreational shellfish harvest and are currently or planning to engage in shellfish aquaculture. For these reasons and likely more that are unforeseen, Tribes are potentially vulnerable to ocean and coastal acidification. Several Tribes have treaties reserving their right to fish in usual and accustomed fishing areas, and some have created fishery commissions to coordinate Tribes' roles as natural resource co-managers. In cases where Tribes do not retain rights, Tribal engagement will be essential for maintaining cultural rights while managing fisheries that may continue to undergo closures [327]. Tribes possess traditional ecological knowledge that could serve to enhance our understanding of climate stressors and effects that are missed by other types of records and which could help build a broader understanding of resilience and adaptive capacity. Species that hold value for Tribes include **salmon** and **steelhead, halibut, Pacific hake, sturgeon, abalone,** and **lamprey**, among others [328]. A recent regional vulnerability assessment for the four coastal treaty Tribes from the Olympic Coast of Washington underscored the importance of species, such as **crab, razor clams, halibut, and olive snails**, to the Tribes and the vulnerability of these species to projected conditions.

Evaluating Sensitivity of Communities: Current Work and Research Gaps

While evaluating the economic and social value of marine species threatened by acidification is an important first step, understanding the factors that influence the sensitivity of communities to changes in these resources is also key. For example, if commercial fisheries make up a larger portion of the local economy or fishermen are dependent on a few species that are all potentially sensitive to acidification, this could lead to more adverse impacts. Certain demographic factors, like poverty, education, and crime levels, may also indicate communities that would be more sensitive to further economic or cultural hardship. Additionally, a community's sensitivity to acidification may be influenced by other social and ecological stressors that the community is facing, such as COVID-19, poverty, or food insecurity. However, adaptation strategies can address multiple social stressors. Washington Sea Grant leveraged findings from ocean acidification vulnerability work to develop a food security rapid COVID-19 response in partnership with the Makah Tribe. Considering the synergistic, antagonistic, and cascading effects of these multiple and compounding stressors on human communities is important when evaluating how they may be affected by increasing acidification.

Social indicators can be useful in assessments to monitor conditions, inform adaptation planning, and improve human wellbeing [329]. Social indicators for coastal communities have been incorporated into NOAA's California Current Integrated Ecosystem Assessment's annual state-of-the-ecosystem reports [330]. Coastal communities are evaluated using a community social vulnerability index that is derived from social vulnerability data (demographics, poverty, housing, labor force structure), and this is mapped against a commercial fishing reliance index that reflects per-capita engagement. In 2021, the communities that scored high for both fishing reliance and social vulnerability were La Push, Taholah, Westport, and Baycenter, Washington, and Port Orford and Winchester Bay, Oregon [330]. Communities with high scores are expected to be the most sensitive to downturns in the commercial fishing industry; further work is needed to develop indicators to be applied in an ocean acidification-specific evaluation.

Washington Sea Grant has also developed a suite of social indicators for the four coastal Washington counties in support of the Washington integrated ecosystem assessment. They developed 59 indicators across 10 domains of human wellbeing: basic needs; access to social services; health; education; social connectedness; governance: planning and management; safety; environmental conditions; economic security; and population demographics [329].

Ultimately, fine-scale assessments of social vulnerability are needed to understand which communities are most at risk from ocean acidification and what actions are needed in response. Three regional vulnerability assessments for the West Coast provide important insights and inform future work in the region.

The first project focused on evaluating the vulnerability and adaptive capacity of stakeholders that are reliant on oysters and mussels in the Pacific Northwest. The project explored variations in shellfisheries' exposure to ocean acidification and quantified production losses. They also identified potential pathways for adaptation, as well as barriers to and costs of different strategies, which were incorporated into behavioral models to predict the likelihood of users adopting specific strategies. This work helped determine the cost of ocean acidification to shellfish stakeholders and model adaptation pathways that would maximize resilience. This framework could be used to assess shellfisheries in other regions that have yet to experience ocean acidification impacts.

The second project assessed the ecological and social vulnerability of Tribal communities on the Olympic Coast (Washington) through a place-based approach. It used original social science research, synthesis of existing chemical and biological data from open ocean to intertidal areas, and model projections, to assess current and projected Olympic Coast vulnerabilities associated with ocean acidification. They aimed to identify community-driven strategies that could increase the Tribes' ability to prepare for and respond to ocean acidification. This information will help decision-makers better anticipate, evaluate, and manage societal risks and impacts. The research was done in partnership with Tribal co-investigators and regional resource managers from start to finish and is rooted in a focus on local priorities for social, cultural, and ecological health and adaptive capacity.

The third regional vulnerability assessment aims to fill knowledge gaps about the vulnerability and adaptive capacity of West Coast coastal communities, particularly those reliant on shellfish aquaculture or harvests, to ocean acidification. The project will assess the factors that contribute to the vulnerability of six communities in Oregon and California to ocean acidification and what specific strategies these communities are implementing to adapt, in addition to evaluating the barriers they face. This study addresses the common gap of implementable actions tailored to impacted communities by identifying specific strategies the communities are taking or wish to implement to adapt to acidification. This work's findings will inform policy and investments at the state government level that can foster and support more resilient communities by supporting these strategies. For example, this project identified that while shellfish growers are concerned about ocean acidification, they are experiencing other more pressing stressors, such as marine pathogens [331]. Building resilience to such stressors through research or policy changes could also make communities resilient to acidification.

Adaptive Capacity of Communities

The degree to which ocean acidification is perceived as a threat could shape how communities take action; therefore, education and collaboration with stakeholders could serve to increase adaptive capacity. There are existing examples of community-driven adaptation that can serve as useful models for future efforts built around collaboration. Washington Sea Grant worked with the Squaxin Island Tribe to explore the cultural importance of Tribal shellfish harvesting and how it may be impacted by changing environmental conditions, such as ocean acidification. They worked with the community to identify indicators of health and well-being and found that physical health, cultural use and practice, and community connections were the most vulnerable. This led to the idea of establishing a community garden, which was then implemented by the Tribe. Another example of a Tribe developing their own resilience and adaptation strategy is the first foods and resources curriculum developed by the Swinomish Indian Tribal Community. Lastly, Washington Sea Grant also led an ethnographic effort with West Coast fishing communities facing climate change to understand the social factors that are involved in fishermen's responses to change, with the goal of better preparing for and mitigating the effects of climate change.

There are a variety of organizations that could assist to increase community resilience to ocean acidification, either through sharing data or research outcomes, informing needed mitigation strategies, raising awareness of how ocean acidification could impact communities, or being able to leverage existing relationships focused on addressing environmental or social stressors. These include, but are not limited to, Sea Grant programs, National Marine Sanctuaries, National Estuary Program sites, and National Parks. The Olympic Coast National Marine Sanctuary was designated as an ocean acidification sentinel site. One example of Sea Grant's work is that Washington Sea Grant social scientists are partnering with Tribal communities to foster culturally-specific resilience actions, such as restoration of clam gardens. Additionally, the Sea Grant Indigenous Aquaculture Hub is bringing together practitioners from Indigenous communities in Washington, Hawaii, Alaska, and British Columbia to review Indigenous practices as an adaptation and resilience strategy. In order to address the negative impacts of nutrients, including acidification, Washington State has initiated the Puget Sound Nutrient Source Reduction Project, with the goal of reducing anthropogenic nutrient sources. The California Current Acidification Network plays a role in building capacity around acidification in the region. The network is a collaboration of interdisciplinary scientists, resource managers, industry, and others from local, state, federal, and Tribal levels and has an important role in helping communities understand the potential impacts of ocean acidification.

Existing policy structures can help build resilience to ocean acidification impacts on the West Coast, which has a rich history of ocean acidification planning. These structures can aid in ensuring that acidification is considered in the context of other ocean management concerns, including the development of offshore wind farms on the West Coast. Washington was the first state to convene a body focused on acidification; in response to hatchery production issues, their governor created the Washington State Blue Ribbon Panel on Ocean Acidification in 2012. The panel's report provided recommendations for understanding, reducing, and adapting to the consequences of ocean acidification, which were updated in 2017. From 2013-2016, California convened the West Coast Ocean Acidification and Hypoxia Science Panel in partnership with Oregon, Washington, and British Columbia. The panel developed a suite of products that synthesized the science around ocean acidification and recommended actions that could be taken by states to address it. Based on this panel's recommendation, California convened the California Ocean Acidification and Hypoxia Task Force in 2018 to provide scientific guidance to the California Ocean Protection Council to inform continued actions to address acidification and hypoxia. In Oregon, the state created the Oregon Coordinating Council on Ocean Acidification and Hypoxia in 2017 to provide recommendations to the state on ensuring the sustainability of marine resources in the face of increasing acidification. Additionally, all three West Coast states were founding members of the International Ocean Acidification Alliance and have developed ocean acidification action plans, which address building the resilience of communities and industries [332]. These documents outline adaptation measures and steps to build resilience against ocean and coastal acidification. Evaluating different management alternatives for addressing ocean acidification and creating tools to evaluate their socioeconomic benefits will aid in successful response to societal challenges induced by ocean acidification.

6.2 Knowledge Informing Social Vulnerability

6.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

Over the last decade, federal, state, local, and Tribal partners have supported a range of ocean and coastal acidification observations and monitoring efforts on cruises, moorings, volunteer observing ships, profiling floats, and gliders in the continental shelf waters of the U.S. West Coast [333]. Research cruises (e.g., NOAA West Coast Ocean Acidification Cruises) provide the highest-quality physical, chemical, and biological measurements, yielding valuable information on the extent of cumulative ocean acidification exposure and associated biological response [251, 264, 302, 307, 309, 334). Sensors on fixed moorings (e.g., buoys operated by Olympic Coast National Marine Sanctuary, Monterey Bay Aquarium Research Institute, and the California Coastal Observing Network, among others) and autonomous vehicles (e.g., NOAA's saildrones and wave gliders) provide observations with high temporal or spatial resolution, respectively, and can capture the full range of carbonate chemistry variability [193, 335-337]. Discrete sampling, such as that done in National Parks, also contributes to understanding of carbonate chemistry and is often done in coordination with cruises or continuous monitoring programs.

Monitoring is also important in areas of ecological and cultural significance, such as National Marine Sanctuaries, state-designated marine protected areas, National Estuary Program sites, National Estuarine Research Reserve System sites, and areas designated as Essential Fish Habitat by NOAA Fisheries, as these areas contain habitats and species that may be vulnerable to ocean and coastal acidification. Monitoring has been supported by a variety of partnerships on the West Coast. On the Olympic Coast, the Quinault Indian Nation and Quileute Tribe have made valuable contributions to oceanographic and biological monitoring efforts. Community science partnerships have increased monitoring in the intertidal, including in marine reserves [338]. Industry collaborations provide monitoring data in estuaries in the vicinity of shellfish aquaculture operations (e.g., Netarts, Oregon, Humboldt Bay, California, Tomales Bay, California, Willapa Bay, Washington).

The Pacific Coast Collaborative and Interagency Working Group on Ocean Acidification worked together via the West Coast Ocean Acidification Task Force to conduct a more complete inventory of monitoring assets in the region; this inventory has been used to create a map of ocean acidification and hypoxia monitoring on the West Coast. Although ocean and coastal acidification monitoring in West Coast waters is robust, assets were deployed for a variety of reasons; many monitoring sites were established for specific research or management objectives and have challenges with continuity given a lack of continuous, long-term funding [339]. Data collection along the coast varies both in temporal and spatial density, as well as in sensors used, which parameters are measured, and quality control of the data. This highlights the need for strategic coordination to make improvements to monitoring and building a robust monitoring network.

Throughout the region, there is the need for more monitoring of both benthic and pelagic environments and establishing monitoring in areas that can inform water quality, aquaculture and fisheries, and sanctuaries management. Because species will respond to ocean and coastal acidification in combination with other stressors, co-stressor monitoring should be incorporated, including temperature, dissolved oxygen, nutrients, and harmful algal bloom (HAB) species and domoic acid. There is also a need for more biological monitoring to be co-located with chemical ocean acidification monitoring to understand the impacts of acidification on species and delineate ecosystem responses to physical and chemical changes over time; the California Ocean Science Trust and Ocean Protection Council are working to address this [340]. More frequent sampling and tracking of zooplankton, ichthyoplankton, and forage fish, both temporally and spatially, will inform how the base of food webs is being impacted, which could have implications for both recreational and commercial fisheries.

There are gaps in spatial coverage along the region, with coverage generally weakest at nearshore and at depth, where exposure might be greatest [341]. Maintaining long-term ocean acidification monitoring stations across spatial gradients is important for long-term trend assessment and model predictions, but this requires sustained investment and support [341]. Biogeochemical Argo floats are helping to fill the gap of monitoring at depth; five floats have been deployed in the California Current Ecosystem and are measuring pH across the upper 2,000 meters. There are gaps in monitoring in coastal and estuarine environments, where monitoring can help elucidate how local atmospheric inputs, riverine inflow, local pollution inputs, and other factors contribute to near-shore acidification in critical ecosystems. Current cruise sampling does not take place in most major estuaries or coastal rivers, though the Washington Ocean Acidification Center conducts three seasonal cruises throughout the Salish Sea for ocean acidification variables and plankton, including pteropod shell dissolution [342, 343]. More frequent monitoring that captures daily pH fluctuations and the range of variability in pH are necessary for more accurate understanding of biological responses in the nearshore habitat [310, 344].

In some West Coast waters, algorithms have been developed to predict aragonite saturation state from more commonly measured temperature, salinity, and dissolved oxygen, which can supplement data gaps [345-347]. There is also a need to ensure that carbonate chemistry data are easily discoverable and accessible to researchers, stakeholders, and decision makers, as this is not always the case. The Olympic Coast National Marine Sanctuary (OCNMS) has proposed making their mooring report available in near real time so that the affected communities, including four coastal treaty Tribes (Makah, Hoh, Quileute, Quinault), can access information on current conditions.

Improvements to ocean acidification monitoring on the West Coast can be done by leveraging existing monitoring programs and assets. Enhanced collaborations between federal and state agencies, Tribes, and local communities will also be essential for expanding monitoring capabilities [348]. The current partnership between NOAA OAP and IOOS for mooring observations has been effective and could be further expanded. IOOS assets, such as gliders, can be outfitted with sensors to measure or derive ocean acidification variables. Partnerships with fishermen, shellfish growers, and community science groups could be an opportunity to expand monitoring [348, 349]. Further opportunities to leverage existing monitoring programs to expand carbonate chemistry data collection will be explored in the IWG-OA monitoring prioritization plan.

Ocean and Coastal Acidification Modeling

Biogeochemical models play a crucial role in providing information about the extent and variability of ocean acidification, especially as there are limitations to the data provided by a fixed number of monitoring assets. Several ocean acidification models have been developed for portions of the West Coast that describe current and future conditions. Hindcast models have also been used to describe the spatial extent and duration of ocean acidification extremes in the region [350].

The University of Washington's former Joint Institute for the Study of the Atmosphere and the Ocean (JISAO) developed a model system called J-SCOPE (JISAO's Seasonal Coastal Ocean Prediction of the Ecosystem), which provides seasonal forecasts (three to six months out) of ocean conditions for Washington and Oregon, including aragonite saturation state. J-SCOPE forecasts are developed to inform management decisions for fisheries, protected species, and ecosystem health. The Washington Ocean Acidification Center and NANOOS jointly support the LiveOcean model that forecasts ocean acidification and other variables 72 hours out for the Washington-Oregon coastal ocean and the Salish Sea. Using this spatial domain, Siedlecki et al. made projections in 2021 out to the end of the century, concluding that coastal processes modify projections of some climate-driven stressors in the California Current System [316]. A third biogeochemical model in the Pacific Northwest has been developed by the Department of Energy's Pacific Northwest National Laboratory for the Salish Sea; the model is used for analysis of water quality and circulation, nutrient pollution management, and response to sea level rise, climate change, and ocean acidification. The model has been used to create end-of-century projections for pH, temperature and salinity in the Salish Sea; while the Salish Sea is predicted to be more resilient than the continental shelf due to vertical circulation and mixing, pH is expected to be as low as 7.2 in certain areas of Puget Sound [315].

A research team at UCLA and collaborators have developed an ocean acidification and hypoxia model for the entire California Current Ecosystem, with regional downscaling into coastal sub-regions with finer spatial resolution. The model has been used to validate historical estimates of acidification, demonstrate the consequences of local pollution input, and create forecast climate scenarios. The model has also been used to study the impacts of enhanced nutrient pollution in the Southern California Bight; the simulation showed that nitrogen inputs significantly increase phytoplankton biomass, reduce oxygen levels, and increase acidification [351]. Further studies include central California pollution effects, biological impacts, wastewater treatment scenarios, and nearshore processes.

Support for continued development and improvement of ocean acidification numerical models is needed to improve the quality of estimates at daily to decadal timescales. There are geographic gaps (e.g. in Northern California) in availability of ocean acidification forecasts and projections. Model predictions can serve as useful tools, but it is important to coordinate with potential users (e.g., Tribes, state and federal natural resource managers, place-based managers, pollution managers, aquaculture industry) to understand the resolution and timescales that would provide relevant information for supporting decisions. Potential resource management decisions that model simulations can inform include field out-planting of shellfish within optimal temperature and carbonate chemistry windows [15].

Sustained monitoring observations across spatial gradients, including near-shore to off-shore, are important for improving model predictions. Observation optimization studies can also inform how additional observations could improve models. One current study is working to identify gaps in ocean acidification observations on the California Coast, by assessing improvement in forecast models resulting from incorporation from field observations. Additionally, further research is needed into the mechanisms and processes driving variability in the carbonate system over different timescales, as this will reduce uncertainty in predictions [305, 352, 353].

6.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

Knowledge of marine species' ocean and coastal acidification sensitivities has substantially increased since the early recognition of the role of changing seawater carbonate chemistry in oyster hatchery production problems in the Pacific Northwest [239, 314]. Laboratory work has revealed that numerous West Coast species, including **Dungeness crabs** [263, 354], **coho salmon** [208], **krill** [355], **urchins** [356], and **pteropods** [357, 358], are sensitive to ocean acidification conditions. Field evidence on pteropods, foraminifera, and copepods supports these conclusions [302, 309, 251, 358-364]. These effects manifest in shell deformity, weakness, and thinning in calcifying organisms such as clams, oysters, and gastropods [365, 366], carapace dissolution in crabs [264], and impacts on larval development in economically important species, such as oysters and Dungeness crab [18, 264].

Needed Research on Economically Important Species

The West Coast is home to economically significant marine species with important life stages that inhabit depths below the productive, sunlit surface. While the surface ocean contains the highest anthropogenic CO_2 concentration from air-sea exchange processes, the subsurface environment is subject to considerably greater stress due to the combined effects of both natural and anthropogenic CO_2 sources [301-303, 309, 316, 367-369]. Many regionally important species, like Dungeness crab, occupy a variety of habitats throughout their life cycles, from the coast to the shelf edge, and from benthic to surface waters [338, 370].

There are large gaps in understanding the cascading impacts of acidification to food webs that will be key for understanding impacts to commercial species that occupy higher trophic levels [371, 372]. Species sensitivity research that considers co-stressors should also be expanded—only an estimated 20% of around 100 economically relevant species have been studied for ocean acidification sensitivity, particularly over multiple life stages [341]. There is also a need to expand genetic studies that can understand the adaptation potential or inherent resilience of commercial species, such as Pacific oysters. While commercial harvesting focuses on Pacific oysters, there is also interest in restoring populations of native Olympia oysters, which had historical importance on the West Coast, making it important to continue research on this species as well [373, 374].

Current and Needed Research on Impacts to Populations and Ecosystems

Ecosystem-wide, ocean-acidification impacts projections are often derived from syntheses of disparate studies or through ecosystem modeling. Scenarios of ocean acidification imposed on current ecosystem models project an interactive effect of ocean acidification and upwelling along the California Current system, which may negatively impact epibenthic invertebrates such as crab, shrimp, bivalves, grazers, and detritivores [371, 375, 376]. There may also be food web effects for higher trophic-level species, such as fish and sharks [371, 372, 377, 378]—impacts which may also affect fisheries. It is also possible that ocean acidification can cause ecosystem-level impacts by affecting animal behavior and species interactions. For example, ocean acidification can disrupt anti-predation behavior in sea snails in response to sea stars, which may have widespread ecological implications, and influence the olfactory system of salmon [208, 365, 379].

Large gaps exist in understanding population-wide and ecosystem changes to ocean acidification. Unknowns include how changes at the individual and species level will influence broader populations, communities, and food webs [217, 380]. Tribal long-term observations of ecosystem change and traditional ecological knowledge should be used to inform this research. Results from species-specific and laboratory-controlled studies are more difficult to extrapolate to larger temporal and spatial scenarios than studies that use research approaches in natural systems covering longer timescales, multiple life stages, and multiple stressors latitudinally throughout the water column [323, 381, 382]. West Coast-focused meta-analyses and synthesis work suggest that sensitivity research on a broader range of species, ways to infer both sensitivity and vulnerability among related species, and species risk studies are needed to effectively project ocean acidification impacts on marine ecosystems [343, 361, 370, 375, 383-386). When possible, carbonate chemistry parameters at which biological impairment begins should be quantified.

Coupling biological monitoring with chemical monitoring is a key need to understand impacts on ecosystems and inform water quality assessments. Additionally, indicators are needed to monitor the biological ramifications of progressing ocean and coastal acidification. Pteropods could be used as effective indicators because of their well-understood sensitivity to acidification conditions, which allows for more certain projections and monitoring of biological responses of this species [343].

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

Hypoxia commonly co-occurs with ocean acidification along the U.S. West Coast [303]. This is especially the case in deeper waters off the coastal shelf, where reduced mixing prevents re-oxygenation. Hypoxia can be further exacerbated by warming ocean temperatures—resulting in increased ocean stratification and decreased oxygen solubility in warmer waters. The concurrence of ocean acidification and thermal stress in the form of marine heat waves and El Niño events, such as that experienced in 2014-2016, can result in large negative impacts to local species [360].

Kelp and seagrass are also highly sensitive to temperature stress and disease, which in turn affects their ability to support species vulnerable to acidification and to sequester carbon [387-389]. Other habitats vulnerable to acidification and co-stressors include oyster reefs and deep-sea corals. Marine heat waves, upwelling, hypoxia, and ocean acidification can all overlap temporally along the California Current System, but research is needed to understand additive and interactive effects. There is potential that these co-stressors could cause shifts in ecosystem structure that feedback to tip vulnerable ecosystems into new states; future research should consider such complexities [390].

Coastal eutrophication can also lead to localized hypoxia and acidification, as excess nutrients promote increased respiration of sinking organic matter, resulting in acute increases in $p\mathrm{CO}_2$ and depletion of oxygen [351, 386]. Hypoxia, warming waters, and ocean acidification also interact with phytoplankton species that form HABs. HABs on the West Coast produce toxins that can bioaccumulate in shellfish, other invertebrates, and sometimes fish, leading to illness and death in seabirds and marine mammals. HABs have large economic impacts; the large-scale HAB event in 2015 associated with the 2014-2016 marine heatwave delayed the lucrative Dungeness crab fishery opening by five months [391]. Acidification can increase toxicity and growth rates of some HABs in laboratory settings, and more research is needed to understand how hypoxia and ocean acidification affect the frequency and severity of HAB events [340, 392, 393]. The impacts of ocean and coastal acidification and multiple stressors on West Coast ecosystems will be variable in space and time, as regions along the West Coast will face differing levels and combinations of stressors that will all need to be monitored and addressed individually [338].

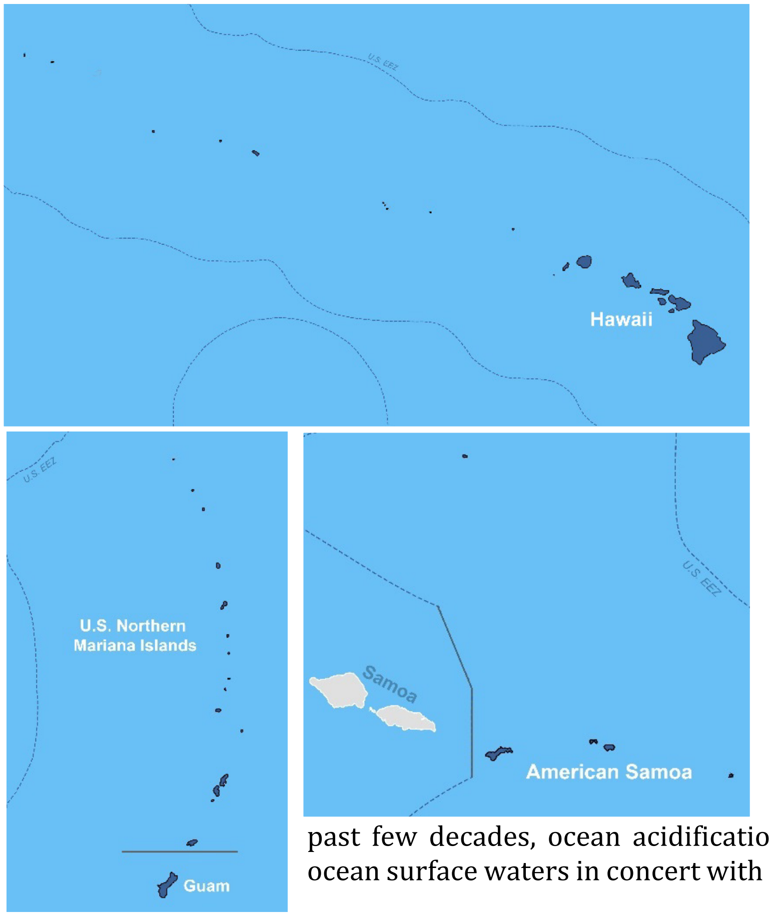
Understanding causes of biological and ecological resilience to ocean acidification and simultaneously occurring co-stressors will be crucial to management in the region. Currently, there are gaps in understanding genetic traits that convey resilience at the strain, species, population, ecosystem, and interactions level [341]. Molecular approaches may be helpful in discerning mechanisms driving species sensitivity [217]. Genetic research can aid in understanding inter- and intra-specific variation to ocean acidification sensitivity; abalone populations have been shown to have varying ocean acidification tolerance depending on their source—those from a strong upwelling region are generally more tolerant to ocean acidification [394].

Researchers are also working to understand if submerged aquatic vegetation could offer localized resilience by alleviating low-pH conditions [395]. There is also potential for seagrass to provide mitigation through long-term storage of blue carbon, although this could be jeopardized by eelgrass wasting disease, which is exacerbated by warming [331, 396-399]. States on the West Coast are interested in utilizing seagrasses and seaweeds in both resilient aquaculture and carbon sequestration, although large questions remain about the efficacy of long-term carbon storage and how ocean change could impact the potential for expanding cultivation [389].

7.0 Pacific Islands Region

Key Points

- The Pacific Islands are home to diverse communities, many whose way of life is strongly tied to the marine environment.
- Coral reefs, which support tourism and provide coastal hazard mitigation, are expected to be impacted by ocean and coastal acidification.
- While there is extensive coral reef monitoring, other ecosystems are not as well-monitored for ocean and coastal acidification.



The U.S. Pacific Islands region includes the Exclusive Economic Zones surrounding the State of Hawaiʻi, the Territories of Guam and American Samoa, the Commonwealth of the Northern Marianas Islands (CNMI), and the U.S. Pacific Remote Islands. These islands are widely scattered across the western and central Pacific Ocean, covering an immense geographic area that spans dramatic gradients in climate and ocean conditions. Some areas are more urbanized and subject to nutrient pollution, sediment loading, and physical disturbance, including from tourism. However, there is limited local anthropogenic stress in most of the region, as many of the islands and atolls are remote, uninhabited, and federally protected. The Pacific Islands are impacted by climate change and variability, which drives large interannual and decadal shifts in ocean conditions. Over the past few decades, ocean acidification has measurably progressed in open ocean surface waters in concert with rising atmospheric CO_2 concentrations.

The region is home to a group of island communities whose way of life is intrinsically linked to the marine environment. There is a broad diversity and range of island communities, people, and economies in the region, ranging from islands such as Ofu and Olusega in American Samoa, with a population of a few hundred, to islands such as Oʻahu, with a population near one million. The region has many distinct qualities from the continental United States and is home to underserved communities that have not received equitable treatment and investment historically.

7.1 Social Vulnerability: Understanding Impacts to Communities and Their Potential for Adaptive Capacity

Many communities are tied to coral reef ecosystems, which provide goods and services through subsistence, fisheries, tourism, and coastal hazard mitigation. These marine species and ecosystems will likely be negatively impacted by ocean acidification, but it is unclear exactly how this will translate to social, cultural, and economic impacts. Communities in the Pacific Islands are facing parallel environmental threats from climate change, including sea level rise, ocean warming, and extreme weather events, that are also expected to worsen in the coming decades [400-402]. While this may make communities more sensitive to further threats from ocean acidification, actions taken to increase resilience to ocean warming and sea level rise could create tangential resilience to ocean acidification as well. More work is needed to understand exactly how communities will be affected and respond to increasing acidification. The following section describes the socioeconomic value provided by marine species to communities and describes how their sensitivity and adaptive capacity could be evaluated to better understand social vulnerability to ocean acidification.

Economic Impacts from Ocean and Coastal Acidification

The marine environment provides economic value to the Pacific Islands by supporting commercial and non-commercial fisheries, aquaculture, tourism, and recreation, in addition to providing economically important ecosystem services. Fisheries and the marine environment also hold deep spiritual and cultural meaning for many communities [403, 404]. The marine environment contributes cultural ecosystem services (i.e. non-material benefits) that contribute to human well-being [405, 406]. Overall, there have not been direct studies assessing the negative impact to these sectors that could occur from ocean acidification. Although the exact impacts that will result from ocean acidification are unknown, the following sections describe the value that potentially threatened marine resources provide to these communities.

Commercial Fisheries: Commercial fisheries provide economic value to the Pacific Island communities and promote regional food security. Table 13 shows the landings revenue generated across Hawaiʻi, American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands (data on number of jobs, sales, and income generated by the seafood industry were not available for the entire region). Important species include **tunas (skipjack, albacore, yellowfin, and bigeye), wahoo, dolphinfish, swordfish, moonfish, mahimahi, and Pacific blue marlin**. In 2018, Honolulu was the seventh highest valuable port in the Nation in seafood value ($106 million), and Pago Pago in American Samoa was the nation's fifth-ranked port in seafood value ($132 million) and ninth-ranked port in pounds landed (186.7 million) [13]. Additionally, the Starkist Samoa Cannery continues to play a vital role in the U.S. food supply chain, with average annual canned tuna exports to the United States of approximately $400 million per year in recent years [407].

Table 13: The total adjusted commercial revenue (U.S. dollars) generated by commercial fisheries by state or territory in the Pacific Islands in 2019 (Data from Western Pacific Regional Fishery Management Council).

	HAWAI'I	AMERICAN SAMOA	GUAM	CNMI
Total Adjusted Commercial Revenue	$109,049,733	$4,090,754	$455,701	$649,216

Non-commercial Fishing: There is also a substantial amount of non-commercial fishing, which includes recreational fishing, subsistence, and traditional Indigenous fishing, in the Pacific Islands [408]. These fisheries also are important economic contributors to communities, in addition to having social and cultural value by continuing subsistence and traditional fishing practices. In Hawaiʻi, recreational fishermen took 3.5 million saltwater fishing trips in 2019; Table 14 details the economic value of the industry to the state [13]. Some of the key species for Hawaiʻi's recreational fishing include **bigeye and mackerel scad, jacks, goatfishes, dolphinfish, snappers, wahoo, and yellowfin tuna**. The same economic data are not available for American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands, which makes it difficult to assess potential impacts from ocean acidification. Important species include **rainbow runner, dogtooth tuna, and bluefin trevally** for American Samoa; **skipjack tuna, trevally, dolphin fish, and long-tail red snapper** for CNMI; and s**kipjack tuna, yellowfin tuna, wahoo, dolphin fish, and convict tang** for Guam [409]. Additionally, some individuals fish for multiple purposes; they may sell a portion of their catch and use the rest to feed their families or gift to their neighbors. Fishers play a vital role in supporting local food systems, nutrition, food security, and promoting community social cohesion [410].

Table 14: The economic impact of recreational fishing expenditures in Hawaiʻi in 2019 [13]. Sales represents the gross value of both direct sales by the angler and sales made between businesses and households resulting from the original sale, and income includes wages, salaries, and self-employment income. All amounts are reported in 2019 U.S. dollars.

	Jobs	Sales	Income
HAWAI'I	2,911	$399,967,000	$123,736,000

Tourism: Tourism is very important to the economy of the Pacific Islands. Much of this tourism is supported by the natural marine environment of the region, including coral reefs. As ocean acidification progresses, coral reefs may be threatened, which could hurt the tourism industry. Capturing the value of coral reefs to the tourism industry is difficult, but some economic studies have provided estimates. For example, in 2004, Spurgeon et al. estimated the value of corals in American Samoa to be $1.28 million in direct and indirect use value, and $8.8 million in non-use value (beauty value, bequest value, existence value) [411]. An economic valuation of Hawaiʻi's coral reefs estimated over $300 million in benefits to the recreation or tourism industry [412]. In Saipan, Commonwealth of the Northern Mariana Islands, research estimated that coral reefs provided over $42 million to the tourism industry, while coral reefs provided over $94 million to the tourism industry in Guam [413, 414]. NOAA's Coral Reef Conservation Program is conducting a multi-year ecosystem services valuation of all U.S. coral reefs to provide updated estimates.

Coastal Hazard Mitigation: As mentioned previously, coral reefs play a crucial role in coastal hazard mitigation by attenuating wave energy and preventing flooding. A USGS study provided an estimation of yearly value provided in flood protection by coral reefs (in 2010 U.S. dollars) [108]. Coral reefs protected economic activity annually of over $492 million in Hawaiʻi, $7 million in American Samoa, $8 million in the Commonwealth of the Northern Mariana Islands, and $10 million in Guam. Ocean acidification could contribute to reef degradation, resulting in direct economic impacts through loss of coastal resilience.

Cultural Impacts from Ocean and Coastal Acidification

Cultural ecosystem services represent the non-material benefits provided by a natural resource, such as aesthetic, emotional, or spiritual experiences. The marine environment, including coral reefs and other species, contribute to personal and community well-being in a variety of ways. For example, research in West Hawaiʻi identified some of the most important cultural ecosystem services to be fulfilling stewardship; heritage, tradition, and culture; recreation; sense of place; social relations; and spirituality [406]. Further work to develop metrics for cultural ecosystem services and human well-being is needed for these values to be incorporated into social-ecological management frameworks, as there are challenges to doing so [15, 415].

Evaluating Sensitivity of Communities: Current Work and Research Gaps

There is still a large research need to evaluate and project effects of ocean acidification on marine resource-dependent industries, local fisheries, ecosystem services, and the well-being of human communities. This will require coupling environmental and ecological dynamics with human-use sectors and non-use values in ecosystem models [15]. Creation of these models will require identifying relationships between biophysical, fishery, and ecosystem parameters and social, cultural, and economic drivers [15]. Large socioeconomic data gaps remain that will need to be addressed to create these models and assessments. Additionally, work can be done to parameterize economic impact models and social indicators to evaluate how ocean acidification affects the vulnerability of industries and potential impacts to communities. Also, regional economic impact and behavioral models for marine resource-reliant industries can help evaluate alternative management strategies for mitigating ocean and coastal acidification [15]. Local mitigation planning and management will be supported by coupling analysis of biological sensitivity with social vulnerability and adaptive capacity frameworks and working in partnership with communities [15].

Aside from assessing the impact to economically, socially, and culturally valuable marine resources from increasing acidification, understanding social vulnerability to acidification will depend on also assessing factors that increase sensitivity of human communities. NOAA Fisheries has developed a suite of social indicators at a national level that are meant to characterize and evaluate a community's vulnerability and resilience to disturbances (see page 3). While these indicators have not been used to evaluate vulnerability to ocean acidification, they may be useful in providing data to assess general social vulnerability of communities. The national indicator dataset only includes information for Hawaiʻi in the Pacific Islands, but NOAA has taken steps to evaluate indicators for additional communities, with initial results presented in Kleiber et al. in 2018 [416]. They noted that these indicators can be refined over time, and not all indicators may be appropriate measures of vulnerability for island communities. For example, certain measures of social vulnerability may not be relevant to the non-market-based economy and land tenure traditions of American Samoa. Ongoing work will apply these community vulnerability indicators to consider ocean acidification impacts on fishing community engagement and reliance [15]. There are also other social vulnerability frameworks that could be used to evaluate vulnerability to acidification; existing climate change vulnerability assessments in the region may inform assessments of vulnerability to ocean and coastal acidification at finer scales. For example, a climate change vulnerability assessment for the island of Saipan rated community vulnerability to impacts of acidification on fish as medium [417].

There has been limited work to assess social vulnerability specific to ocean acidification in the Pacific Islands Region. Some Atlantis ecosystem model studies have incorporated conceptual models of human dimensions impacted by ocean acidification related to fisheries and marine tourism [418-420]. NOAA's National Coral Reef Monitoring Program conducts socioeconomic surveys in Hawaiʻi, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands once every three to five years. These surveys help provide understanding of how residents' perception and awareness about threats to coral reefs, including ocean acidification, is changing over time [421-425]. Better understanding of public awareness and perception is important for informing future planning and investments in adaptation strategies for local communities [15]. Conducting vulnerability assessments with an emphasis on social, cultural, and economic vulnerabilities was identified as an action item in the Hawaiʻi Ocean Acidification Action Plan. Together with assessments of changing ocean conditions and social perceptions, a better understanding of community vulnerabilities will inform effective management strategies [15].

A new regional vulnerability assessment funded by NOAA is working to address vulnerability in the Hawaiian Islands. This project is addressing the need to better understand spatial and temporal variability in ocean conditions and how they are likely to change over time by projecting the frequency, duration, spatial variability, and severity of ocean acidification events across the region for the period 2020-2070. The project will also evaluate the vulnerability of communities using relationships between ecological and social components and building upon previously described work to develop social indicators. This work will give managers the ability to evaluate tradeoffs between different management practices to determine which interventions are most effective in preserving ecosystem integrity and enhancing societal wellbeing. NOAA's Pacific Island Fisheries Science Center also has ongoing research to couple the community social vulnerability framework with the Pacific Islands Vulnerability Assessment to explore communities' vulnerability to climate change.

Adaptive Capacity of Communities

Understanding vulnerability will also depend on identifying individual and management actions, as well as organizations that can increase resilience to ocean acidification and provide support to communities. This may be informed by existing climate adaptation planning efforts in the region [426]. One potential example is the incorporation of ocean acidification into ecosystem-based fisheries management, using metrics of human wellbeing and cultural ecosystem services [15]. Increasing financial and political investments could also impact the success of adaptation actions; this could be challenging for some of the small island territories and represents an important opportunity to address equity and environmental justice [15]. Additionally, increasing community awareness of ocean acidification could be a step in building resilience. Overall, community engagement is of utmost importance; community perspectives should be respected and incorporated when identifying adaptation and management actions. Additionally, science communications should be developed in culturally appropriate formats.

There are organizations already working with local communities to address climate change impacts to the marine environment that could help build local resilience, such as Hawaiʻi Sea Grant. Adaptation can also be built at the local government level. The State of Hawaiʻi has joined the International Alliance to Combat Ocean Acidification and has developed an ocean acidification action plan. Two of the goals of the plan are to build adaptation and resilience of coastal communities to the impacts of ocean acidification and to increase public understanding of ocean acidification.

7.2 Knowledge Informing Social Vulnerability

7.2.1 Exposure: Understanding Current and Future Levels of Ocean and Coastal Acidification

Ocean and Coastal Acidification Monitoring

Monitoring is key to understanding the level and variability of ocean acidification across the Pacific Islands region. NOAA's long-term coral reef monitoring, conducted as part of the former Pacific Reef Assessment and Monitoring Program (RAMP; 2000-2012) and current National Coral Reef Monitoring Program (NCRMP; 2013-present), has included co-located carbonate chemistry sampling and surveys of key ecological indicators for ocean acidification at 38 islands and atolls in the Pacific. The region also has several oceanographic moorings that collect near-continuous carbonate chemistry measurements. There is one open-ocean mooring at the Hawaiʻi Ocean Time-Series site north of Oʻahu, where monthly research cruises have occurred over the last 30 years, collecting measurements that document changes in ocean acidification. Four near-shore moorings were deployed around Oʻahu starting in 2005; in 2020, the two south-shore buoys were pulled out of the water. There are plans to redeploy these two buoys and an additional one off of the islands of Maui, Kauaʻi, and Hawaiʻi. The two buoys remaining in Oʻahu are in Kaneohe Bay; one characterizes the water entering the Bay, and the other on the back side of the barrier reef characterizes how corals modify the waters entering the Bay. There is also one mooring in Fagatele Bay, American Samoa, that was deployed in 2019. These high-frequency data complement the spatially-diverse but temporally infrequent *in situ* NCRMP monitoring, providing more insight into diel, seasonal, and interannual trends at sentinel sites [193, 427]. Despite being infrequent (once every three years in each Pacific Island jurisdiction), the *in situ* monitoring done as part of NCRMP remains some of the only long-term water chemistry datasets in the region.

In the open ocean, the international observing collaboration established under the Global Ocean Acidification Observing Network (GOA-ON) provides ocean acidification data integrated from repeat ship-based hydrography, volunteer observing ships, time-series stations, and moorings for the Pacific pelagic areas that support important commercial fisheries and highly-migratory protected species. Additionally, a public-private partnership involving the U.S. Department of State, NOAA Ocean Acidification Program, and The Ocean Foundation has supported capacity-building efforts across numerous Pacific Island nations, specifically focused on enhancing ocean acidification research and monitoring. Institutions across seven Pacific nations (Palau, Papua New Guinea, Fiji, Samoa, Tuvalu, Tokelau, Vanuatu) have received monitoring equipment kits, designed by GOA-ON, which have enabled high-quality ocean acidification research and monitoring to occur in locations where ocean chemistry data had not previously been collected. This program is expanding to send additional equipment kits to institutions in the region. A Pacific Islands regional ocean acidification training center has been founded, which will be used for training kit recipients, supplying them with spare parts, and providing ongoing data management and technical support for any ocean acidification researcher in the region. Additionally, NOAA is supporting graduate students in the Pacific Islands through a new fellowship program.

However, the exposure of much of the Pacific Islands region to ocean acidification remains poorly characterized. Assessing spatial and temporal trends remains a high priority; however, constraining regional-scale patterns of ocean acidification across the broad oceanographic gradients and large spatial area of the Pacific Island region presents an enormous challenge. Collecting additional data that describe spatial and temporal variability in ocean biogeochemistry and identifying ocean acidification hotspots and refugia will be important for informing management actions. Monitoring by moored buoys is also limited; additional monitoring in coral reef and off-shore locations would be beneficial. Currently, monitoring buoys are only deployed on one side of Oʻahu; expansion to the other Hawaiian Islands and other Pacific Islands is needed. Additionally, more off-shore discrete sample sites paired with nearshore discrete sample sites would allow researchers to better constrain the carbonate chemistry changes driven by coral reef benthic communities. There are also gaps in subsurface monitoring, especially in pelagic and deep-sea ecosystems, including mesophotic and deep-sea corals. Additional monitoring is needed to understand ocean acidification impacts on habitats across latitudinal and depth gradients across the Pacific, especially since waters undersaturated with respect to aragonite are occurring at shallower depths [165]. The Pacific Islands Ocean Observing System may be able to address some of these gaps through additional investment in their monitoring infrastructure.

Regional ocean and coastal acidification monitoring led by other nations in the Pacific region can potentially be leveraged to support U.S. efforts. Although each island in the Pacific has unique local conditions, useful comparisons can likely be drawn due to the similarities of Pacific Island climate, geology, coastal hydrology, and ecology; integrating disparate data sources from across the region may also enhance regional models and inform knowledge gaps. The Korean Institute of Ocean Science and Technology is engaged in ocean acidification monitoring; they support a mooring in Palau and a mooring in the Chuuk Lagoon in the Federal States of Micronesia; the latter is deployed in partnership with the United States. The Pacific Islands and Territories Ocean Acidification (PITOA) Hub can serve as a platform for building partnerships between U.S. and non-U.S. researchers. PITOA is a network of ocean acidification scientists and professionals in the region, and it is a regional hub of the Global Ocean Acidification Observing Network (GOA-ON).

Ocean and Coastal Acidification Modeling

Ocean acidification modeling efforts in the Pacific Islands region are still in the initial stages of development. Developing statistical models that fill in the spatial gaps between in situ observations, developing coupled hydrodynamic and biogeochemical models, and integrating remote sensing and model data to create hindcasts and predictive products are regional priorities [15]. To date, work on ocean acidification models in the region has only occurred in the Hawaiian Islands. There is a gap in models of ocean acidification in Guam, American Samoa, and the CNMI. For the main Hawaiian Islands, work has been done to couple hydrodynamic and biogeochemical models to improve the understanding of carbonate chemistry dynamics, and this will be expanded to the Northwestern Hawaiian Islands. There is also ongoing work to use remote sensing data, assimilative models, and *in situ* data to create time-varying regional maps of acidification in the main Hawaiian Islands.

To evaluate how coral reefs will respond to present and future ocean acidification stress, NOAA researchers are building statistical models to link offshore carbonate system measurements to interactions among nearshore carbonate system observations, benthic compositions, and on-reef seawater residence times, which is the amount of time a given parcel of water is over the reef. Survey data for benthic composition and carbonate chemistry data are available through NCRMP. Hydrodynamic model data are also available for a subset of these islands, but the scale of these models is often inappropriate to resolve local coastal processes. Ongoing efforts utilize existing regional ocean modeling system (ROMS) data to derive nearshore residence time information to better constrain the degree to which local benthos influences overlaying seawater chemistry. Preliminary estimates of residence time for Guam (Mariana Islands) and subsequent statistical modeling utilizing these estimates, combined with the wider NCRMP dataset, highlight the importance of including physical drivers, like residence time, in predictions of nearshore carbonate chemistry. Once preliminary modeling is complete for Guam, this method will be applied to the Florida Keys as well as other islands across the Pacific where suitable hydrodynamic model data are readily available. Ultimately, these efforts support development of a nearshore biogeochemistry model that will facilitate forecasting of future ocean acidification conditions on coral reefs.

There is a need for additional temperature, salinity, and carbonate chemistry data to calibrate and validate ocean acidification models. Additionally, there is a need for downscaled hydrodynamic and biogeochemical models (i.e., models with data shown at a finer spatial scale) at sufficient resolution to robustly capture nearshore areas of small Pacific Islands and atolls. Improved modeling will better characterize the exposure of the Pacific Islands region to acidification, as well as the spatial and temporal variability.

7.2.2 Biological Response: Understanding the Impacts of Ocean and Coastal Acidification to Marine Ecosystems

Current Knowledge of Impacts to Species and Habitats in the Region

In the Pacific Islands, **coral reefs** are the most vulnerable ecosystem to ocean acidification. Corals face a wide range of threats; 15 species in the region have been listed as threatened under the Endangered Species Act. The reef structure, composed of calcium carbonate, is susceptible to dissolution and decreased carbonate production. These weaker organisms are more likely to be eroded not only by physical forcing (e.g., waves), but from bioeroders (i.e., species that erode and weaken calcareous skeletons) such as sea urchins, bivalves, and boring sponge. Therefore, reef structure and complexity are expected to decline, making reefs less effective at protecting coastlines from breakwater, but also impacting the high biodiversity that structurally complex reefs normally support [124]. Not only can ocean acidification directly impact corals through reduced calcification rates, limited growth, and decreased density, but other physiological parameters like tissue thickness can be reduced, with each coral species having varying degrees of response to acidification conditions [428-431]. Branching and structurally complex corals (e.g., *Acropora spp.*) are predicted to be more sensitive than robust bouldering corals (e.g., *Porites spp.*) [432]. Furthermore, ocean acidification can indirectly impact corals through affecting recruitment success and by making coral bleaching even more harmful [433, 434].

Ocean acidification also reduces reproduction and survival for other calcifying reef organisms, such as **crustose coralline algae, crustaceans, and shellfish**. Crustose coralline algae provide a substrate for invertebrates to settle on, as is especially important in the rocky intertidal zone. However, under ocean acidification, crustose coralline algae has a weakened structural integrity and also decreased abundance, which means coral recruits have less area to settle [435-437]. Ocean acidification also alters the biochemistry of the crustose coralline algae and their associated microbial community, which also impacts chemical cues employed to induce coral larvae to settle on it [438].

Coral and crustose coralline algae cover are both predicted to decline under ocean acidification, which will impact coral reef ecosystems as a whole, since less habitat will be available for invertebrates, fish, and other marine life to settle and live on. Reduced invertebrate diversity and number and reduced demersal zooplankton, have been associated with habitat loss under ocean acidification [439, 440]. Very little is known about the impacts on zooplankton communities in the tropics and in the Pacific Islands, but these important microscopic animals remain at the bottom of the food chain, and impacts to them will have cascading impacts on the rest of the food web.

Knowledge of how ocean acidification may impact coral reefs is limited in the Pacific Islands, although most of the focus has been conducted in shallow waters, where it is most accessible to survey and conduct experiments. There is also a continued need to assess the direct and indirect impacts of ocean acidification in mesophotic and deep-sea coral communities. Regardless of ocean acidification status, little is known about the expanse of these habitats in general, since surveys require crewed and uncrewed submersibles and the development of advanced acoustics to map their habitat. These habitats should be explored and their vulnerability to ocean acidification assessed. Deep-sea coral communities could be potentially impacted by ocean acidification even more so than their shallow counterparts, since deep water masses carry an accumulated amount of CO_2 [441]. Additionally, these deep-sea corals generally evolved in environments with little environmental variability. Thus, any changes due to anthropogenic CO_2 might be outside their boundaries of survival, making them even more vulnerable to anthropogenic change, especially since deep corals generally have slower growth rates and thus a more limited capacity to recover to disruptions. How ocean acidification impacts marine communities in the pelagic realm away from the coastline is largely not understood in the Pacific Islands. Once established trends are well-understood in these underexplored environments, then management can be established to help protect those habitats and species that are most vulnerable to ocean acidification.

Needed Research on Economically Important Species

While fisheries have important economic value and contribute to nutritional needs, few studies have been conducted that specifically target ocean acidification impacts on economically important fish species in the region, including tunas, swordfish, wahoo, dolphinfish, moonfish, mahimahi, among others. This is because most ocean acidification research in coral reefs has focused on calcareous organisms, not fish, and most of the fish species from coral reefs studied for ocean acidification impacts has been targeted to territorial species (like damsel fish) that stay local to a specific reef and do not have an expansive, mobile range. These species also tend to be small and are not consumed by humans. Many constraints exist on trying to monitor the impacts of ocean acidification on mobile fish species that are economically important; for example: (1) even if there is a naturally high CO_2 zone, mobile fish can easily swim out of this zone and thus are not impacted by high CO_2 long term, (2) in the laboratory, fish species consumed for food are often large and do not easily keep in aquaria. Additionally, their behavior alters in aquaria, though tank experimental conditions can be manipulated to replicate ocean acidification conditions. The few laboratory ocean acidification experiments that have been conducted on economically important fish tend to focus on juvenile stages, in part because they are easier to maintain in aquaria and because larval stages are often more vulnerable to ocean acidification than adult fish [442]. These constraints limit knowledge and understanding of how ocean acidification may impact the growth, reproduction, or fitness of economically important fish that live both in coral reefs and in pelagic environments.

Research should also explore indirect effects of ocean acidification on these economically important species. Indirect mechanisms can include changes in habitat or food sources that then have cascading effects that ultimately alter the economically important species. Habitat changes due to ocean acidification in coral reefs are predicted to reduce seafood production [443]. Furthermore, ocean acidification impacts on primary and secondary production are hard to predict and little-understood in the Pacific Islands. Any alteration in food sources (like phytoplankton and zooplankton communities) will eventually impact the species that feed on them, thus further investigations into how Pacific Islands are vulnerable to changes in food web dynamics would be pertinent [444]. Integration of plankton and trawl surveys, fish diet studies, fisheries data, stock assessments, and lab experiments may help assess indirect effects through food web impacts.

Research gaps also remain for coral species, which provide economically important ecosystem services. Although mechanisms on how ocean acidification will impact corals and crustose coralline algae have been observed in laboratory conditions, and even *in situ* at CO_2 seep sites, little is known about how present-day ocean acidification is already impacting current reefs. Information on how or if reefs in the Pacific Islands are already experiencing changes in corals or crustose coralline algae due to ocean acidification are not well-understood and could be further explored.

The Pacific Islands are home to a multitude of marine species that are threatened and endangered, including Hawaiian monk seals, hawksbill sea turtles, green sea turtles, and several cetacean species. These species support tourism, in addition to holding deep cultural and social value. Our knowledge of how ocean acidification will impact them is only speculative at this point, and more research is needed to understand potential future impacts. Potential mechanisms in which these species might be impacted by ocean acidification include food-web dynamics, food availability, or changes in the habitats where they feed, breed, nest, or live. Green sea turtles, for example, may benefit from additional seagrass biomass that may be produced under high CO_2 conditions, as primary producers like seagrass can tolerate higher CO_2 conditions and can even buffer ocean acidification by absorbing CO_2 [445].

Current and Needed Research on Impacts to Populations and Ecosystems

The majority of ocean acidification research has been conducted in laboratories on single species, with an emphasis in recent years to try and understand ecosystem-level responses. Mesocosm experiments and natural CO_2 seeps in tropical environments have provided some insight into how ecosystem functioning might alter under ocean acidification. For example, most ecosystem-scaled studies predict some level of change with shifts in corals and benthic habitat. The exact shift has differed depending on the study; for example, corals reefs are predicted to shift from highly complex, branching corals to less-complex, bouldering corals, or to shift from corals to macroalgae, or to shift from hard corals to soft corals [432, 446, 447]. Although the predicted shift varies, nonetheless, all studies predict change, and no study predicts that the ecosystems will be unaffected by long-term ocean acidification conditions. Thus, coral reefs of today are not likely to be the same coral reefs of the future. Currently, there are strong latitudinal gradients in coral species and diversity; it is unknown if all corals will change in the same way or if the gradients themselves will change.

Aside from mesocosms and natural CO_2 seeps, ecosystem modeling remains a useful tool to help predict and forecast ocean acidification impacts on ecosystem functioning. Recent Atlantis ecosystem model studies, including the Guam Atlantis model, have begun to incorporate ocean acidification drivers and species responses [419]. However, refining these models will require additional data on downscaled ocean acidification projections and sensitivities of local taxa to ocean acidification [371]. Additional ecosystem modeling efforts in the Pacific Islands focus on the Hawaiian Island Chain and are incorporated into the Regional Ocean Modeling System (ROMS) models, which focuses on the physical ocean circulation. Efforts are underway to combine ROMS with the Carbon, Ocean Biogeochemistry, and Lower Trophics (COBALT) model developed by NOAA's Geophysical Fluid Dynamics Laboratory. Modeling forecasts are intended to produce long-term estimates that might examine the impacts of warming and ocean acidification on fisheries around Hawaiʻi. Similar modeling efforts currently underway in Hawaiʻi could be extended to other regions across the Pacific Islands to better model the physical and chemical oceanography around the islands where coral reefs exist.

Researchers should also consider other factors that are expected to drive ecosystem change, and future modeling efforts could include:

1. Pairing local interactions with climate scenarios in regional models to help evaluate the impacts of different management strategies and predict ecosystem dynamics

2. Assessing calcium carbonate accretion/dissolution in reefs across spatial gradients, paired with long-term monitoring of benthic and fish communities, to assess ocean acidification impacts to ecosystems and their resilience potential (to inform potential restoration spots)
3. Conducting more field, lab, and multi-stressor experiments on focal taxa (calcareous plankton, larval fish, shallow and deep-sea corals, mollusks, coralline algae, seagrass, and bioeroders) to build ocean acidification response curves and assess trophic interaction/food web impacts
4. Improving ecosystem model parameterization by synthesizing chemical observations with species-specific ocean acidification sensitivity data and response curves
5. Including ocean acidification drivers and taxa responses in trophic interaction ecosystem models
6. Evaluating changes driven by global forcing in otherwise pristine environments on some of the least-impacted islands in the world, versus changes that also include local anthropogenic forcing in some of the heavily populated islands, such as Oʻahu.

Current and Needed Research on Ocean and Coastal Acidification and Co-Stressors

In addition to ocean acidification, other stressors due to climate change and anthropogenic disturbances impact coral reefs and include ocean warming, sea-level rise, increased storms, sedimentation, poor water quality, hypoxia, fishing pressure, and crown-of-thorn outbreaks. Increasing thermal stress has led to unprecedented and frequent mass bleaching events that have decimated reefs globally [448]. As sea level rises, corals will either have to shift their depth or grow faster to keep their current depth [449]. Increased water depth with sea-level rise can also alter wave dynamics and sediment suspension, having negative impacts for corals [450]. Extreme rainfall events, tropical storms, and hurricanes have increased in frequency and intensity due to climate change, which subsequently lowers salinity and increases sediment transport, affecting coral reef community structure [451]. In areas adjacent to deforestation, increased storm events are generally associated with increased sedimentation that can smother corals [452].

Pollution in other forms, like high nutrients from agriculture and/or urban development, can run off into rivers and deposit sediment into coastal areas with coral reefs, decreasing water quality, which can impact corals through shifts in communities, mortality, and increased disease and bioerosion. The region has a large number of cesspools, which are a major source of human-derived nutrients and could be flooded with future sea level rise [453, 454]. Increased erosion and runoff due to increased land development could also act to increase pollution. In some coral reefs, poor water quality leads to coastal acidification which can amplify any ocean acidification due to anthropogenic CO_2. Poor water quality is also associated with widespread hypoxia and has also been linked to crown-of-thorn outbreaks, in which these coral-eating sea stars have decimated entire reefs [455, 456]. To fully understand the fate of coral reefs, multiple stressors must be considered in association with ocean acidification. Few studies have targeted multi-stressor impacts on coral reefs across the Pacific Islands.

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