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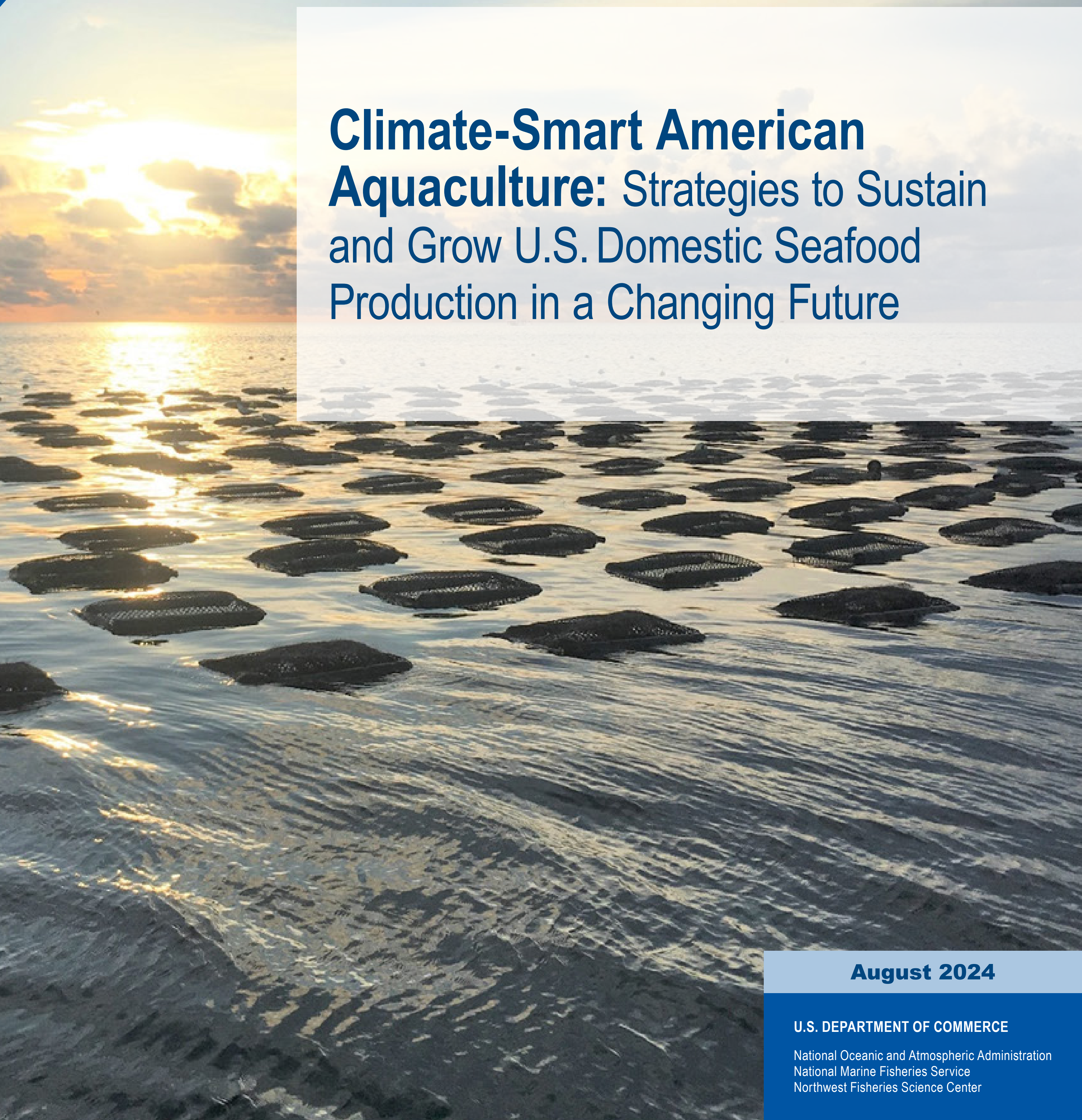
Climate-Smart American Aquaculture: Strategies to Sustain and Grow U.S. Domestic Seafood Production in a Changing Future



August 2024

U.S. DEPARTMENT OF COMMERCE

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Climate-Smart American Aquaculture: Strategies to Sustain and Grow U.S. Domestic Seafood Production in a Changing Future

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Background

There is scientific evidence that the addition of carbon dioxide to the atmosphere from human activity has led to warming air temperatures (a.k.a. global warming) and decreasing ocean pH (a.k.a. ocean acidification). Global warming in turn is driving changes in ocean temperature, sea level, ocean circulation, weather patterns, storm intensity, and rain (amount and intensity). The term climate change includes all of these environmental changes.

We developed this report to provide aquaculture researchers, managers, and industry professionals with the latest information about how climate change is likely to have the greatest effects on U.S. marine aquaculture. We describe potential climate impacts to specific U.S. coastal regions and to the United States as a whole, and identify adaptation and mitigation strategies for aquaculture.

We also describe existing federal programs that can help support a thriving U.S. marine aquaculture sector. These opportunities range from forecasts that can alert aquaculturists when harmful algae or bacteria are present in marine waters, to species and habitat restoration, to carbon mitigation. We conclude with recommendations for strategies that will make U.S. aquaculture more resistant to the negative effects of climate change.

Key Takeaways

Climate change may severely affect ocean fisheries that depend on wild fish. However, if we act now, many opportunities exist for aquaculture to be successful in the face of climate change. A successful, strategically developed marine aquaculture sector can support seafood production, carbon mitigation, and species and habitat restoration that can in turn help wild fisheries. However, if marine aquaculture is to be successful in the face of climate change, we must work closely across the U.S. seafood sector and beyond to ensure a secure future for U.S. seafood. This requires support for and commitment to climate-informed development of this industry.

Links used in this section:

- Climate change: https://www.fisheries.noaa.gov/topic/climate-change
- U.S. marine aquaculture: https://www.fisheries.noaa.gov/topic/aquaculture
- Adaptation and mitigation strategies: https://ices-library.figshare.com/articles/report/Workshop_on_pathways_to_climate-related_advice_WKCLIMAD_/22196560
- Alert aquaculturists when harmful algae or bacteria are present: https://coastalscience.noaa.gov/forecasting%20and%20modeling/
- Carbon mitigation: https://sciencecouncil.noaa.gov/wp-content/uploads/2023/06/mCDR-glossy-final.pdf

Executive Summary

Earth's climate is changing. Our planet and its oceans are warming, and effects on the marine environment are accelerating. Overwhelming scientific evidence implicates increased heat trapping of greenhouse gases from human activity. In particular, increases in atmospheric carbon dioxide (CO_2) are identified as the cause. Molecules of CO_2 from the atmosphere are absorbed into the oceans, where they react and form carbonic acid. Carbonic acid lowers the pH of seawater, with cascading effects on ocean chemistry and ecosystems.

On land, increased surface temperatures cause swift melting of glaciers and sea ice, leading to changes in ocean circulation, weather patterns, and sea level rise. Climate models from the United Nations International Panel on Climate Change (IPCC) predict that by 2040 the United States will experience an increase in median sea surface temperature of 0.6°C off the coast of northwestern North America and 0.7°C off the coast of eastern North America, with increases of 2°C in the coastal northeast and middle Atlantic Ocean.

In this report, we present a synthesis of likely climate change impacts on the U.S. aquaculture sector now and over the coming decades. In this time frame, wild-capture fisheries are expected to decline, with shifts in species distributions and limited options for management. Conversely, aquaculture presents a suite of seafood production, innovation, and resilience-building opportunities that could stabilize and sustainably increase domestic seafood production, even during a protracted period of warming.

We begin with a summary of information available to date on climate drivers expected to have the greatest effects on the U.S. aquaculture sector. Then, we review climate projections for IPCC geographic regions that overlap with U.S. National Marine Fisheries Service (NMFS) management regions. Our review of geographic effects is followed by a summary of adaptation and mitigation strategies for aquaculture. Finally, we highlight existing federal initiatives that present opportunities for collaboration to support a thriving U.S. aquaculture sector. These opportunities range from forecasts that support resilient seafood production, to species and habitat restoration, to carbon mitigation.

Based upon these evaluations, we conclude with the following recommended climate resilience strategies for U.S. aquaculture:

- Identify and prioritize climate impacts and stressors that are likely to affect production in the near term.
- Develop a targeted research strategy to direct attention to known stressors driven by climate change.
- Support development and industry operation of best management practices to maximize production despite climate change.
- Develop information needed for insurance programs and relief policies to minimize the economic impacts of extreme events such as marine heatwaves and storms.
- Refine and implement a climate adaptation strategy, focusing on opportunities to support sustained and enhanced domestic seafood production through aquaculture.

- Refine and implement a carbon mitigation strategy, focusing on opportunities to mitigate climate change through aquaculture.
- Develop and highlight aquaculture as a food production alternative with a smaller carbon footprint and shorter emission-intensive supply chain as an important component of emission reduction/avoidance efforts.
- Develop carbon budgets designed to allow the industry to benefit from carbon trading.

Strong negative climate-driven impacts on marine fisheries are predicted. However, if we act now, substantial opportunities exist for aquaculture to adapt to climate change and potentially mitigate its effects. Working closely across the domestic seafood sector and with others will help ensure a secure future for domestic seafood.

Introduction

The United Nations Intergovernmental Panel on Climate Change (IPCC) recently reported that, regardless of future greenhouse gas reduction and mitigation efforts, humans have set in motion global climate trends that will continue for at least the next several decades (Masson-Delmotte et al. 2021). These trends result from the increased production of heat-trapping combustion products, primarily carbon dioxide (CO_2). Increases in atmospheric CO_2 from human activity have led to warming ocean temperatures, declining ocean pH, declining dissolved oxygen, and rising sea levels.

According to the 2017 report, *Climate Change Impacts on Fisheries and Aquaculture*, substantial global declines are anticipated for fisheries around equatorial regions, with negative effects on food security and employment for the communities that rely on them (Phillips and Pérez-Ramírez 2017). Despite many realized and anticipated climate impacts, opportunities remain to improve the resilience of seafood production, with growth in aquaculture presenting significant opportunities.

In their contribution to the publication, *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis*, Peterson et al. (2017) identify climate impacts to fisheries and aquaculture across six regions of the U.S. Exclusive Economic Zone (EEZ). They report that—although climate impacts vary by region in type and magnitude, creating winners and losers in specific localities—there is a high risk of significant decline in U.S. fisheries overall (Peterson et al. 2017).

In the United States, wild-capture fisheries are expected to decline and shift northward with climate change, with limited options to mitigate these effects. In contrast, aquaculture presents multiple opportunities for growth, adaptation, and increased resilience to current and future climate impacts on domestic seafood production. Innovations in marine aquaculture provide a suite of options that can sustain and adapt seafood production to ensure food security and economic benefit.

In 2019, the U.S. aquaculture industry produced $1.5 billion in edible food (NMFS 2022)—all with a smaller carbon footprint per unit of production than land-based farming (Tilman and Clark 2014, Mcleod et al. 2020). Perhaps more importantly, the U.S. aquaculture industry has room for spatial and economic growth. To illustrate, the United States exported $4.4 billion in edible seafood in 2020, but imported $21.4 billion.

In addition to this significant seafood trade deficit, the United States now trails in seafood production. In 2020, the United States fell to 18th place in world aquaculture production after ranking in the top five during the early 1990s (FAO 2023). This drop in ranking was due to both decreasing production in the United States and increasing production in other countries, and it occurred despite U.S. jurisdiction over the second-largest EEZ in the world.

A thriving and strategically developed marine aquaculture sector can support resilient seafood production, carbon mitigation, and species and habitat restoration to increase the resilience of wild fisheries. However, if marine aquaculture is to thrive in the face of climate change, support for and commitment to climate-informed development will be required.

This report was developed to provide aquaculture researchers, managers, and industry professionals with the information needed for an efficient transition to future climate conditions. For the U.S. marine aquaculture sector, we describe the anticipated effects of climate change, assess climate impacts to specific coastal regions and to the United States as a whole, and identify adaptation and mitigation strategies.

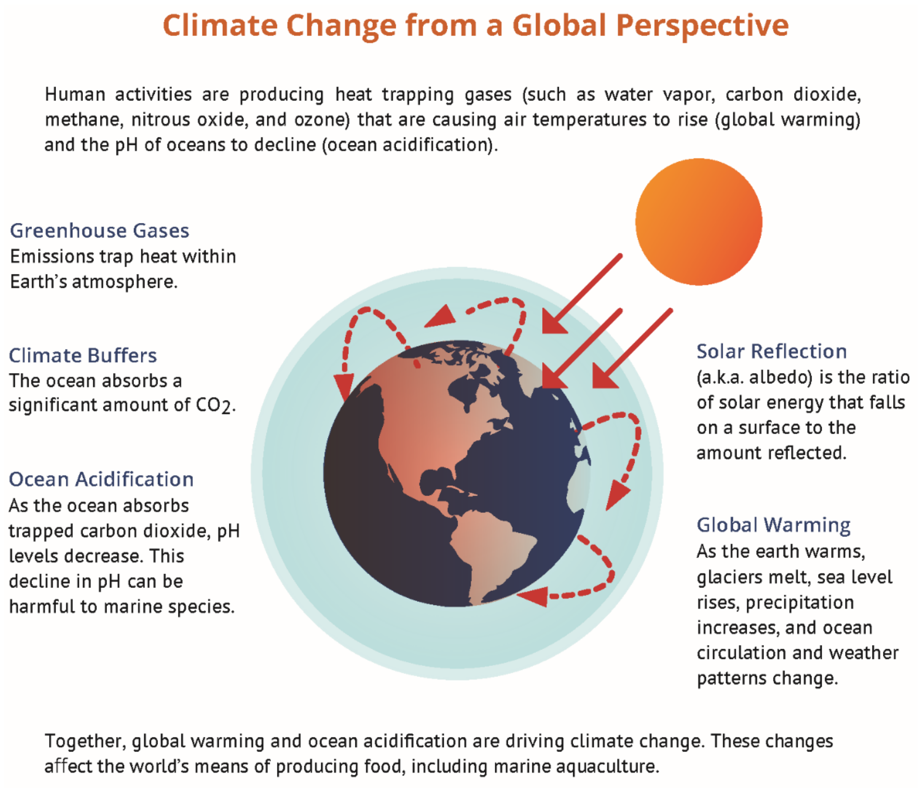
New, sustained resources to develop climate-smart aquaculture are needed to realize the goals outlined in this document. However, the effects of climate change are already being felt in many regions, and risks increase if we wait for additional resources to be secured. To provide a starting point for actions that can be taken immediately, without additional resources, we highlight areas where investments could be at least partially secured through leveraging existing resources and programs.

1 Climate Drivers and Their Impacts on Aquaculture

1.1 Background

The IPCC defines *climate driver* as a “physical climate condition that directly affects society or ecosystems” (Table 1), and further states that a “single climatic impact driver may lead to detrimental effects for one part of society while benefiting another, while others are not affected at all” (Masson-Delmotte et al. 2021). The interactions of just a few climate drivers—including sun intensity, Earth albedo (or solar energy reflectivity), greenhouse gases, aerosols, and ocean currents—are responsible for variation in weather conditions over the short term, on annual to decadal scales. They also drive long-term global climate change on the scale of decades to centuries.

Postindustrial long-term climate trends are primarily driven by greenhouse gas emissions. These gases include water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Since the Industrial Revolution, increases in these gases relative to other climate drivers are serving to trap heat within the atmosphere—warming the air, water, and land. This phenomenon has been referred to generically as *global warming* (Figure 1). Increases in carbon dioxide emissions in particular are also contributing to a decrease in ocean pH, or *ocean acidification*, from oceans absorbing more carbon dioxide from the atmosphere (Figure 2).



Climate Change from a Global Perspective

Human activities are producing heat trapping gases (such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone) that are causing air temperatures to rise (global warming) and the pH of oceans to decline (ocean acidification).

Greenhouse Gases
Emissions trap heat within Earth’s atmosphere.

Climate Buffers
The ocean absorbs a significant amount of CO_2.

Ocean Acidification
As the ocean absorbs trapped carbon dioxide, pH levels decrease. This decline in pH can be harmful to marine species.

Solar Reflection
(a.k.a. albedo) is the ratio of solar energy that falls on a surface to the amount reflected.

Global Warming
As the earth warms, glaciers melt, sea level rises, precipitation increases, and ocean circulation and weather patterns change.

Together, global warming and ocean acidification are driving climate change. These changes affect the world’s means of producing food, including marine aquaculture.

Figure 1. Global-scale phenomena contributing to atmospheric warming and ocean acidification.

Regardless of current and future mitigation efforts to slow or offset these trends, the combined effects of atmospheric warming and ocean acidification will drive changes in baseline ocean temperatures, carbonate chemistry, sea level, salinity, and dissolved oxygen. These changes are projected to affect wind speed and direction, ocean flushing patterns,

Table 1. Terms used in this report and their definitions. All were adopted from terms used in recent reports of the Intergovernmental Panel on Climate Change (Masson-Delmotte et al. 2021) and the International Council for the Exploration of the Sea (ICES 2023).

Adaptation	Active or passive responses, actions, policies, and planning to adjust to or reduce the impacts of current or future climate change (e.g., through reduction in the exposure, sensitivity, or other effects of climate change). Climate adaptation ranges from incremental and passive responses at the local and regional level to large-scale planning and transformation of social and ecological processes. Some adaptation measures have co-benefits for **mitigation**.
Climate change driver	1) A physical climate condition that directly affects society or ecosystems. Single climatic **impact** drivers may lead to detrimental effects for one part of society while benefiting another, while others are not affected at all. 2) An environmental change induced by climate change that directly or indirectly **impacts** fisheries or aquaculture.
Confidence/certainty	The quality of evidence supporting estimates of **risk/opportunity** and **impacts**, as well as the effectiveness and feasibility of **mitigation** and **adaptation** strategies.
Impact	Impacts are broadly defined and can affect physical, biological, economic, or social parts of the ecosystem. Impacts can spur further impacts (akin to a chain of events) and can therefore be direct or indirect. They can also be positive or negative. In a classic risk assessment, which is focused on negative impacts, the term *hazard* is often used for this concept. However, we adopted the term *impact* because we understand impacts to be both positive and negative and to include the potential for a chain of impacts (indirect impacts).
Mitigation	Refers to *climate change mitigation* and is defined by activities or policies that limit or reduce emissions of greenhouse gases or remove and sequester atmospheric carbon and therefore reduce the strength and/or probability of **climate change drivers** in projection scenarios.
Risk/opportunity	The integrated negative (risk) or positive (opportunity) outcome of exposure, sensitivity, and response to **impacts**. Risk and opportunity are influenced by inherent values, objectives, and priorities associated with different systems or individuals (and of those assessing risk or opportunity). Risk and opportunity are assessed by ranking the probability (likelihood) and strength (magnitude) of the **impact** they represent on aquaculture.

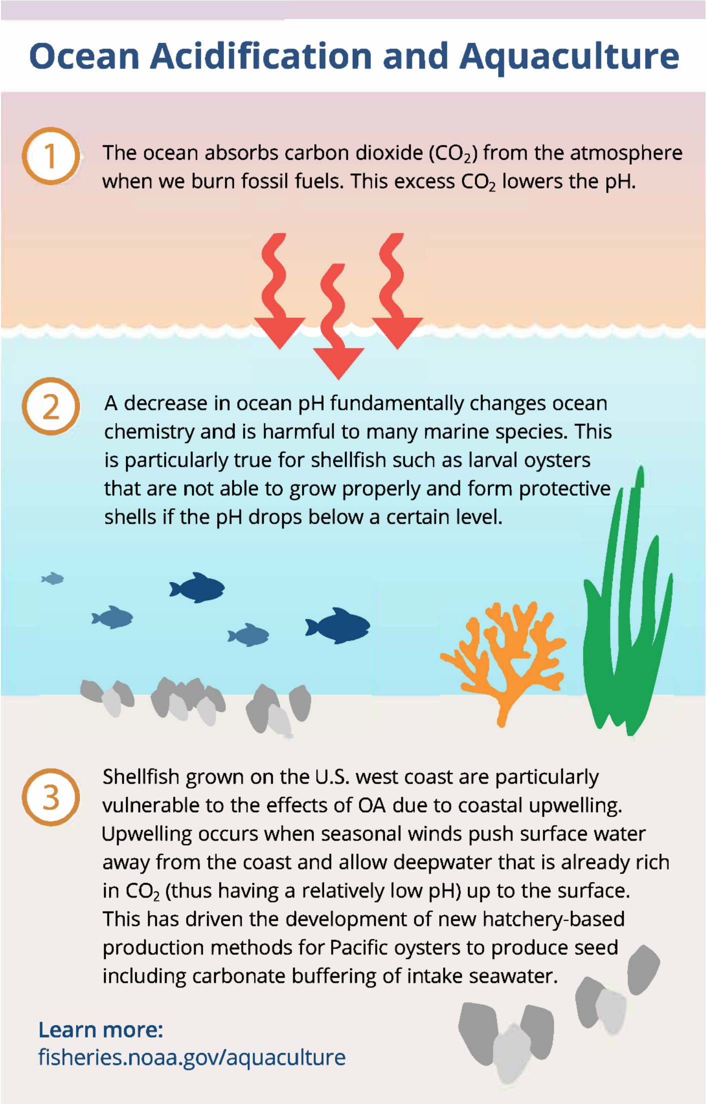
nutrient cycling, sedimentation rates, and many more physical and biological ocean attributes. Importantly, the degree and direction to which these attributes change will differ at various local and regional scales. As such, climate change is likely to present significant challenges to the marine aquaculture industry over the next several decades.

1.2 Perspectives from the U.S. Aquaculture Industry

1.2.1 *Workshop on Pathways to Climate-Aware Advice*

In fall and winter 2021–22, a group of international experts on aquaculture and fisheries participated in the *Workshop on Pathways to Climate-Aware Advice* hosted by the International Council for the Exploration of the Sea (ICES 2023). Participants explored how to account for the short-, medium-, and long-term influences of climate change on marine aquaculture, fisheries, and ecosystems. Key discussion points and perspectives identified during the workshop were summarized in an ICES scientific report (ICES 2023).

Workshop organizers used a modified Delphi approach to quantify these perspectives (Hallowell and Gambatese 2010). Participants with expertise in aquaculture (*n* = 9) were provided a list of climate-driven attributes (similar to those in Table 2) with corresponding changes or impacts to aquaculture. They were asked to rate these attributes and impacts on a scale of one to ten, with one being the highest, based on likelihood of occurrence and projected magnitude of impact to different types of marine aquaculture (including both positive and negative impacts). Table 3 shows how these indicators and impacts were ranked and offers a global perspective on potential impacts to finfish, shellfish, and seaweed culture.



Ocean Acidification and Aquaculture

① The ocean absorbs carbon dioxide (CO_2) from the atmosphere when we burn fossil fuels. This excess CO_2 lowers the pH.

② A decrease in ocean pH fundamentally changes ocean chemistry and is harmful to many marine species. This is particularly true for shellfish such as larval oysters that are not able to grow properly and form protective shells if the pH drops below a certain level.

③ Shellfish grown on the U.S. west coast are particularly vulnerable to the effects of OA due to coastal upwelling. Upwelling occurs when seasonal winds push surface water away from the coast and allow deepwater that is already rich in CO_2 (thus having a relatively low pH) up to the surface. This has driven the development of new hatchery-based production methods for Pacific oysters to produce seed including carbonate buffering of intake seawater.

Learn more:
fisheries.noaa.gov/aquaculture

Figure 2. Carbon dioxide absorption in the ocean contributes to ocean acidification (Steps 1 and 2) in the western Pacific Ocean. Ocean acidification has already affected the culture of Pacific oysters on the U.S. West Coast (Step 3).

The degree and direction of climate impacts is expected to differ by region, species, and aquaculture method, among other factors (Peterson et al. 2017, Gowda et al. 2018, Gutiérrez et al. 2021, Iturbide et al. 2021). Nevertheless, many of the top-ranked areas of impact were common among the finfish, shellfish, and seaweed aquaculture sectors. These included changes to survival and growth, and altered water chemistry, turbidity, and salinity from increased flooding and erosion. An additional shared category was found in disease-related effects, such as changes to the geographic range of pathogens and parasites, as well as changes in pathogen dynamics and host susceptibility.

Other effects of climate change common to all sectors included changes in broodstock distribution and spawner timing, species range contraction or expansion, and changes in feed availability. It is important to note that these changes will affect finfish, shellfish, and seaweed (and the various species within these groups) to differing degrees, and that some impacts may have been interpreted as positive (or neutral) rather than as negative (see Section 2).

Table 2. Summary of climate-driven attributes and their expected influence on aquaculture, as presented for ranking during the *Workshop on Pathways to Climate-Aware Advice*. Rankings are shown in Table 3.

Air temperature

- Decline in seafood quality post-harvest.

Decreased freshwater supply due to changes in precipitation and drought

- Changes in water quality dynamics including nutrient load, temperature, and dissolved oxygen.
- Terrestrial crop failures and increased reliance on aquaculture as protein source.
- Changes in availability of land-based feed (e.g., soybeans, maize, rice).

Dissolved oxygen

- Changes in distribution of broodstock and spawner timing.
- Changes in pathogen and parasite presence and susceptibility to disease.
- Species range contraction/expansion, necessity to culture certain life stages in lab.
- Changes in growth rate/season for current species.
- Changes in survival for current species.
- Changes in feed availability.

Flushing patterns at offshore farms

- Accumulation of waste.
- Changes in availability of ocean-based feed (e.g., fish meal, fish oil, raw fish).
- Changes in water quality dynamics.

Freshwater temperature

- Changes in water quality dynamics.
- Changes in pathogen/disease dynamics.

Increased frequency of extreme weather events

- Catastrophic events (e.g., marine heatwaves, heat domes, hurricanes, tropical storms, dust storms) can destroy farmed species.
- Damage to equipment/facilities and/or inability to access.
- Changes in water chemistry/turbidity (e.g., from erosion/flooding) leading to physiologic stress.
- Changes in feed availability.
- Toxins released into water/air with effects on farmed species and/or humans.

Landslides

- Catastrophic events such as landslides can destroy farmed species and potentially eliminate habitat.

Ocean pH

- Changes in reproduction.
- Changes in survival.
- Changes in growth.
- Changes in susceptibility to disease.
- Changes in seed production/juvenile availability necessitating laboratory culture.
- Increase/decrease in habitat area suitable for aquaculture.

Ocean salinity

- Increase/decrease in habitat area suitable for aquaculture.
- Changes in growth and other sublethal effects.
- Changes in survival.
- Changes in pathogen and parasite presence and susceptibility to disease.
- Changes in feed availability.
- Target species range expansion/contraction.
- Nontarget species range expansion/contraction.
- Disruption of feed systems.

Table 2 (continued). Summary of climate-driven attributes and their expected influence on aquaculture.

Ocean temperature

- Changes in distribution of broodstock and spawner timing.
- Changes in pathogen and parasite presence and susceptibility to disease.
- Target species range contraction necessitating culture of certain life stages in lab.
- Changes in growth rate/season for current species.
- Changes in survival for current species.
- Changes in feed availability.
- Nontarget species range expansion/contraction.

Phytoplankton bloom timing/location

- Changes to normal phytoplankton bloom timing/location.
- Changes to phytoplankton bloom timing/location creating toxic areas (harmful algal blooms).

Sea level rise

- Increase/decrease in habitat area suitable for aquaculture.
- Necessity to relocate/renovate shorebased processing facilities, docks, distribution centers.

Snowpack loss, including loss of permafrost

- Changes in water quality dynamics.
- Increase/decrease in habitat area suitable for aquaculture.

Wind speed/direction, ocean circulation (currents and eddies)

- Changes in water quality dynamics.
- Increase/decrease in habitat area suitable for aquaculture.
- Changes in availability of feed.

Table 3. Top-ranked climate-related concerns based on combined likelihood and magnitude of impact scores (1–10, with 1 being highest) for finfish, shellfish, and seaweed culture, 2021–40 (ICES 2023).

Rank	Climate-related concern
Finfish	
1	Changes in water chemistry/turbidity/salinity (e.g., from erosion/flooding).
2	Changes in growth.
3	Changes in pathogen disease dynamics.
4	Changes in survival.
4	Changes in the susceptibility to disease.
5	Changes in pathogen and parasite presence.
6	Harmful algal blooms.
7	Catastrophic effects on cultured species (i.e., death).
8	Changes in the distribution of wild broodstock.
8	Changes in the frequency of damage to equipment/facilities.
9	Changes in reproduction and growth.
9	Changes in dissolved oxygen levels.
9	Changes in water quality dynamics.
9	Target culture species range expansion/contraction.
10	Increase/decrease in habitat area suitable for aquaculture.

Table 3 (continued). Top-ranked climate-related concerns based on combined likelihood and magnitude of impact scores for finfish, shellfish, and seaweed culture, 2021–40.

Rank	Climate-related concern
Shellfish	
1	Changes in growth.
2	Ocean acidification.
2	Changes in survival.
3	Changes in water chemistry/turbidity/salinity (e.g., from erosion/flooding).
4	Changes in reproduction and growth.
5	Changes in susceptibility to disease.
6	Changes in pathogen disease dynamics.
7	Harmful algal blooms.
8	Changes in normal phytoplankton bloom timing/location.
8	Changes in pathogen and parasite presence.
9	Changes in water quality dynamics.
10	Changes in the availability of natural feed for filter feeders (phytoplankton).
10	Changes in wild seed production/juvenile availability.
Seaweed	
1	Ocean acidification.
2	Changes in water quality dynamics.
3	Changes in water chemistry/turbidity/salinity (e.g., from erosion/flooding).
4	Changes in pathogen and parasite presence.
5	Changes in survival.
5	Changes in susceptibility to disease.
5	Changes in growth.
6	Changes in pathogen disease dynamics.
7	Catastrophic effects (i.e., death) on cultured species.
7	Changes in dissolved oxygen levels.
8	Changes in nutrient availability for seaweed (nitrogen, phosphorous, potassium).
9	Increase/decrease in habitat area suitable for aquaculture.
10	Changes in the range of nontarget species which impact aquaculture.

1.2.2 Data collection by the Office of Aquaculture

To obtain information about broader national concerns with regard to climate change, and to understand the most pressing information needs of the U.S. aquaculture industry, the National Marine Fisheries Service's (NOAA Fisheries) Office of Aquaculture informally collected data at several regional and national aquaculture meetings during 2022. As part of this exercise, participants representing aquaculture farms ($n = 30$), hatcheries ($n = 19$), nonprofits ($n = 30$), restaurants and seafood retailers ($n = 10$), software and/or gear developers/retailers ($n = 10$), and other industry representatives ($n = 10$) were asked to rank climate impacts in order of importance to their sector (i.e., finfish, shellfish, seaweed).

As shown in Table 4, increased water and air temperature was consistently scored as the highest-ranking concern. Harmful algal blooms, ocean acidification, and increased frequency and intensity of weather events were ranked moderately, with ranks varying by sector. Sea level rise and “other” were consistently scored as the lowest-ranking concerns.

Additional comments indicated that climate-related concerns of the U.S. aquaculture industry were similar to those identified above in the ICES global perspective, with disease related to increasing water temperature being a top concern. Effects from changing water chemistry were also a major concern, along with declining salinity in nearshore areas, hypoxia, and contamination from human waste and plastics.

The U.S. aquaculture industry was also concerned about target species range contraction and about non-native species range expansion and increases. Hatchery failures due to multiple stressors, including the aforementioned, were additional areas of concern, as were crop losses due to harmful algal blooms and exposure to Vibrio spp. Industry participants were also concerned about the growing cost of insurance due to increased risk of climate-related loss.

Industry representatives included in our information-gathering exercise said they would like to see better regulatory guidance through national legislation for conducting marine aquaculture in federal waters and legislation that is more protective of marine waters and the habitats they provide. They believe such legislation should encourage sustainable aquaculture rather than create additional regulatory barriers. They support the role of government in sharing information about climate change and aquaculture as it becomes available, and in conducting research to determine which species will be most tolerant to climate change. Industry representatives would also like government to consider subsidies for ecological services (e.g., carbon mitigation) as well as crop insurance programs and tax credits for aquaculture.

Based upon information we collected, representatives of the U.S. aquaculture industry have indicated that they are ready to adopt the necessary techniques and tools to adapt to climate change. They are willing to be partners in innovation, provided that external funding is available for this purpose. They have expressed willingness to embrace technologies that will reduce their carbon footprint, and they acknowledge that improvements in infrastructure would include improving access to farm sites and processing plants, which may include reducing the distance between such sites.

Table 4. Climate-driven attributes, ranked by U.S. marine aquaculture industry representatives in order of perceived impact to the industry. Attributes were rank ordered from 1–6, with 1 being the most concerning. Numbers in parentheses indicate the number of respondents polled from each sector. Data are available from the NOAA Fisheries Office of Aquaculture.

Rank	Climate-driven attribute
Finfish (*n* = 12)	
1	Increased water and air temperature
2	Harmful algal blooms
3	Ocean acidification
4	Increased frequency and intensity of weather events
5	Sea level rise
6	Other
All Shellfish (*n* = 70)	
1	Increased water and air temperature
2	Increased frequency and intensity of weather events
3	Harmful algal blooms
4	Ocean acidification
5	Sea level rise
6	Other
	Mussels (*n* = 16)
	1 Increased water and air temperature
	2 Increased frequency and intensity of weather events
	3 Ocean acidification
	4 Harmful algal blooms
	5 Sea level rise
	6 Other
	Oysters (*n* = 38)
	1 Increased water and air temperature
	2 Harmful algal blooms
	3 Ocean acidification
	4 Increased frequency and intensity of weather events
	5 Sea level rise
	6 Other
	Clams (*n* = 16)
	1 Increase in water and air temperature
	2 Increased frequency and intensity of weather events
	3 Harmful algal blooms
	4 Ocean acidification
	5 Sea level rise
	6 Other
Seaweed (*n* = 13)	
1	Increase in water and air temperature
2	Harmful algal blooms
3	Ocean acidification
4	Increased frequency and intensity of weather events
5	Sea level rise
6	Other

2 Geographically Specific Risks

In the AR6 cycle, IPCC Working Group I was tasked with assessing the physical scientific basis of climate change and then to use this information to project future warming and climate impacts. To make these assessments and predictions, the group divided the globe into a number of primary geographic regions based upon how they are influenced by various coastal and ocean currents (Table 5).

These IPCC regions do not correspond directly to management regions of NOAA Fisheries, and in most cases they include countries adjacent to the United States. Table 5 shows IPCC regions and the corresponding U.S. fishery management regions that overlap them.

Table 5. Climate regions designated by the IPCC and overlapping management regions of NOAA Fisheries.

IPCC region	**NOAA Fisheries management region(s)**
Eastern North America	Coastal areas of the northeast and middle Atlantic, served by NOAA Fisheries' Greater Atlantic Regional Fisheries Office; coastal areas off the southeastern Atlantic and Gulf of Mexico, served by NOAA Fisheries' Southeast Regional Office.
Caribbean	Puerto Rico and the U.S. Virgin Islands, served by NOAA Fisheries' Southeast Regional Office.
Northwest North America	Alaskan coastal areas served by NOAA Fisheries' Alaska Regional Office.
Western North America	Coasts of Washington, Oregon, and northern California, served by NOAA Fisheries' West Coast Regional Office.
North Central America	Coastal areas of southern California served by NOAA Fisheries' West Coast Regional Office.
North Pacific	Hawaii and U.S.-affiliated Pacific islands served by NOAA Fisheries' Pacific Islands Regional Office.

2.1 Climate Drivers

Each IPCC region is projected to have a unique set of future climate conditions. As such, a regionally specific approach toward adaptation will be needed if the U.S. aquaculture industry is to be sustained and grow in the future. Table 6 summarizes projected changes in sea surface temperature, sea level, surface pH, and coastal precipitation for each IPCC region for 2021–40.

The number of projected *cooling degree days* is also shown in Table 6 for this same period. A cooling degree day is defined as the number of degrees by which the average temperature exceeds 65°F (18.3°C) on a given day or group of days. For example, a day with an average temperature of 75°F (23.8°C) would have 10 cooling degree days, as would two days with an average temperature of 70°F (21.1°C). Cooling degree days were originally used in building construction to estimate energy needs for heating and cooling; however, in this context they reflect an index of environmental warming that combines temporal and magnitude effects.

Climate predictions cited in Table 6 were made using IPCC Working Group I's Interactive Climate Atlas (Gutiérrez et al. 2021, Iturbide et al. 2021). Projections were based upon low-to-intermediate greenhouse gas emissions scenarios. Emissions scenarios are rated in terms of *shared socioeconomic pathway* (SSP), with low (L) at SSP = 12.6 and intermediate (I) at SSP = 24.5. Under higher emissions scenarios, these changes and the challenges they present are projected to be even more extreme than shown in this exercise. These projections form the basis for future climate forecasting.

All projected changes in climate attributes are described as change in annual measures (e.g., median percentage or number of days). Changes in seasonal and/or daily values will most certainly be more extreme. Climate change effects will likely be detected first at their extremes and with extended durations. Furthermore, impacts to aquaculture will vary based on the types of species cultured within each region, as some species are more resilient than others to the effects of climate change.

2.2 Aquaculture Impacts

The IPCC regions are broad and often overlap national jurisdictions; therefore, we describe and summarize by NOAA Fisheries management region the individual climate drivers expected to be significant to the environment and to aquaculture.

These descriptions come with a few caveats; for example, the IPCC region of Eastern North America overlaps two NOAA Fisheries management regions: the Greater Atlantic Region, serving coastal areas of the northeast and middle Atlantic states, and the Southeast Region, serving coastal areas off the southeastern Atlantic states and the Gulf of Mexico (Table 5). Climate drivers and aquaculture impacts within the Caribbean IPCC region were considered similar to those described for the southeastern Atlantic and Gulf of Mexico states—although slightly more extreme with respect to increasing temperature. Finally, because NOAA Fisheries' West Coast Region serves two different IPCC regions, we describe its northern/central and southern portions separately, with the former covering Washington, Oregon, and north-to-central California and the southern part covering southern California (Table 5).

Although we focus on direct effects to coastal and marine environments, we must also be aware that, because ecosystems are interconnected, changes in inland processes—such as drought and/or increased precipitation, or changes in hydrography (i.e., shifts from snow- to rain-driven regimes)—will influence the chemical and physical nature of the water entering estuaries and oceans. Indirect effects (e.g., climate-driven changes in agriculture) may also impact aquaculture through dynamics in the overall need for food.

For example, in the *Fourth National Climate Assessment*, Gowda et al. (2018) reported that extreme precipitation events are increasing across the United States. These events are correlated with accelerated sediment and nutrient loading in estuaries and the nearshore environment. A spike in nutrients can in turn lead to focal areas of hypoxia that can have catastrophic effects on the local fauna (Hagy et al. 2004, Kemp et al. 2005, Rabalais et al. 2010, Du et al. 2018).

Such events are of particular concern for cultured species, which are generally either sessile by nature or anchored in place within cages. Table 7 shows marine aquaculture species produced for food or broodstock, by state and associated NOAA Fisheries management region. Table 8 shows climate drivers and their predicted impacts to cultured species by fisheries management region over the next 20 years based on our comprehensive analysis of the regional climate data detailed below.

Table 6. Projected change in climate-driven attributes, reported as change in annual mean within the near term (2021–40) compared to levels during 1995–2014, by IPCC region. Emissions scenarios (ES) are rated in terms of *shared socioeconomic pathway* (SSP), with low (L) at SSP = 12.6 and intermediate (I) at SSP = 24.5. Numbers in parentheses represent lower and upper ranges based on 95% confidence intervals. Data from IPCC Working Group I Interactive Atlas (Gutiérrez et al. 2021, Iturbide et al. 2021).

Attribute	**ES**	**Eastern North America (Δ)**	**Caribbean (Δ)**	**Northwest North America (Δ)**	**Western North America (Δ)**	**North Central America (Δ)**	**North Pacific (Δ)**
Sea surface temperature (°C)	L	0.7 (0.2, 1.2)	1.2 (1.0, 1.5)	0.6 (0.2, 1.0)	0.7 (0.1, 1.3)	0.6 (0.3, 0.9)	0.6 (0.3, 1.0)
	I	0.7 (0.3, 1.3)	1.2 (1.0, 1.6)	0.6 (0.1, 1.1)	0.6 (0.1, 1.1)	0.6 (0.3, 0.9)	0.7 (0.4, 1.0)
Sea level rise (m)	L	0.2 (0.1, 0.3)	0.1 (0.0, 0.2)	0.1 (0.0, 0.3)	0.1 (0.0, 0.1)	0.1 (0.1, 0.2)	0.1 (0.0, 0.2)
	I	0.2 (0.1, 0.3)	0.1 (0.0, 0.2)	0.1 (0.0, 0.3)	0.1 (0.0, 0.1)	0.1 (0.1, 0.2)	0.1 (0.0, 0.2)
Surface pH	L	−0.1 (−0.1, −0.1)	−0.1 (−0.1, −0.1)	−0.1 (−0.1, −0.1)	−0.1(−0.1, −0.1)	−0.1 (−0.1, 0.0)	−0.1 (−0.1, −0.1)
	I	−0.1 (−0.1, −0.1)	−0.1 (−0.1, 0.1)	−0.1 (−0.1, −0.1)	−0.1 (−0.1, −0.1)	−0.1 (−0.1, −0.1)	−0.1 (−0.1, 0.1)
Cooling degree days	L	111.4 (47.3, 168.6)	274.6 (122.3, 332.8)	5.6 (0.8, 16.4)	42.0 (17.6, 95.2)	111.2 (73.9, 199.6)	123.0 (69, 177.2)
	I	116.9 (51.6, 182.2)	286.0 (144.2, 347.5)	5.4 (0.6, 14.7)	43.1 (20.4, 94.0)	121.1 (82.8, 215.1)	126.6 (72, 179.2)
Total precipitation (%)	L	3.1 (0.6, 5.2)	0.5 (−0.7, 6.8)	4.5 (1.0, 8.5)	2.4 (0.6, 5.2)	0.8 (−6.2, −6.6)	1.5 (−0.7, 4.7)
	I	2.4 (1.0, 5.8)	0.5 (−5.7, 9.0)	3.8 (1.1, 6.8)	1.6 (1.0, 5.8)	−2.0 (−5.5, 4.8)	1.0 (−2.3, 4.2)
Maximum 1-day precipitation (%)	L	4.4 (0.9, 8.7)	3.4 (−7.3, 16.6)	5.1 (1.1, 8.9)	4.2 (0.2, 8.8)	3.8 (−1.4, 8.1)	3.5 (−0.5, 7.4)
	I	4.2 (0.4, 8.1)	2.9 (−5.1, 14.9)	4.3 (0.8, 8.1)	4.4 (0.6, 9.0)	2.5 (−2.0, 8.7)	3.6 (−1.0, 7.8)
Surface wind (%)	L	−1.1 (−3.0, −0.2)	−0.2 (−1.7, 1.2)	−0.3 (−1.8, −1.1)	−0.8 (−2.8, −0.6)	−0.5 (−2.1, −0.6)	−0.7 (−1.5, 0.1)
	I	−0.9 (−2.3, −0.4)	−0.5 (−1.8, 1.1)	−0.3 (−1.5, −1.3)	−0.7 (−2.0, 1.3)	−0.7 (−1.5, −1.2)	−0.8 (−1.6, 0.0)
Sea ice concentration (%)	L	−0.2 (−0.5, 0.0)	n/a	−4.3 (−7.7, −1.9)	n/a	n/a	n/a
	I	−0.2 (−0.7, 0.0)	n/a	−4.4 (−8.2, −1.1)	n/a	n/a	n/a

Table 7. Marine aquaculture species produced for food or broodstock, by NOAA Fisheries management region (USDA 2019, NMFS 2022). Major vs. minor species classification was based on comparisons of farm gate value for a particular region. Characterization as a minor species does not imply insignificant farm gate value.

NOAA Fisheries mgmt. region	State(s)	Major aquaculture species[a]	Minor aquaculture species[a]
Greater Atlantic	DE, MD, NJ, NY, VA	Eastern oysters, hard clams	Other clams, other oysters, snails, softshell crabs, macroalgae, microalgae, eels, coho salmon, steelhead trout
	CT, MA, ME, NH, RI	Eastern oysters, hard clams, Atlantic salmon	Other clams, other oysters, mussels, macroalgae, eels, steelhead trout, branzino, barramundi, Pacific white shrimp, scallops
Southeast	GA, NC, SC	Eastern oysters, hard clams	Other clams, other oysters, softshell crabs, sturgeon, Pacific white shrimp
	FL	Eastern oysters, hard clams	Other clams, other oysters, eels, algae (incl. macro- and microalgae), Atlantic salmon, red drum, sturgeon, pompano, Pacific white shrimp
	AL, LA, MS, TX	Eastern oysters	Other oysters, softshell crabs, macroalgae, microalgae, red drum, Pacific white shrimp
Alaska	AK	Pacific oysters	Hard clams, other clams, other oysters, mussels, macroalgae
West Coast	Northern CA, OR, WA	Pacific oysters, geoduck clams, Manila clams	Hard clams, other clams, other oysters, mussels, macroalgae, Atlantic salmon,[b] steelhead trout, sturgeon
	Southern CA	Pacific oysters	Manila clams, other clams, other oysters, mussels, abalone, macroalgae, microalgae, steelhead trout, sturgeon
Pacific Islands	HI, U.S.-affiliated Pacific islands	Microalgae	Manila clams, other clams, Pacific oysters, other oysters, abalone, macroalgae, almaco jack,[c] sturgeon, misc. food fish, Pacific white shrimp[d]

[a] Farm gate value is market value minus selling costs.

[b] Atlantic salmon and other non-native fish farming will be phased out in Washington by 2025.

[c] Only one ocean-based finfish farm in the region.

[d] Production is primarily for broodstock.

Table 8. Climate drivers that may affect aquaculture within the next ~20 years, by NOAA Fisheries management region and major species cultured (dots denote climate drivers most likely to affect aquaculture). Predictions based on climate models from IPCC's *Fourth National Climate Assessment* (Markon et al. 2018).

	Greater Atlantic Region	Southeast Region	Alaska Region	West Coast Region	Pacific Islands Region
Climate drivers	**Eastern oysters, hard clams, Atlantic salmon**	**Eastern oysters, hard clams**	**Pacific oysters**	**Pacific oysters, geoduck clams, Manila clams**	**Microalgae**
Warming sea and air temperatures	•	•	•	•	•
Ocean acidification	•		•	•	
Sea level rise; erosion, flooding, sea water intrusion, shoreline habitat loss	•	•	•	•	•
Increased storm frequency and intensity	•	•		•	
Harmful algal blooms	•	•	•	•	
Hypoxia		•		•	•
Increased precipitation (frequency or intensity)	•	•	•	•	•
Changes in normal phytoplankton biomass	•	•	•	•	•

2.3 Eastern North America: Greater Atlantic and Southeast Regions

The Eastern North America IPCC region includes the U.S. states along the western Atlantic Ocean and the Gulf of Mexico and is served by NOAA Fisheries' Greater Atlantic Regional Fisheries Office and Southeast Regional Office. Within these regions, IPCC climate models predict an increase in annual median sea surface temperature of 0.7°C, given either low or intermediate emission scenarios over the next 20 years (Table 6). Cooling degree days are also projected to increase by 111.4 and 116.9 under low and intermediate scenarios, respectively.

Sea level is expected to increase by 0.2 m over this same period under both emission scenarios, as sea ice concentration in the northwestern Atlantic Ocean decreases by 0.2%. Total precipitation is projected to increase by 3.1% and 2.4% under the respective low and intermediate scenarios, along with maximum one-day precipitation, which is projected to increase by 4.4% and 4.2%. Surface wind is projected to decrease by 1.1% and 0.9%, and surface pH is projected to decrease by 0.1 unit under the respective low and intermediate scenarios.

2.3.1 Greater Atlantic Region

Climate drivers

The Greater Atlantic Region includes the coasts of Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, and Virginia. Ocean and coastal temperatures in this region have increased at a rate greater than the global average (Pershing et al. 2015). This may be caused by a combination of global warming and the complementary effects of local climate regimes.

The Greater Atlantic Region is expected to continue warming faster than any other region in the contiguous United States, with a projected increase in annual median temperature of 2°C by 2035 (Dupigny-Giroux et al. 2018). For some locations, increasing temperatures are more pronounced in summer than in winter months (Friedland and Hare 2007). However, winters are becoming milder, and overall warming is contributing to a more consistent climate with less seasonality observed along the northeastern continental shelf (Dupigny-Giroux et al. 2018).

Warming temperatures have served to shift the timing of snow melt such that it now occurs earlier in the year compared to preindustrial times, thus altering the hydrologic cycle (Hodgkins and Dudley 2006). This timing shift has in turn altered the historic timing of phytoplankton blooms, thus altering the base of the food web.

The Greater Atlantic Region is also expected to experience an increase in coastal erosion and flooding, at a rate of three to four times the global average (Dupigny-Giroux et al. 2018). These projections are based on projected increases in the amount of annual precipitation, more-concentrated rainfall, sea level rise, and increased storm intensity (Easterling et al. 2017, Wuebbles et al. 2017, Hayhoe et al. 2018). In particular, increased intensity of hurricanes is projected. However, these increases will vary by location (Horton and Liu 2014, Knutson et al. 2015, Kossin et al. 2017).

Such impacts may result in shoreline and infrastructure loss, as marshy lowlands become submerged. Conversely, they may result in shoreline gain as sediment from erosion and storms builds along the coast. The extent and direction of these changes will vary geographically; areas that are also experiencing subsidence (sinking) are particularly vulnerable to sea level rise.

Increasing erosion and surface runoff from farmland has additional negative effects on estuaries and nearshore ocean areas through excess nitrification. Excess nitrogen contributes to a process called eutrophication, whereby excessive nutrients promote dense aquatic plant and algal growth. As plants and algae decay, they consume oxygen and produce carbon dioxide, thus contributing further to ocean acidification. The Gulf of Maine in particular is noted for its vulnerability to acidification arising from limited buffering capacity due to copious freshwater nutrient inputs and subsequent eutrophication (Dupigny-Giroux et al. 2018).

Aquaculture impacts

Hard clams, eastern oysters, and Atlantic salmon are major aquaculture species for the Greater Atlantic Region based on farm gate value (Tables 7 and 8), and climate change will affect these species in a variety of ways. Warming temperatures will cause a number of potential impacts, including changes in pathogen and parasite presence and disease dynamics. Notably, an increased incidence of temperature-related disease outbreaks has already been observed in these regions for oysters, a major aquaculture species, and lobsters, a commercially important wild-catch fishery (Cooke et al. 1998, Hoffmann et al. 2001, Castro et al. 2012).

Warming estuaries and oceans may also affect seafood safety with respect to human consumption. For example, as temperatures increase, so does the threat from bacteria such as *Vibrio parahaemolyticus*, a causative agent of shellfish poisoning (Jones et al. 2011, Vezzulli et al. 2016), and from harmful algal blooms, which can cause paralytic shellfish poisoning (Gobler et al. 2017).

Although changes in temperature within the optimal range may serve to enhance growth in cultured species, once outside this range, increasing temperatures are likely to have negative effects on growth. Additionally, periods of extreme high temperature can negatively affect survival. Monthly mean coastal water temperatures in the southern part of the Greater Atlantic Region currently range approximately 24–27°C during the summer months (NCEI 2024), and this is considered optimal for growth of eastern oysters, a major aquaculture species in the region (Shumway 1996 and references therein). In the northern portion of the region, summer temperatures are slightly cooler, ranging approximately 18–24°C (NCEI 2024).

For eastern oysters, 30°C is generally considered to be the threshold at which physiologic function starts to decline as temperature increases further (Shumway 1996, Marshall et al. 2021). However, temperature and salinity tolerances can vary by life stage and location (Lowe et al. 2017). Changes in temperature and seasonality can also lead to changes in phytoplankton bloom timing and in the distribution of wild broodstock; they can also promote range expansion or contraction of predatory species such as marine mammals.

Climate impacts from altered water quality dynamics and water chemistry are also concerning with respect to their potential negative effects on shellfish culture (Figure 3). Along with ocean acidification, changes in properties such as turbidity and salinity can affect shellfish growth, survival, and susceptibility to disease if they fall outside the tolerance range of a given species. Changing shorelines, currents, and tide levels will also undoubtedly affect the areas suitable for shellfish aquaculture.

Ocean acidification will be particularly detrimental to major aquaculture species of the Greater Atlantic Region, such as hard clams and eastern oysters, as well as to minor species such as snails and softshell crabs (Table 7; Wallace et al. 2014, NOAA CPO 2017, NMFS 2022), because low pH can negatively influence shell formation and stability for these animals (Ekstrom et al. 2015, CMRA 2017, NMFS 2022). Such impacts could be especially harmful for industries that lack the hatchery capacity needed to shield the most sensitive early life stages.

Key information needs for the Greater Atlantic Region

Regional aquaculture coordinators and federal researchers from NOAA Fisheries' Greater Atlantic Region described the following as the most pressing information needs related to climate change in response to our questioning in spring 2022:

- Information regarding the stability of various mariculture species into the future based on projected climate change models.
- Potential replacement species for future aquaculture endeavors within the region when culture of traditional aquaculture species is no longer viable or practical due to the effects of climate change.

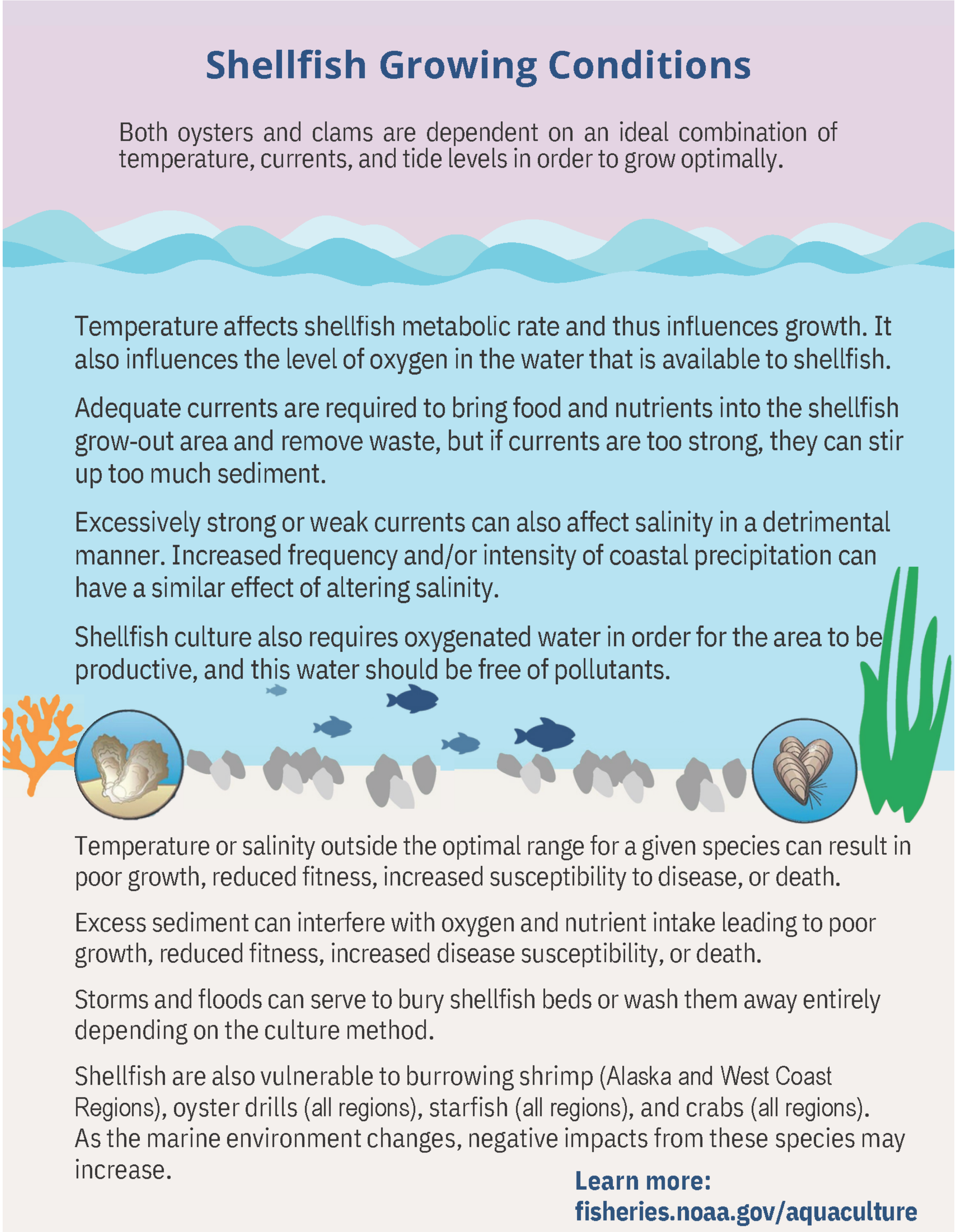
2.3.2 Southeast Region

Climate drivers

North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, and Texas are included in the Southeast Region, where both sea surface and air temperatures are increasing. These increases have been manifesting a rising intensity of heatwaves throughout the region, with a concurrent rise in the number of freeze-free days. Annual numbers of warm nights (> 23.8°C) have also increased along the coasts of this region. Within the Gulf of Mexico, microscale climate regimes are likely to produce heterogeneous patterns of heating when combined with other climate effects (Peterson et al. 2017).

As water temperatures increase, dissolved oxygen (DO) decreases. In the southern part of the Southeast Region, temperatures can drive oxygen to levels incompatible with life. The northwestern Gulf of Mexico is particularly vulnerable to becoming hypoxic because, in addition to its relatively warm summer temperatures, it is also heavily stratified from the large freshwater and nutrient influx from the Mississippi River.

Stratification, or layering of water masses with differing chemical and physical properties, prevents mixing, and thus inhibits the reoxygenation of oxygen-depleted bottom waters. Furthermore, nutrient-rich discharge from the Mississippi River promotes the growth of algal blooms. These blooms consume oxygen as they die. As a result, this area of the Gulf



Shellfish Growing Conditions

Both oysters and clams are dependent on an ideal combination of temperature, currents, and tide levels in order to grow optimally.

Temperature affects shellfish metabolic rate and thus influences growth. It also influences the level of oxygen in the water that is available to shellfish.

Adequate currents are required to bring food and nutrients into the shellfish grow-out area and remove waste, but if currents are too strong, they can stir up too much sediment.

Excessively strong or weak currents can also affect salinity in a detrimental manner. Increased frequency and/or intensity of coastal precipitation can have a similar effect of altering salinity.

Shellfish culture also requires oxygenated water in order for the area to be productive, and this water should be free of pollutants.

Temperature or salinity outside the optimal range for a given species can result in poor growth, reduced fitness, increased susceptibility to disease, or death.

Excess sediment can interfere with oxygen and nutrient intake leading to poor growth, reduced fitness, increased disease susceptibility, or death.

Storms and floods can serve to bury shellfish beds or wash them away entirely depending on the culture method.

Shellfish are also vulnerable to burrowing shrimp (Alaska and West Coast Regions), oyster drills (all regions), starfish (all regions), and crabs (all regions). As the marine environment changes, negative impacts from these species may increase.

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Figure 3. Key mechanisms by which cultured clams and oysters are vulnerable to climate impacts.

of Mexico is described as having the largest “dead zone,” or area of seasonal hypoxia (DO ≤ 2 mg/L), in the western hemisphere (Rabalais et al. 2007, Bianchi et al. 2010). Algal blooms also promote the release of CO_2 as they decompose, further contributing to acidification.

Precipitation in the form of rain is projected to increase and to be more concentrated in time within the Southeast Region, although some local areas may experience a decrease in precipitation. Storm activity is also projected to increase within the Gulf of Mexico based upon a positive correlation between tropical cyclones and local increases in sea surface temperature (Emmanuel 2005, Vecchi and Soden 2007, Ramsay and Sobel 2011). Although increased flooding and storm surges can damage coastal infrastructure, they can also serve to alleviate heat stress and improve oxygenation through wind-driven mixing of cool, low-oxygen bottom waters with warm, higher-oxygen surface waters (Manzello et al. 2007, Rabalais et al. 2009).

This expected increase in precipitation will heighten flood risk in coastal and low-lying areas of the region, with increases in storm intensity amplifying these risks. The combined effects of flooding and storm damage may be devastating to shorelines and coastal infrastructure. Areas most vulnerable to storm damage, such as the Gulf Coast of Louisiana, are already experiencing sea level rise through glacial melt and local subsidence—a phenomenon wherein land sinks with compaction of the aquifer system, heavy soil deposits, and/or the presence of sinkholes (Penland and Ramsey 1990).

Some areas in the Southeast Region are experiencing sea level rise at a rate noticeably greater than the global average. The southeastern Atlantic Coast is one of these areas because of its heavy influence by the Gulf Stream current. Ezer et al. (2013) and Rahmstorf et al. (2015) observed signs that the Gulf Stream current is weakening, which may lead to decreased upwelling and increased sea level rise. The risk of flooding in these coastal areas will be particularly high during king tides (also known as spring or perigean spring tides).

Aquaculture impacts

Eastern oysters and hard clams are the major aquaculture species for the Southeast Region based on farm gate value (Table 7). As such, it is likely that top regional impacts will be related to warming temperatures. These include: changes in pathogen or parasite presence and susceptibility to disease; changes in growth rate or season; decreased survival; catastrophic loss; target species range contraction; nontarget species range expansion or contraction; and catastrophic loss (i.e., large-scale mortality of cultured species within a relatively short time).

In general, increased sea surface temperatures have been associated with higher disease prevalence (Cooke et al. 1998, Hoffmann et al. 2001, Elston et al. 2008, Castro et al. 2012, Hewson et al. 2014). Sea surface temperature can also affect phytoplankton bloom timing, thus influencing the base of the food web.

In the Gulf of Mexico, mean coastal water temperatures exceed 30°C from July through October (NCEI 2024). Again, for eastern oysters, 30°C is generally considered to be the temperature at which physiologic function starts to decline (Shumway 1996, Marshall et al. 2021). In the Atlantic Ocean, coastal temperatures off Florida approach or exceed 30°C from July through September, and those off North and South Carolina approach 30°C in August (NCEI 2024).

Warming temperatures have also been associated with species range shifts. Along the Texas Gulf Coast, Fujiwara et al. (2019) studied the range of 150 species of fish and invertebrates. They found that over a 35-year period, many tropical species expanded their range northward, presumably in response to warming ocean temperatures. Range expansion of mangrove forests—which filter water, protect shorelines, and provide important habitat for marine organisms—is attributed to warming air temperatures and other climate-related phenomena (Cavanaugh et al. 2014).

Species range expansion may be beneficial to aquaculture in that it can present new opportunities for culture. In the case of mangrove forests, range expansion can serve to enhance culture conditions through stabilizing and purifying the environment. Conversely, the introduction of novel species to an area also presents an opportunity for introducing new predators, diseases, and parasites.

Increasing ocean temperatures have been particularly harmful to coral reef systems off the coast of Florida through bleaching, a phenomenon whereby heat-stressed corals expel their symbiotic algae and die. Corals are extremely important to the southeastern Atlantic and Gulf of Mexico regions: they not only provide habitat for a plethora of marine organisms, but also protect local shorelines from storm surge damage.

As in the northeastern Atlantic and other U.S. regions, warming estuaries and oceans in the southeastern Atlantic and Gulf of Mexico coasts may threaten seafood safety through increasing the prevalence of harmful bacteria such as *Vibrio parahaemolyticus* (Martinez-Urtaza et al. 2010, Jones et al. 2011, Vezzulli et al. 2016) and harmful algal blooms (Heil and Muni-Morgan 2021). In Florida and Texas, climate-related changes in upwelling, nutrient availability, and ocean circulation patterns are predicted to affect the frequency of occurrence and duration of *Karenia brevis* blooms (Heil and Muni-Morgan 2021). This algae species produces neurotoxins which can accumulate in shellfish, potentially causing neurotoxic shellfish poisoning in humans (Walsh et al. 2006, Watkins et al. 2008). These blooms can also cause large fish kills by depleting oxygen and contributing to ocean acidification as they decompose.

High air temperatures can also degrade seafood quality postharvest and reduce the window of time available to get seafood to market safely. Extreme heat can present a direct threat to human safety for those working in the aquaculture industry.

Declines in DO levels that result from increasing temperatures and eutrophication are also detrimental to finfish and shellfish aquaculture. However, culture of macroalgae and perhaps shellfish may be used to reduce hypoxic dead zones created by the growth and subsequent decay of algae through removing excess nutrients such as nitrogen and phosphorous that promote algal growth. Macroalgae can also serve to oxygenate the water column locally, thus improving the habitat and resiliency of wild stocks (Vásquez et al. 2014, Buschmann et al. 2017, Duarte et al. 2017, Racine et al. 2021).

More concentrated precipitation events can influence local water quality dynamics, with significant effects on shellfish culture. Shellfish growth relies on a stable balance of nutrients, temperature, salinity, and dissolved oxygen—conditions that promote the growth of diverse phytoplankton communities (Figure 3). Storms and floods can bury or wash away shellfish beds, while rising sea levels can significantly change the habitat area suitable for shellfish culture.

These impacts can necessitate relocation of shellfish beds and/or shorebased processing facilities, docks, and distribution centers. Consequently, an increase in storm frequency or intensity can be catastrophic to cultured species. Intense storms can result in direct mortality or indirect effects, such as changes in water chemistry and food availability, both of which can lead to increased physiologic stress. Severe weather events can also damage and block access to equipment and facilities, displace people working in the aquaculture industry, and release hazardous materials into water/air.

Ocean acidification is particularly problematic for oysters. Fortunately, Ekstrom et al. (2015) reported that over the short term, the southeast in general will be less vulnerable to ocean acidification relative to other locations.

Key information needs for the Southeast Region

In the spring of 2022, aquaculture coordinators of the Southeast Region, along with federal researchers, described the most pressing needs related to climate change as follows:

- Gear designed and manufactured locally and able to withstand the stresses placed on it from extreme weather events such as hurricanes. Local construction will support the regional economy and ensure that historic knowledge about the local environment and aquaculture practices is incorporated into gear design. Additionally, it ensures that there will be a readily available workforce capable of installing, maintaining, and/or decommissioning gear as necessary.
- Continued research and breeding programs to produce seed that is more tolerant of fluctuations in environmental conditions such as dissolved oxygen, temperature, and salinity.
- Workforce development is needed if aquaculture is to expand as a climate-resilient industry. This could be achieved through new recruits to the industry or through transitioning those impacted directly by climate change, e.g., fishermen or workers from other industries, such as oil or gas, being phased out or downsized due to climate considerations.

Representatives from the Southeast Region also requested more information/research to determine the cause of seasonal mortality events observed in oysters, more information about marine pathogens and parasites in general, and disaster preparedness and insurance for damage incurred by extreme weather events.

These representatives also highlighted the lack of knowledge and research about macroalgae culture, particularly with regard to disease susceptibility and how this might be affected by climate change. Finally, they requested comprehensive stock assessments for both cultured and wild species within the region in advance of future climate change so that baseline information is available to evaluate climate effects.

2.4 Northwest North America: Alaska Region

IPCC’s Northwest North America geographic region covers Alaska, where IPCC climate models project an annual median sea surface temperature increase of 0.6°C over the next 20 years, given either the low or intermediate emissions scenario. Cooling degree days are also projected to increase by 5.6 and 5.4 under low and intermediate scenarios, respectively (Table 6). Sea level is expected to increase by 0.1 m over this same period under the low or intermediate scenario, as sea ice concentration decreases by 4.3% and 4.4%, respectively.

Total precipitation is expected to increase by 4.5% and 3.8%, and maximum one-day precipitation is projected to increase by 5.1% and 4.3% under the low and intermediate emission scenarios, respectively. For both scenarios, surface wind is expected to decrease by 0.3% and surface pH to decrease by 0.1 unit in this region.

Climate drivers

Increasing temperatures, retreating sea ice, and ocean acidification are predicted to be major climate drivers for the Northwest North America IPCC region over the next 20 years (Symon et al. 2006, AMAP 2011). According to the Fou*rth National Climate Assessmen*t (Markon et al. 2018), temperatures in Alaska have been warming at twice the global average rate since the 1970s, with the northern part of the state warming faster than the south. This level of intensity with respect to warming is likely attributable to the combined effects of global warming and complementary decadal-scale climate regimes that are inherent to the region.

Importantly, a significant portion of Alaska is underlain by permafrost (i.e., soil that is at or below freezing), and increasing temperatures may lead to increased flooding and erosion of these areas. This can result in higher sediment loads in rivers that empty into bays and estuaries, and a resultant loss of shoreline and coastal infrastructure such as docks and roads.

Loss of sea ice from melting contributes directly to sea level rise and increases the potential for damage to coastal infrastructure from storm surges. Loss of sea ice also contributes to ocean acidification by increasing the area of sea surface/air interface, thereby allowing for increased carbon dioxide absorption by the ocean. Ocean acidification has been expanding into deeper waters off Alaska and other regions for the past few decades. Although there is no current or proposed aquaculture in the Beaufort Sea, pH is so low at this location that, since 2001, it has been considered undersaturated with respect to aragonite, a mineral needed for healthy shell formation and stability in mollusks (Qi et al. 2017).

Aquaculture impacts

Pacific oyster is the major cultured species of Alaska (Table 7), and minor crops include clams, mussels, and macroalgae. Alaska's shellfish industry depends on hatchery-produced cultivars, which provide protection for the most vulnerable early life stages. As such, top regional impacts related to warming temperatures will likely include an increased prevalence of harmful algal blooms and changes in pathogen/parasite presence and susceptibility to disease.

Changes in growth rate, growing season, and feed availability may be positive with increasing temperatures, as long as they remain within the optimal range. However, once these temperatures are exceeded, changes in growth and survival will trend toward the negative. Range contraction or expansion will be species-dependent.

Similar to other regions, warming estuaries and oceans may also affect seafood safety due to increases in the production of harmful algae and bacteria such as *Vibrio parahaemolyticus*. To date, *Vibrio* has not been a significant concern in Northwest North

America compared to other U.S. regions; however, *Vibrio* prevalence is expected to increase with rising ocean temperatures within the region. Harmful algae such as *Alexandrium catenalla*—the neurotoxin-producing dinoflagellate responsible for causing paralytic shellfish poisoning in animals and humans—are endemic to the region, and increasing ocean temperatures and decreasing sea ice are predicted to result in more-frequent and larger blooms (Anderson et al. 2021, Lefebvre et al. 2022).

Changes to snow and ice melt and glacial contraction can affect water quality dynamics and lead to changes in salinity, temperature, and nutrient and sediment loads. As mentioned earlier, sediment loads can have significant effects upon the culture of shellfish, which depend on ideal growing conditions. Thus, sediment effects can lead to changes in the area suitable for aquaculture. Sea level rise can also change the area suitable for aquaculture and can necessitate the relocation of shorebased processing facilities, docks, and distribution centers. However, a phenomenon known as viscoelastic or isostatic uplift—the rise of bedrock that has been depressed beneath a melting glacier—should offset many effects of sea level rise in southeastern Alaska over the near term (Larsen et al. 2005).

Changes in ocean acidification can affect shellfish reproduction, increase disease susceptibility, affect survival, and necessitate hatchery culture of some life stages. However, seaweed aquaculture can potentially help the region adapt to ocean acidification, and may benefit from increased CO_2.

Key information needs for the Alaska Region

In the spring of 2022, regional aquaculture coordinators and federal researchers described the most pressing information needs related to climate change as follows:

- Better forecasting tools for marine heatwaves and harmful algal blooms.
- Information about how climate change is likely to impact normal phytoplankton production (food for shellfish).
- Information about how climate change is likely to alter nutrient dynamics in the region (important for macroalgae and shellfish culture).

Representatives from the Alaska Region highlighted the lack of knowledge and research about macroalgae culture, particularly in the area of disease susceptibility and how it might be affected by climate change. They echoed the need for comprehensive stock assessments for both cultured and wild species within the region in advance of future climate change, so that baseline information is available to evaluate climate effects.

2.5 Western North America: West Coast Region (Northwest)

Washington, Oregon, and northern-to-central California represent the majority of NOAA Fisheries' West Coast Region and fall within the Western North America IPCC geographic region. They are served by NOAA Fisheries' West Coast Regional Office and the Northwest and Southwest Fisheries Science Center. For this area, IPCC climate models project an increase in annual median sea surface temperature of 0.7°C and 0.6°C over the next 20 years, given low and intermediate emissions scenarios, respectively. Cooling degree days are projected to increase by 42 and 43 under the respective low and intermediate scenarios (Table 6).

Sea level is expected to increase by 0.1 m over this same period under both scenarios. Total precipitation is projected to increase by 2.4% under low and 1.6% under intermediate emissions scenarios, and respective maximum one-day precipitation is expected to increase by 4.2% and 4.4%. Surface wind is projected to decrease by 0.8% and 0.7% under the respective low and intermediate scenarios, and pH is projected to decrease by 0.1 unit under both scenarios.

Climate drivers

Climate in the Pacific Ocean off western North America is influenced by a combination of seasonal-, interannual-, and decadal-scale regimes. Similar to other U.S. regions, long-term climate change for the West Coast Region will depend on whether these local regimes complement or oppose the global climate trends of warming and increased precipitation. According to the *Fourth National Climate Assessment* (May et al. 2018), strong El Niño winters will be characterized by an increase in storm surges and large waves. This can result in coastal erosion and damage to shorelines and infrastructure.

In addition to the more gradual warming projected in relation to climate change, the western Pacific Ocean is expected to experience a higher incidence of marine heatwaves (May et al. 2018). For example, during 2013–15, a heatwave known as “the Blob” was detected off the coasts of Oregon and Washington that expanded north to Alaska and south to California (Bond et al. 2015, Whitney 2015). Marine heatwaves such as “the Blob” wreak havoc on local ecosystems and can last days to months. Heatwaves or heat domes contribute to changes in the normal phytoplankton community and promote algal blooms. They also promote ocean stratification (Palacios et al. 2004), thus reducing upwelling and subsequent productivity.

As in other regions, warmer North Pacific surface temperatures in general can lead to increased occurrence of algal blooms, which consume oxygen when they decompose, contribute to ocean acidification, and may produce toxins hazardous to both marine animals and people (Bond et al. 2015, Cavole et al. 2016, Jacox et al. 2016, McCabe et al. 2016).

Compared to other U.S. regions, Pacific Northwest coastal waters are particularly vulnerable to ocean acidification (Gruber et al. 2012). This is a consequence of coastal upwelling, where seasonal winds drive deep seawater up toward the surface. Although these deeper waters tend to be nutrient-rich, they are also lower in oxygen and higher in CO_2 than surface water. In general, upwelling is projected to increase over the next two decades because of warming air temperatures over the mainland, which create strong contrasting temperature fronts along the coast (Bakun 1990, Garcia-Reyes and Largier 2010, Narayan et al. 2010, Sydeman et al. 2014, Rykaczewski et al. 2015).

Conversely, there is also potential for decreased upwelling caused by warming and subsequent stratification of the ocean layers, and this warming may dampen future increases in upwelling and its associated effects (Roemmich and McGowan 1995, McGowan et al. 2003, Palacios et al. 2004). Upwelling ultimately drives the ecosystem in the eastern Pacific Ocean, determining productivity, oxygen availability, and pH. Better models are needed to predict the effects of climate change on ocean upwelling in areas served by the West Coast Region.

Aquaculture impacts

Based upon farm gate value, major aquaculture species of the northwestern Pacific Coast are Pacific oysters, geoduck clams, and Manila clams (Table 7). As such, top regional impacts related to changing temperatures will likely include increased pathogen and parasite presence and susceptibility to disease, as well as target species range contraction, changes in growth rate/growing season, changes in survival, and changes in feed (i.e., plankton availability).

An additional risk to aquaculture is the potential range expansion of nuisance and predator species. Furthermore, algal blooms can be directly toxic to shellfish, deplete oxygen, and enhance ocean acidification.

As in all regions, an overall increase in ocean temperature can actually serve to enhance growth rate or increase the growing season for cultured organisms. Nevertheless, continued warming may eventually produce temperatures that inflict physiologic stress on cultured species. Temperature-related stress can lead to poor growth and condition, increased disease, and eventually death. However, there is some evidence that genetic selection programs may be able to avert some of this impact by "breeding ahead" of climate change (Crozier and Hutchings 2014, Reid et al. 2019).

Additional risks to shellfish culture within the Pacific Northwest include an expected increase in the frequency and/or intensity of storms, resulting in changes to water chemistry and/or turbidity that in turn lead to greater physiologic stress. Increased storm intensity is also expected to change the availability of planktonic feed and increase the incidence of toxic algae (ICES 2023). Wave action and wind from storms can also damage equipment and facilities, preclude access to aquaculture sites, and either bury or wash away shellfish beds and cages and other gear. Pacific oysters and clams are highly vulnerable to damage from storms, heatwaves, and erosion events.

Pacific oysters and clams are also highly susceptible to the effects of ocean acidification. Oyster farmers in the Pacific Northwest have been observing the effects of ocean acidification upon larval shellfish (the most vulnerable life stage) through lower growth and higher mortality since about 2007 (Barton et al. 2012). When pH is too low, larvae are unable to form the shells critical to their further development. The effect of ocean acidification on oyster recruitment has driven industry adaptation in the form of new hatchery production of seed for Pacific oysters, including carbonate buffering of intake seawater.

Moving to hatchery production has opened the door to genetic selection of higher-performing and more resilient cultivars. The aquaculturists who rely upon natural seed are more vulnerable than those who cultivate hatchery seed. Wild-set oysters primarily supply the shucked market, while hatchery oysters supply both shucked and half-shell markets. This may lead to a change in oyster markets, potentially increasing the cost of shucked oysters but decreasing the cost of half-shell oysters.

Key information needs for the West Coast Region (WA, OR, northern CA)

To discern the greatest information needs in the West Coast Region—Washington, Oregon, and northern-to-central California—we queried regional aquaculture coordinators and federal researchers from areas served by NOAA Fisheries' West Coast Regional Office, the Northwest Fisheries Science Center, and the Southwest Fisheries Science Center. Representatives described the following as the two most pressing information needs related to climate change:

- Information about how climate-driven shifts in phytoplankton species diversity may impact both wild shellfish harvest and the success of shellfish aquaculture.
- Better spatial modeling to inform siting of shellfish operations while taking into consideration climate change, harmful algal blooms, and other anthropogenic stressors such as pollutants, wind energy, shipping, and deposit of dredge materials.

Representatives of the northern-to-central West Coast Region also highlighted the need to develop less energy-intensive methods of farming, given the increasing cost of fuel and concerns regarding the release of CO_2. Other priorities included better forecasting tools for predicting disease, harmful algal blooms, and potentially harmful environmental conditions such as heatwaves. They also expressed a need for information about species tolerance boundaries with respect to dissolved oxygen, pH, salinity, and temperature. Such information will be critical in predicting how regional conditions are likely to change in the future, and which species to invest in for success in future aquaculture.

2.6 North Central America: West Coast Region (Southwest)

The IPCC region of North Central America comprises southern California and is served by NOAA Fisheries' West Coast Regional Office and the Southwest Fisheries Science Center. Within the Southern California Bight, IPCC climate models predict an increase in annual median sea surface temperature of 0.6°C over the next 20 years, given either the low or intermediate emission scenarios (Table 6). Cooling degree days are also projected to increase by 111.2 and 121.1 under the low and intermediate scenarios, respectively.

Sea level is expected to increase by 0.1 m over this same period for both low and intermediate scenarios. Total precipitation is projected to increase by 0.8% under the low scenario (with a confidence interval spanning zero) and to decrease by 2.0% under the intermediate emission scenario (also with a confidence interval spanning zero). Maximum one-day precipitation is projected to increase by 3.8% and 2.5% for low and intermediate emissions, respectively. However, similar to total precipitation, the confidence intervals for this attribute also span zero. Surface wind is projected to decrease by 0.5% under the low and 0.7% under the intermediate scenario, and pH is projected to decrease by 0.1 unit under both emission scenarios.

Climate drivers

IPCC's North Central America region includes some of the hottest and driest areas in the United States (Gonzalez et al. 2018). Along the southern California coast, loss of beaches and marsh habitat and damage to infrastructure from storm surges are major concerns over the next two decades. These impacts are expected to result from increases in the frequency of heavy rain, sea level rise, and flooding for this area.

The North Central America region is also expected to experience an increase in the incidence of marine heatwaves, similar to those described for the Northwest North America IPCC region (Gonzalez et al. 2018). In addition to killing marine life outright, heatwaves can significantly alter local ecosystems by contributing to changes in the normal phytoplankton community and by promoting algal blooms. Algal blooms consume oxygen when they decay, enhance acidification, and sometimes produce toxins harmful to humans, birds, fish, and marine mammals. They also promote ocean stratification (Palacios et al. 2004), which may suppress upwelling and subsequent productivity (Roemmich and McGowan 1995, McGowan et al. 2003).

Similar to the upwelling dynamics described for Washington, Oregon, and northern–central California, upwelling off the coast of southern California brings oxygen-poor and CO_2-rich bottom waters to the surface. Thus, this area is also acutely vulnerable to additional CO_2 from the atmosphere.

Aquaculture impacts

For southern California, the major aquaculture species based on farm gate value is Pacific oyster, with other shellfish produced as minor species (Table 7). As such, top regional impacts related to warming temperatures will be similar to those described for Washington, Oregon, and northern-to-central California. These include changes in pathogen and parasite presence; susceptibility to disease; target species range contraction; changes in growth rate and growing season; changes in survival; changes in planktonic feed availability; and changes in nontarget species range, with potential increases in nuisance species and predators such as burrowing shrimp, Japanese oyster drill, starfish, crabs, skates, and diving ducks. Increasing storm surges and ocean acidification are also of particular concern for this region.

Increasing temperatures have been correlated with disease-related mortality in Pacific oysters. For example, Burge et al. (2006) observed that mortality of *Crassostrea gigas* seed cultured at two sites in Tomales Bay followed temperature extremes of 27.13°C and 22.98°C and was correlated with sustained temperatures ranging from 16°C to 25°C and from 16°C to 22°C. They hypothesized that temperature maxima >25°C were responsible for inducing replication of the ostreid herpesvirus-1 (OsHV-1) in these cultured oysters.

Marine heatwaves can lead to acute physiologic stress, changes in planktonic feed availability, and declines in seafood quality postharvest. They can also promote harmful algal blooms that are directly toxic to shellfish, deplete oxygen when they decay, and enhance ocean acidification. An increase in the frequency of marine heatwaves is especially concerning for oyster triploids (i.e., with three sets of chromosomes), which are less robust than their diploid conspecifics to the effects of multiple environmental stressors (George et al. 2023).

Changes in the concentration of dissolved oxygen associated with warming temperatures and/or eutrophication can affect shellfish growth, survival, and reproduction. Low DO can stress organisms physiologically, thus increasing their susceptibility to disease, and these impacts may necessitate culture of some life stages in a hatchery. Low DO may also affect feed availability in the form of phytoplankton.

As in other IPCC regions, ocean acidification can lead to depressed reproduction and growth of shellfish, reduced survival, and increased susceptibility to disease. These risks can necessitate hatchery culture of some life stages, and can serve to reduce the amount of habitat suitable for aquaculture.

Increased frequency and intensity of storms can change water chemistry and/or turbidity, which can in turn lead to physiologic stress for shellfish, change the availability of feeds, and increase the incidence of land-origin toxins released directly into the water. Wave action and wind from storms can also damage equipment and facilities, preclude access to aquaculture sites, and either bury or wash away shellfish beds/gear. Sea level rise alone will influence the habitat suitable for aquaculture in the future, and may necessitate the relocation or renovation of shorebased processing facilities, docks, and distribution centers.

Key information needs for the West Coast Region (southern CA)

Regional aquaculture coordinators and science center researchers from the West Coast Region described the following as the two most pressing information needs related to climate change in southern California:

- Studies on temperature thresholds for disease outbreaks in nonsalmonid aquaculture species that could be cultured in U.S. waters.
- Better forecasting tools for disease outbreaks, harmful algal blooms, marine heatwaves, and storms so that industry can be better prepared to mitigate impacts.

Representatives of the southern West Coast Region highlighted the fact that warming temperatures will benefit some cultured organisms while negatively affecting others. As such, they repeated the need expressed in other regions for information about species tolerance boundaries with respect to dissolved oxygen, pH, salinity, and temperature, along with information about how regional conditions are likely to change in the future given climate projections. They echoed the call from the Southeast Region to complete comprehensive baseline stock assessments now so the effects of climate change in the future can be assessed more accurately.

2.7 North Pacific: Pacific Islands Region

The North Pacific IPCC geographic region is composed of Hawaii and the U.S.-affiliated Pacific Islands. With respect to IPCC climate models, this region is projected to realize an increase in annual median sea surface temperature of 0.6°C and 0.7°C over the next 20 years, given low and intermediate emission scenarios, respectively (Table 6). Cooling degree days are also projected to increase by 123 and 126.6 under the respective low and intermediate scenarios, and sea level is expected to increase by 0.1 m under both emission scenarios.

Under the respective low and intermediate scenarios, total precipitation is projected to increase by 1.5% and 1.0%, and maximum one-day precipitation is projected to increase by 3.5% and 3.6%. Surface wind is projected to decrease by 0.7% and 0.8 % under the respective low and intermediate emission scenarios, and pH is expected to decrease by 0.1 unit under both scenarios.

Climate drivers

Similar to Eastern North America and Caribbean, increasing ocean temperatures in the North Pacific IPCC region have led to coral bleaching, and this trend is expected to continue. Deterioration of coral reefs will result in the loss of both fish habitat and a physical barrier that has protected coastal areas against storm surges. Ocean acidification compounds this stress by interfering with reef recovery. Sediment and debris runoff from storms can also bury and suffocate corals.

In an area where the euphotic zones are already characterized as nutrient-poor due to their warmth and high stratification, additional warming is predicted to further suppress ocean productivity (Richardson and Schoeman 2004, Behrenfeld et al. 2006, Steinacher et al. 2010). Additionally, as ocean temperatures warm, dissolved oxygen levels are projected to decrease (Bopp et al. 2013, Hoegh-Guldberg et al. 2015).

Areas suitable for aquaculture in Hawaii and the Pacific Islands are generally either at or within a few feet of sea level (either marine or land-based). Although annual precipitation is projected to decrease with climate change, the rainfall that does occur is expected to be more extreme and concentrated, potentially enhancing erosion and flooding. The projected increase in sea level rise due to glacial melt and thermal expansion can exacerbate flooding. Saltwater intrusion from sea level rise and storm surges will stress and potentially kill mangrove forests. These forests provide important aquatic habitat for fish as well as protect coastlines, filter water, and protect coral reefs from heavy sediment runoff.

Although tropical cyclones appear to be shifting northward (away from the islands), this region is heavily influenced by large-scale climate regimes such as the El Niño–Southern Oscillation and the Pacific Decadal Oscillation. Effects of these large-scale regimes can be magnified by global climate change, and the potential for enhanced severity of storms and higher waves is of particular concern.

Aquaculture impacts

In Hawaii and the U.S.-affiliated Pacific Islands, the major aquaculture species based on farm gate value is microalgae (Table 7). Minor species include Pacific white shrimp for broodstock, Pacific oysters, Manila clams, and macroalgae. Many of these species are cultured in land-based systems that will inherently be more robust to the effects of climate change. However, there is ocean production of *Seriola rivaliana* and a variety of finfish, shrimp, and algae are produced in *loko i'a*, or fish pond systems.

Potential effects of warming temperatures include changes in pathogen and parasite presence and susceptibility to disease; target species range contraction; changes in growth rate, growing season, and survival; and nontarget species range expansion or contraction. Temperature-related declines in oxygen saturation can impart physiologic stress to finfish and shrimp, leading to poor growth, increased susceptibility to disease, and even death. Low dissolved oxygen can also disrupt feeding and growth.

Sea level rise can affect the area covered by traditional fish ponds and may necessitate the relocation or renovation of shorebased facilities, docks, and distribution centers. An increase in storm frequency during El Niño years can be catastrophic to aquaculture, either killing organisms directly by burying them under sediment or by destroying or dislodging pond walls, moorings, and cages. Wind and wave action can also damage ponds, equipment, and facilities and inflict physiologic stress by changing ocean chemistry, disrupting the food web, and increasing turbidity.

High-energy storms may also cause infrastructure damage, such that toxins or pollutants from land are released into the water. Increased precipitation intensity can lead to changes in water quality dynamics that affect nutrient and sediment loads, temperature, and dissolved oxygen. This can affect phytoplankton bloom timing and location, which in turn can cause changes in growth and survival for shellfish.

Key information needs for the Pacific Islands Region

The most pressing information need expressed by aquaculture coordinators and federal researchers of the North Pacific IPCC/NOAA Fisheries Pacific Islands Region was information about the life-history requirements for most cultured and wild endemic species.

3 Adaptation Strategies for Aquaculture

As defined here, *adaptation* refers to activities that help build resiliency to climate change, allowing aquaculture to function even under increasing impacts (Table 1, Figure 4). Adaptation is different than *mitigation*, which is defined here as activities that reduce the strength or probability of climate change in the first place.

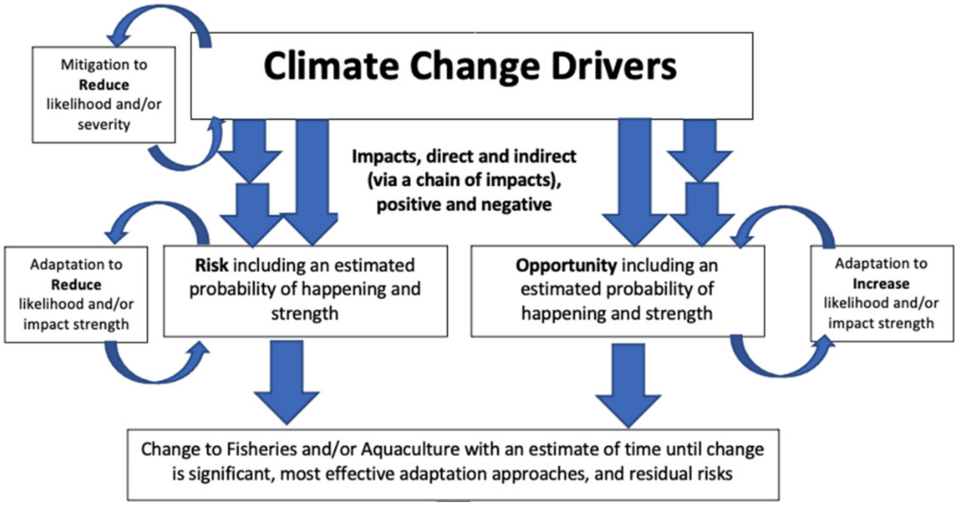

Figure 4. Conceptual model showing relationships among the concepts explored in this report (Table 1). Conceptual terms were adopted from Masson-Delmotte et al. (2021) and ICES (2023). Stacked arrows indicate indirect effects and single arrows indicate direct effects. Curved arrows denote a feedback loop.

As detailed in Section 2, climate drivers such as warming of both sea and air, ocean acidification, sea level rise, and increasing storm frequency and intensity are predicted to have significant effects on U.S. coastal and marine waters. Potential negative effects of climate change on U.S. aquaculture species are expected to range from mild and moderate (e.g., decreased growth, poor meat quality, or increased susceptibility to disease) to severe (e.g., death of cultured organisms). If addressed early through research, improvements in gear, cultivars, and farm practices, and thoughtful and effective policy, the U.S. marine aquaculture industry can resist and adapt to many of these challenges.

Participants from the *Workshop on Pathways to Climate-Aware Advice* identified adaptation strategies and recommendations to address major climate drivers that affect aquaculture production (ICES 2023). Their recommendations are summarized in Tables 9 and 10, and are described briefly in the sections below (in no particular order).

Table 9. Climate drivers affecting aquaculture and their respective categories for adaptation (ICES 2023). Key: *IMTA* = integrated multitrophic aquaculture, *RAS* = recirculating aquaculture system.

Adaptation strategy	Warming sea/air temp.	Ocean acidification	Sea level rise[a]	Increased storms[b]	Harmful algal blooms	Hypoxia	Increased precip.[b]	Altered phytoplankton biomass
Adapt farm practices	•	•	•	•	•	•	•	•
Better bioenergetics models						•		
Better business models	•							
Better communication with industry sectors	•							
Better therapeutics	•							
Biosecurity	•							
Depuration of products prior to sale					•			
Event forecasting	•	•		•	•	•	•	•
Focus on health	•							
Focus on nutrition	•							
Genetic selection	•	•		•	•	•	•	•
Hatcheries	•	•			•			
IMTA		•	•	•		•	•	•
Insurance	•		•	•	•		•	
Modify gear	•		•	•	•		•	
Monitoring	•	•	•	•	•	•	•	•
Public outreach	•							
RAS	•							
Relocate farm	•	•			•	•		•
Restore corals/mangroves			•	•			•	
Sanctuaries	•							
Site suitability and spatial planning	•		•	•		•	•	•
Species selection for tolerance	•	•	•	•		•	•	
Strategic cage and structure placement			•	•			•	
Stronger regulations	•				•			•
Upland management			•			•		

[a] Sea level rise with erosion and flooding, seawater intrusion, and/or shoreline habitat loss.

[b] Increased frequency and/or intensity.

Table 10. Adaptation strategies to address major climate impacts for aquaculture production (ICES 2023). Key: *IMTA* = integrated multitrophic aquaculture, *RAS* = recirculating aquaculture system, *Cat*. = catastrophic, *Reprod*. = reproduction, *Suscept*. = susceptibility, *Distrib*. = distribution, *Freq*. = frequency.

	Climate impacts								
	Finfish, shellfish, and seaweed								
Adaptation strategy	**Cat. effects (i.e., death)**	**Growth**	**Pathogen/ parasite presence**	**Pathogen disease dynamics**	**Reprod. and growth**	**Survival**	**Suscept. to disease**	**Distrib. of wild broodstock**	**Freq. of equip./ facilities damage**
Event forecasting	•		•	•			•		•
Adapt farm practices	•	•	•	•	•		•		•
Modify gear	•	•							•
Genetic selection	•	•	•	•	•	•	•	•	•
Insurance	•	•	•	•	•	•	•		•
Monitoring	•		•	•			•		•
Research	•							•	•
Sanctuaries	•								
Site suitability/spatial plan	•	•			•	•			•
Species selection for tolerance	•	•	•		•	•		•	
Hatcheries		•			•	•		•	
Better therapeutics		•	•	•	•	•	•		
Biosecurity			•	•			•		
Focus on health			•	•			•		
Focus on nutrition			•	•			•		
RAS			•	•			•		
Better business models					•	•			
Farm practice/site suitability						•			
IMTA									
Better communication with industry sectors									
Public outreach									
Relocate farm									
Stronger regulations									
Upland management									
Research and farm practice									
Research and species selection									
Monitoring/event forecasting									

Table 10 (continued). Adaptation strategies to address major climate impacts for aquaculture production. Key: *IMTA* = integrated multitrophic aquaculture, *RAS* = recirculating aquaculture system, *sp.* = species, *exp./cont.* = expansion/contraction, *WQ dynam* = water quality dynamics, *Freq./loc.* = frequency/location, *HABs* = harmful algal blooms.

	Climate impacts							
	Finfish, shellfish, and seaweed (cont'd)			**Finfish and shellfish**		**Finfish**	**Seaweed**	**Seaweed and shellfish**
Adaptation strategy	**Target sp. range exp./ cont.**	**Habitat area suitable for aquaculture**	**Seafood safety and quality**	**Dissolved O_2/general WQ dynam.**	**Freq./loc. of HABs**	**Issues dealing with feed**	**Ocean acidification**	**Nutrient and plankton availability**
Event forecasting			•	•	•		•	
Adapt farm practices	•	•	•	•	•	•	•	•
Modify gear					•			
Genetic selection	•	•		•	•		•	•
Insurance	•	•			•			
Monitoring			•	•	•		•	
Research	•				•	•		•
Sanctuaries								
Site suitability/spatial plan	•	•		•				•
Species selection for tolerance	•	•	•	•				
Hatcheries	•				•		•	
Better therapeutics								
Biosecurity								
Focus on health	•				•			
Focus on nutrition	•			•				
RAS								
Better business models	•							
Farm practice/site suitability								
IMTA		•		•			•	•
Better communication with industry sectors			•					
Public outreach			•					
Relocate farm			•	•	•		•	•
Stronger regulations			•			•	•	•
Upland management				•				
Research and farm practice							•	•
Research and species selection							•	
Monitoring/event forecasting								•

3.1 Monitoring and Event Forecasting

Environmental monitoring to develop event forecasting at meaningful scales is necessary for aquaculturists to plan for and react to extreme events, including marine heatwaves, storms, dead zones (areas of hypoxia), pollution incidents, and biological and geological change. Any of these events may result in catastrophic losses to cultured organisms through death, disease, or escape, or through damage to gear, equipment, or shoreline infrastructure.

Event forecasting includes monitoring, prediction, early detection, and real-time reporting of events such as harmful algal blooms and proliferation of harmful bacteria (e.g., *Vibrio parahaemolyticus*). Readers are referred to Aguilar-Manjarrez et al. (2018) for a summary regarding the use of spatial technology such as satellite remote sensing, aerial surveys, and remotely operated underwater vehicles for reducing disaster risk.

An important subset of monitoring and event forecasting for aquaculture is the science of marine epidemiology. Knowledge about the various pathogens and parasites present in an area, their virulence, and their preferred conditions can be combined with knowledge of ocean currents and environmental conditions to help inform aquaculturists about when and where a given species may be most susceptible to infection/disease. Armed with this information, aquaculturists can make informed decisions about the seasonal timing of grow-out and harvest.

To catch early signs of stress or disease, better forecasting will require:

1. Comprehensive and consistent methods for monitoring cultured species in situ (e.g., appearance, condition, performance, behavior).
2. Better monitoring and forecasting of local and regional environmental conditions, including temperature, salinity, dissolved oxygen, pH, particulate matter, nutrient availability, pathogen presence, biotoxins, and applicable contaminants.
3. Monitoring cages, mooring lines, etc., to ensure continued structural integrity/function.
4. Developing models and reporting functions to make projections and inform aquaculturists.

With respect to ocean acidification and productivity, better information is also needed to project whether upwelling for a given area will increase or decrease with climate change.

3.2 Farm Practices

The topic of farm practices encompasses a diverse number of improvements to husbandry, farm management, and technology. It is impossible to know all that will be developed in the coming decades in response to a changing climate. Nevertheless, here we highlight ideas for improved farm practices that can provide adaptation to, and in some cases mitigation from, climate change.

Extreme weather events, warming temperatures, changes in flushing patterns, effluent effects, and harmful algal blooms will affect not only the health of cultured organisms, but potentially also the quality and safety of postharvest seafood. Armed with sufficient information about the environment and potential stressors to their crop, aquaculturists can tailor farm, harvest, and storage practices to reduce and mitigate these effects. For example, a grower might time production to avoid seasonal extremes in weather and ocean conditions, or reduce stocking densities during periods when water temperatures approach the maximum tolerance for a given species.

Hatcheries were often mentioned as an approach to increase adaptation of the industry to climate change. Indeed, a clear example is found in the response of the U.S. West Coast oyster industry to recruitment failures caused by ocean acidification. By maintaining a hatchery environment favorable to the early life stages of a farmed organism, the most sensitive part of the life cycle can be protected. In addition, the development of hatcheries is a prerequisite to genetic selection and the benefits that can be realized from cultivars that are resistant to the stresses of climate change.

Adaptation of farm practices might also include: 1) feeding fish and shrimp to maximize growth during periods when environmental conditions are ideal, 2) using probiotics or other supplements to promote organism health, or 3) harvesting early to prevent catastrophic losses of the type that may occur during an extreme weather event.

Nutrient requirements for marine fish need to be defined, and the usefulness of alternative feeds examined. Further investigation is needed for alternate feeds such as insects, microalgae, macroalgae, and a variety of additional plants, single-cell organisms, and byproducts. The environmental footprint of alternatives could be used to formulate feeds with the least environmental cost.

As aquaculture expands in the face of climate change, there may be increasing needs for effective and approved therapeutics, enhanced biosecurity, and plans for detecting and handling various disease outbreaks in species of interest. Certification programs may develop to ensure consumer confidence in U.S. seafood and hatchery seed. At local processing plants, seafood can be incorporated into value-added products immediately postharvest to mitigate for rising air temperatures and increasing concern for seafood safety.

With climate change, ideal practices are those that will work within the constraints of the natural environment but will also be rapidly adaptable to prevailing conditions. For example, submersible net pens are used to avoid both wave action from storms and high sea surface temperatures. For farms reliant on manufactured feeds, the ability to feed and monitor animals automatically or remotely would allow adaptation when access to a particular site is temporarily interrupted.

3.3 Improved Gear and Equipment

Increased frequency of catastrophic events such as heatwaves, and increases in the severity of storms, will also dictate modifications to gear and equipment. Equipment and gear can be designed and built to ensure that they will not break free and drift or break open and release cultured organisms into the wild. Structural requirements should be robust, and standards could be adopted such that gear can withstand the most extreme local predictions for wind and wave energy through the end of the century.

Gear deployed near shore may be designed to protect the shoreline and to complement the existing ecosystem. Materials and designs should optimize feeding and observation of cultured species, and minimize biofouling. Finally, ideal structures should be portable to the extent that they can be collected and stored onshore if necessary. This will require an investment in ocean science, technology, engineering, and mathematics. Where appropriate, refugia and landbased hatcheries can protect against catastrophic loss during extreme events.

3.4 Insurance and Disaster Relief Programs

Support from disaster relief programs and insurance can provide aquaculture businesses with vital protection against catastrophic loss from extreme weather events, harmful algal blooms, or severe pathogen infections. Relief and insurance programs can also protect against loss of equipment and facilities. The U.S. Department of Agriculture's Risk Management and Farm Service Agencies currently administer a variety of targeted crop insurance and disaster assistance programs for aquaculturists (USDA RMA 2023). Government support programs can also be put in place to help relocate farms when environmental and biological conditions have changed such that a given species is no longer viable, or when traditional aquaculture sites have been lost due to climate-driven physical environmental changes.

The future scope of insurance and disaster relief programs will depend upon progress made in all other adaptation strategies. For example, development of adaptive strategies described in Section 3.1 will enable private and public insurance groups to better calculate and manage exposure to hazards. Likewise, better gear, selected cultivars, and improved farm practices will help reduce the risks of loss, thus lowering insurance costs.

3.5 Innovative Adaptation Strategies

For areas where water quality is projected to decline with depleted oxygen saturation or low pH, innovative adaptation strategies are needed. These might include the use of hatcheries to culture vulnerable life stages, such as "head start" programs, or programs to hold and spawn broodstock. Various farm practices can also be employed to alter the local environment. These include the co-culture of finfish, shellfish, and seaweeds (known as integrated multitrophic aquaculture, or IMTA), ocean alkalinity enhancement, aeration, and restoration/protection of sea grass beds, coral reef systems, and mangrove forests.

Better understanding of the role of plankton in nutrient and energy transfer is also needed, as well as information on how to balance nutrient ratios for proliferation of beneficial plankton rather than harmful algal blooms. Siting species that extract nutrients (e.g., shellfish) in areas with excess, and siting species that release nutrients (e.g., finfish) in areas lacking or insensitive to nutrients, may be key strategies for long-term sustainable development.

3.6 Selective Breeding

To the extent possible, genetic selection can be explored to cultivate robust breeds that can thrive under current and projected environmental conditions—for example, under conditions of low DO and/or pH. Species may be selected for performance and pathogen resistance, and actions can be taken to minimize the risk of introgression with wild species should they escape. Genetic breeding programs may also be developed to modify spawn timing in stocking programs where climate change has affected the distribution or spawn timing of wild broodstock.

3.7 Site-Suitability Models and Spatial Planning

Ideally, future aquaculture sites and cultured species will be selected proactively using site-suitability models, maps, and spatial planning. These tools are needed to identify sites and species that are naturally resilient to climate effects such as increasing temperature, decreasing oxygen, and ocean acidification. Ideal cultured species would be fast-growing and robust to infection, and would have a short life cycle.

In the future, site-suitability models may be built on historical and projected environmental conditions. They should also take into account the current and projected range of target culture species, local wild species, and potential nuisance species whose range is expected to expand as local conditions change. Areas expected to have persistently inhospitable conditions and areas where long-term planning is difficult could be avoided (e.g., dead zones and areas slated for future oil and gas development). Spatial planning can also be used proactively to identify areas where aquaculture can make up for projected losses in wild fisheries.

4 Mitigation Strategies for Aquaculture

We have identified potential climate change challenges to the U.S. aquaculture industry by region (Section 2) and presented strategies for how the industry can adapt to address these challenges in partnership with government (Section 3). However, the benefits of a thriving U.S. aquaculture sector will go beyond providing a climate-smart, sustainable protein source for human consumption. Aquaculture can also provide ecosystem services that help mitigate the effects of climate change.

Mitigation includes activities that remove carbon from the atmosphere and oceans or keep it from being released in the first place (Table 1, Figure 4). Thus, mitigation helps to reduce the severity and probability of climate change-induced impacts. Mitigation differs in this way from adaptation, which includes activities that can help build resiliency so that aquaculture can function even under increasing climate effects.

Two recent reports have explored options for ocean-based carbon dioxide sequestration (NASEM 2022, Cross et al. 2023), and both have potential applications in marine aquaculture. These applications are: 1) the use of seaweeds to directly take up carbon dioxide from the ocean and fix it into seaweed tissue, and 2) increasing ocean biomass through conservation (wild blue carbon) or aquaculture (farmed blue carbon).

Further studies are needed on the use of macroalgae for carbon removal and sequestration at a large scale, and on the role of aquaculture to increase this process beyond what is being done by natural macroalgae populations (Hurd et al. 2009, 2014, Xiao et al. 2017, Paine et al. 2021). Troell et al. (2022) concluded that long-term carbon sequestration by seaweeds is not likely at a scale that can mitigate global warming, but considered that the decarbonization value of seaweed may lie in its use to replace food, feed, and/or other materials that generate higher greenhouse gas emissions.

Either by direct sequestration of CO_2 into seaweed biomass, or by virtual sequestration through replacing other, more carbon-intensive products, seaweed farming is thus far an underdeveloped climate mitigation strategy for aquaculture.

The National Academies of Sciences, Engineering, and Medicine list marine ecosystem recovery as a carbon removal strategy. As they explain, recovery of the marine ecosystem can enhance the natural biological uptake of carbon dioxide through protection and restoration of coastal ecosystems, such as kelp forests and free floating *Sargassum*, and also through the recovery of fishes, whales, and other animals in the oceans (NASEM 2022). Similarly, Cross et al. (2023) outline the mechanisms of carbon uptake and transfer in coastal wetlands and marine ecosystems in their discussions of coastal blue carbon and marine ecosystem biomass.

Processes analogous to those for seaweed farming occur for wild algae—with the exception that there is no harvest, so the biomass produced either sinks to deep zones, where it is effectively sequestered, or it is used to support the growth of higher trophic levels. Higher trophic levels also deposit some of the carbon they have taken from algae (macro- and micro-) in the form of bones, shells, and feces.

Carbon from marine animals drops to the benthos, where it is recycled through bacterial decomposition, fixed as hard structures, or passed to other trophic levels. Thus, animals act as carbon pumps, taking carbon from primary producers, passing some of it along, and turning some back into CO_2 via respiration—but also sequestering some of it. Overall, the whole cycle fixes more CO_2 than it releases.

The carbon cycle can be enhanced—and thus store more carbon—by increasing the speed of the cycle and/or by increasing the biomass of organisms at all stages of the cycle. Stock enhancement and culture-based habitat enhancement are two areas where aquaculture can directly contribute to ecosystem recovery through decarbonization. Examples include culture and planting of mangroves and corals with high temperature tolerance to rebuild key habitat, as well as more traditional stock enhancement. There is also evidence that the structures used for aquaculture may improve habitat for some species, potentially leading to enhanced ecosystem recovery; however, this is still an area of active research.

Blue carbon is defined by NOAA as carbon captured by the world's ocean and coastal ecosystems (NOS 2023). Ecosystem recovery, as suggested by the National Academies of Sciences, Engineering, and Medicine, would increase the capture of wild blue carbon (NASEM 2022). Cross et al. (2023) expand this concept and include farmed blue carbon as a potential approach to increasing both marine biomass and the speed of the carbon cycle. Aquaculture is key to developing farmed blue carbon. The role of animal aquaculture in carbon capture is an undeveloped area of research and would likely benefit from targeted research.

The concepts of *embedded carbon* and *virtual carbon* have been less well developed for aquaculture. Embedded carbon refers to the amount of carbon needed to make a given product. Virtual carbon is the amount of carbon saved or added once the product is sold or imported relative to a similar or the same product made elsewhere. Similar products may release very different amounts of carbon. Likewise, the same product made at different locations may result in different amounts of carbon release.

Aquaculture products are widely thought to have lower embedded carbon than land-produced products for which they can substitute. For example, macroalgae is used as a low-carbon source of high-value bioproducts. Such products include food, feed, nutritional supplements and fertilizers, biofuels (Chopin and Tacon 2021), bioenergy (Hughes et al. 2012, Klinger 2021, Jones et al. 2022), and bioplastics (Troell et al. 2022). Domestic production for local markets is also thought to have lower virtual carbon.

These concepts form the basis for carbon trading, but are poorly developed for most aquaculture practices. Embedded carbon is an area that may benefit from further modeling and research, leading to industry eligibility for carbon credits and trading. Finally, some aquaculture products could directly help to reduce carbon emissions from other industries—for example, algae scrubbers on coal power plants.

A promising example from marine aquaculture is the use of red seaweeds as a feed supplement for reducing enteric methane emissions from ruminants. Roque et al. (2021) found red seaweed (*Asparagopsis taxiformes*) supplementation of feed reduced methane emissions by over 80% in beef steers, without compromising the quality of the meat. This is important because ruminant production of methane during enteric fermentation/digestion makes up an estimated 14.5% of anthropogenic greenhouse gas emissions annually (Roque et al. 2021).

5 Related Federal Initiatives and Opportunities for Future Collaboration

Negative climate impacts on aquaculture production are expected to be significant and challenging over the next 20 years. Nevertheless, marine aquaculture presents a range of unique opportunities to sustain a robust domestic seafood production sector and to mitigate the effects of climate change. Such opportunities are largely unavailable to wild-capture fisheries, with obvious implications for seafood. Implementation of the strategies suggested here can play a critical role in easing regional transitions and realizing opportunities for a thriving U.S. seafood sector as the climate changes.

Aquaculture practices that support species and habitat restoration for wild fisheries and that mitigate climate change through carbon sequestration present key opportunities. As one of the lead agencies facilitating U.S. aquaculture and the national response to climate change, NOAA can play a significant role in providing industry with “climate-smart” information and practices to fully realize these opportunities and enhance smooth adaptation.

In summarizing these opportunities, we assumed that no new funding would be available. The practical result of this assumption is that not all of the adaptation or mitigation strategies can be addressed immediately. Even so, there are actions that can be taken without new funding. To this end, NOAA and partners are currently engaging in several initiatives, working groups, and projects, which are briefly outlined below. This section provides near-term opportunities from existing NOAA programs and collaborations that could be enhanced to help aquaculture adapt to climate change. Each opportunity assumes that no new resources for aquaculture and climate will be available.

5.1 Climate, Ecosystems, and Fisheries Initiative

The Climate, Ecosystems, and Fisheries Initiative (CEFI) is a cross-NOAA effort to build a nationwide, operational ocean modeling and decision-support system. A decision-support system is needed to reduce impacts, increase resilience, and help marine resources and resource users adapt to changing ocean conditions (Figure 5). This end-to-end support system will provide decision-makers with the actionable information and capacity they need to prepare for and respond to changing conditions today, next year, and for decades to come.

The Climate, Ecosystems, and Fisheries Initiative addresses four core requirements that are essential to climate-ready decision-making for marine resources:

1. Delivery of state-of-the art ocean and Great Lakes forecasts and projections for use in developing climate-informed management advice.
2. Operational capability to use ocean and Great Lakes forecasts and projections to assess risks, evaluate management strategies, and provide robust management advice for changing conditions.
3. Continuous validation and innovation through observations and research.
4. Capability to use climate-informed advice to reduce risks and increase the resilience of resources and the people who depend on them.

CEFI Integrated Ocean Modeling and Decision Support System

▶ Advancing Climate, Ocean, and Ecosystem Understanding

▶ Operational Climate, Ocean, and Ecosystem Decision Support Systems

▶ Climate Ready Decision Making

SCIENCE AND DEVELOPMENT
Drives Innovation and Skill

OPERATIONS AND INFRASTRUCTURE
Drives Dissemination and Decision Support

EXTENSION AND ENGAGEMENT
Drives Service Delivery and Knowledge Transfer

National Community of Practice

Convene a nationwide community of practice to harness broad community expertise to guide development of the CEFI ocean modeling and decision support system at regional and national scales.

Enhanced Observations

Expand ocean- and marine-life observing systems to continuously improve early warnings, longer-term projections and management advice for climate-informed decision making.

Targeted Research that Fuels Innovation

Support collaborative research and modeling to increase innovation and understanding of future oceans, impacts on marine resource and management options.

Enhanced Ocean Modeling Capabilities

Enhance ocean and earth system models and High-Performance Computing (HPC) capacity building on a strong, sustainable national foundation for CEFI regional and global modeling efforts.

Regional Ocean Modeling and Prediction

Regional Ocean Modeling Teams utilize the national ocean modeling framework to produce and deliver regional ocean hindcasts, forecasts, and projections for use by the FACSS and others in developing climate-informed management advice.

CFI Information Hub

Build a comprehensive CEFI Information Hub to provide easy access to regional ocean model outputs (high spatial resolution reanalysis, hindcasts, predictions, and projections optimized for management applications), ecosystem projections and other information relevant to climate-informed resource management.

Fisheries and Climate Decision Support System (FACSS)

Establish expert teams at NMFS Science Centers to accelerate the production of climate-informed assessments and management advice to help decision-makers sustain fisheries, conserve protected resources, and maintain ecosystem services in collaboration with existing programs and external partners.

Ecosystem Prediction

The FACSS—in concert with cross-NOAA and external experts—will provide a variety of products and services for use in climate-informed management advice and decision making including robust projections of future ecosystem conditions.

Increasing Capacity for Climate Ready Decisions

Increase the capacity of decision-makers to use climate-related information and management advice in decisions concerning marine resources and resource-dependent communities.

Rapid Response

Provide forecasts, early warnings, and plans for effective response to near-term extreme events such as marine heat waves and toxic algal blooms.

Climate Ready Decision Support Tools

Provide climate-enhanced risk assessments, stock assessments, management strategy evaluations, adaptation frameworks and other tools for climate-informed decision making.

Improve Surveys and Research

Use climate and ecosystem information to improve the efficiency and effectiveness of fisheries research and surveys to adjust changing ocean conditions and shifting species distributions.

Coordinated Science and Advice

Increase coordinated delivery of climate-related science and management advice internally and externally through national strategies aligned with regional priorities and efficient information sharing.

Figure 5. Elements of the Climate, Ecosystems, and Fisheries Initiative showing research, modeling, and implementation components. Figure courtesy of CEFI (https://www.fisheries.noaa.gov/topic/climate-change/climate,-ecosystems,-and-fisheries).

CEFI is focused on management of wild fish stocks and of protected species and their habitats. However, information services from the initiative will be valuable for aquaculture—with a few additions. Significant considerations that could make the initiative more useful to aquaculture include efforts to:

- Use aquaculture farm locations to observe, understand, model, and forecast pathogens, parasites, harmful algal blooms, and ocean conditions (models) that affect the physiology of both cultured organisms and wild stocks.
- Produce information relevant to aquaculture risk assessments.
- Include aquaculture representatives and experts in the community of practice.
- Include aquaculture-specific research and research to study the potential effects of aquaculture on wild stocks.

5.2 Carbon Dioxide Removal Task Force

NOAA's Carbon Dioxide Removal Task Force recently published a white paper outlining agency roles in the developing field of CO_2 removal and sequestration (Cross et al. 2023). Roles identified for NOAA in this strategy include observation networks, monitoring, ecosystem interactions, modeling, and ocean planning. A complementary report released by NASEM (2022) addresses ocean-based CO_2 removal.

The two reports overlap; however, the latter report includes a large section on the role of living marine ecosystems and resources—and their restoration and conservation, in particular—as a method of atmospheric decarbonization. This sequestration method would require restoration of natural carbon flows and pools.

There are clear areas of intersection between the needs of aquaculture and those of ongoing ocean CO_2 removal initiatives, including:

1. Improved models for potential expansion of large-scale seaweed farming and restoration of seaweed to extract and sequester CO_2 in the deep ocean.
2. Modeling and monitoring studies to understand carbon flow and capture through living marine resources and their ecosystems, including the potential role of plant and animal aquaculture at scale in supporting atmospheric CO_2 reduction and potential sequestration.
3. Extending and leveraging science advice capacity for aquaculture toward the complementary goals of marine CO_2 removal and marine renewable energy. Examples of needed advice capacity include the fields of economics, social science, and marine spatial analysis.
4. Analyzing aquaculture carbon budgets to develop robust estimates of embedded carbon sufficient to allow the aquaculture industry to participate in carbon trading.

5.3 Economic Development Task Force

The National Science and Technology Council's Subcommittee on Aquaculture established an Economic Development Task Force charged with developing a strategic plan to support a robust, resilient, and environmentally sustainable domestic aquaculture sector. The task force has drafted a *Strategic Plan for Aquaculture Economic Development* (NSTCSA 2023). Opportunities to increase the climate resilience of U.S. aquaculture could be provided by adding three objectives to this strategic plan.

The first two would be to support enhancement and expansion of USDA insurance and disaster forecasting programs. The third objective would be to create a program to use aquaculture as a resilient, economically viable option to produce seafood by workers from wild-capture fisheries who have been displaced by climate change. Each of these efforts would support goals identified in the draft strategic plan.

Insurance programs are vital to mitigate the impacts of catastrophic economic loss from extreme weather events, such as marine heatwaves and storms. Improved forecasting capacity would provide critical support for both industry and insurers. As discussed previously, there is a need for various types of climate forecasts tailored for aquaculture producers. Such forecasting capacity would be a central technical goal for the strategic plan and would include development of marine epidemiological models to understand biological risks and to inform industry and insurers.

A climate-adaptive strategy focusing on economic opportunities available through aquaculture should identify development opportunities to maintain and sustainably grow coastal economies from national to community levels. To attain such growth with simultaneous shifting of fish stocks and reduced fishery productivity, a focus on enhanced climate adaptation opportunities within the aquaculture sector will be necessary. Such enhancements can include species selection, engineering for advanced structures and equipment, and hatchery technology to control environmental conditions during vulnerable early life stages. These goals could be added as multi-agency objectives for future work of the aquaculture subcommittee.

5.4 One Health Initiative to Sustainable Seafood

The Centers for Disease Control and Prevention define the One Health program as a collaborative, multisectoral, and transdisciplinary approach, working at the local, regional, national, and global levels to achieve optimal health outcomes while recognizing the interconnection between people, animals, plants, and their shared environment (CDC 2022).

The One Health approach is presently used by NOAA to catalyze collaboration among the seafood community, state and federal governments, academia, industry, and the public. This approach is intended to connect people and capabilities in addressing challenges to domestic seafood production.

The following activities are examples of the One Health approach employed by NOAA Fisheries' Office of Aquaculture to address climate change impacts:

- A project with the NOAA Climate Program Office and the U.S. Global Change Research Program to better understand the connections between climate drivers and environmental effects on current and emerging marine pathogens and parasites.
- Collaborations with the U.S. Fish and Wildlife Service, the U.S. Department of Agriculture, and the U.S. Food and Drug Administration—as well as with tribal and state governments, academia, nongovernmental organizations, and the aquaculture industry—to identify biosecurity risks and develop best management practices for offshore marine aquaculture.
- A project with the U.S. Fish and Wildlife Service to facilitate collaborative public–private partnerships that will study the efficacy and safety of potential medicines, supplements, and probiotics to maintain the health, welfare, and resilience of cultured animals.
- Discussion with NOAA Sea Grant scientists and the scientific community in general on how to better anticipate and forecast disease risks in the marine environment using spatial/temporal hydrodynamic modeling.
- Work with NOAA Sea Grant scientists to explore and document the role of farmed seaweeds and shellfish in enhancing habitat, and thus health, for other farmed and trust species. Such enhancements include supporting biodiversity, mediating nutrient levels, buffering pH, and providing oxygen.

Additionally, several forecasting tools are in various stages of development by NOAA's National Centers for Coastal and Ocean Science. These tools will be essential for ensuring sustainable and safe seafood production and harvest during climate change (OCM 2023). In order for these tools to optimally benefit the aquaculture industry and include climate information, it is important that the Office of Aquaculture be involved with their further development.

As tools are scaled up from regional demonstration products to fully functional national programs, aquaculture involvement is critical and can be accomplished through collaborations facilitated by the NOAA One Health program. A central goal of the program is to develop better agencywide coordination among groups tasked with maintaining human, environmental, and aquatic organism health (NOAA CPO 2023).

Additional tools are needed to allow examination of patterns in sea surface temperature, ocean acidification, hypoxia, and currents, as well as to help forecast extreme heat events with high spatial resolution at various temporal scales. With this information, the aquaculture industry and regulatory agencies will be better equipped to meet and stay ahead of the challenges of climate change. They will be able to anticipate changes in species composition and disease prevalence and spread, as well as to plan for optimal grow-out conditions for given species and regions.

The following forecasting tools are now in development by the National Centers for Coastal and Ocean Science and the National Environmental Satellite, Data, and Information Service:

- Harmful algal blooms (NCCOS 2023).
- *Vibrio parahaemolyticus* (NCCOS 2023).
- Hypoxic dead zones (NCCOS 2023).
- Coral bleaching (NESDIS 2023).

5.5 International Council for the Exploration of the Sea

We can continue to leverage parallel activities and developments among NOAA Fisheries, the International Council for the Exploration of the Sea (ICES), and the North Pacific Marine Science Organization (PICES). This strategy would include encouraging scientists to participate in various workgroups and would support the establishment of one or more new workgroups on climate and aquaculture. Recommendations given here and in the *Workshop on Pathways to Climate-Aware Advice* (ICES 2023) can support the establishment of specific terms of reference for new and existing workgroups. These efforts will support agency goals and those of the broader global community.

5.6 Improved Industry Data

At present, there is no nationwide system for the collection and management of marine aquaculture industry data. To monitor and understand climate change effects on the U.S. marine aquaculture industry, NOAA will require complete, accurate, and timely data on industry production, performance, management, and environmental conditions.

Production and value data are reported annually in *Fisheries of the United States* (NMFS 2022). These data are gathered from a variety of sources including state agencies, industry groups, specialized surveys, and the U.S. Department of Agriculture's Census of Aquaculture (conducted every ~5 years). The disparate and inconsistent nature of these data sources, variable reporting requirements/methods among states, and lack of a structured data collection system result in data that are likely incomplete and potentially lacking in quality.

Furthermore, these data are currently reported with a one-year lag that does not allow climate change effects to be identified and addressed in a timely manner. In addition to production data, having a repository for industry performance, management, and environmental monitoring data would be of great value. Such a database would provide the opportunity to correlate these data to climate change factors over time. Ideally, data would not be industry-dependent and would complement data collected for *Fisheries of the United States*.

Efforts to establish a nationwide data-collection system for marine aquaculture are being explored. These include initiating and expanding state-level use of existing regional fishery information networks (FINs). Methods for industry-independent collection of production data, such as through use of satellites, may also help to better understand and respond to climate impacts. Improved data collection, management, and availability are needed to understand and address climate impacts most effectively and to best serve affected parties in supporting a sustainable domestic marine aquaculture industry.

6 Conclusions and Recommendations

In summary, climate drivers that are expected to cause significant impacts to U.S. coastal and marine waters include warming of both sea and air, ocean acidification, sea level rise, increasing storm intensities, increases in storm surges and large waves, increasing precipitation (amount and intensity), decreasing dissolved oxygen, increased frequency/ presence of harmful algal blooms and harmful bacteria, and changes in the nutrient supply (phytoplankton biomass and timing).

These drivers will likely lead to: changes in the distribution of broodstock and spawner timing; changes in pathogen and parasite presence and susceptibility to disease; changes in reproduction, growth rates, and survival; decreased seafood quality and safety; decreased habitat area suitable for aquaculture; decreased or disrupted feed availability; and physical damage to infrastructure such as docks, roads, and shorebased processing centers. These impacts may necessitate the culture of certain life stages using land-based systems and/or selection for more robust cultivars.

For oysters and clams, by far the most important U.S. marine aquaculture species, the effects of expected climate change may be appreciable. As sea levels rise and storms become more severe, climate impacts may result in complete losses of cultured organisms and equipment. Concurrently, more subtle climate effects may be expressed as decreased growth, poor flesh, or increased susceptibility to disease. Conversely, for some species and regions, performance may be enhanced with warming temperatures, as long as the species tolerance threshold is not exceeded.

We suggest the following strategic science and policy elements that NOAA can do with little or no new resources to support "climate-smart" marine aquaculture:

- Identify and prioritize, by aquaculture species and region, the specific environmental stressors likely to affect production in the near term. This strategy intersects with goals of the burgeoning Climate Ecosystem and Fisheries Initiative. Adjust research programs to address these stressors and add aquaculture needs to the initiative.
- Based on work done or in progress, develop a targeted research strategy, inclusive of federal research and extramural funding, to address known climate-driven stressors.
  - Examples of such strategies are hatchery development and selective breeding or cultivar choice to develop more climate-resilient breeds. Given the high cost of such programs, they should focus on a few species with the best chances of making significant contributions to seafood production. A robust and standardized techno-economic assessment process may help in setting species priorities.
  - Other research strategies should focus on improvements to husbandry, nutrition, health treatments, systems engineering, and forecasting. These strategies will also support understanding the capacity for wild stocks to evolve and adapt to new climate conditions, and could be used to develop methods to breed climate-resilient keystone species for habitat conservation (e.g., heat-resistant corals, seagrasses, and shellfish).

    - The development of such strategies can be proposed as an extramural grant objective, under either the Saltonstall–Kennedy or NOAA Sea Grant programs and/or as a project for the annual Internal Competition for Aquaculture Funds sponsored by NOAA's Office of Aquaculture.
- Support development and industry operation of best management practices to maximize production as climate change proceeds. Best practices would be developed as a collaboration between industry, government scientists, and other partners established and supported through grant funding or internal funds, with a working document developed and updated every five years.
- Refine and implement a climate adaptation strategy that focuses on opportunities available to support sustained and enhanced domestic seafood production through aquaculture. This would include identifying aquaculture sector development opportunities from community to national levels.
    - Objectives would be to maintain and sustainably grow coastal economies considering shifting fish stocks and reduced fishery productivity.
    - A first step would be to identify existing climate adaptation opportunities within the aquaculture sector, such as hatchery technology to control environmental conditions for vulnerable early life stages. This strategy could be implemented through a Sea Grant project with the NOAA Fisheries Science Centers or through a multi-agency objective for future work of the *Strategic Plan for Aquaculture Economic Development* (NSTCSA 2023).
- Refine and implement a carbon mitigation strategy focusing on opportunities to mitigate climate change through aquaculture. Components of this strategy would include carbon and nitrogen removal through seaweed farming. Investigate the use of shellfish and finfish mass balances to determine mitigation potential for animal aquaculture.
- Emission reduction and avoidance efforts should highlight aquaculture as a potential food production alternative with a smaller carbon footprint and shorter emission-intensive supply chains. This strategy may be implemented as part of the NOAA Climate Data Records program or by a new program employing aquaculture to reduce eutrophication and benefit wild ecosystem resiliency (e.g., in the Gulf of Mexico "dead zone").
- Develop carbon budgets designed to allow the industry to benefit from carbon trading. This could also be added as a goal and work product of the *Strategic Plan for Aquaculture Economic Development* (NSTCSA 2023) to leverage resources from other federal agencies, or could be suggested for extramural NOAA programs.

With these improvements in gear and farm practices, and with climate-smart strategic development, the U.S. marine aquaculture industry can resist, adapt to, and even mitigate many of the challenges presented by climate change.

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Species

Below is a list of species referenced in this technical memorandum.

Common name	**Species**
Abalone	*Haliotis* spp.
Almaco jack	*Seriola rivoliana*
Atlantic salmon	*Salmo salar*
Barramundi	*Lates calcarifer*
Branzino	*Dicentrarchus labrax*
Coho salmon	*Oncorhynchus kisutch*
Eastern oyster	*Crassostrea virginica*
Geoduck clam	*Panopea generosa*
Manila clam	*Venerupis philippinarum*
Pacific oyster	*Crassostrea gigas*
Pacific white shrimp	*Litopenaeus vannamei*
Pompano	*Trachinotus carolinus*
Red drum	*Sciaenops ocellatus*
Steelhead trout	*Oncorhynchus mykiss*

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