International Journal of Marine Science, 2024, Vol.14, No.3, 231-244
http://www.aquapublisher.com/index.php/ijms

Review and Progress Open Access

Impacts of Ocean Acidification on Marine Ecosystems and Mitigation Strategies

Liang Chen, Rudi Mai
Tropical Marine Fisheries Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China
Corresponding author: rudi.mai@hitar.org

International Journal of Marine Science, 2024, Vol.14, No.3, doi: 10.5376/ijms.2024.14.0027
Received: 02 Jun., 2024
Accepted: 13 Jul., 2024
Published: 20 Jul., 2024

Preferred citation for this article:
Chen L., and Mai R.D., 2024, Impacts of ocean acidification on marine ecosystems and mitigation strategies, International Journal of Marine Science, 14(3): 231-244 (doi: 10.5376/ijms.2024.14.0027)

Abstract This study explores the mechanisms of adaptation in aquatic species, including phenotypic plasticity, genetic evolution, and molecular mechanisms. Aquatic species exhibit significant phenotypic plasticity, allowing them to respond rapidly to environmental changes. Changes in gene expression related to osmoregulation and metabolic processes demonstrate how species adjust their physiological states to cope with varying conditions. Genetic evolution plays a crucial role in long-term adaptation, driven by processes such as mutation, natural selection, and genetic drift. Research shows that specific genes in marine mammals and freshwater prawns are crucial for their adaptation to aquatic environments. Molecular adaptations involve gene regulation, genomic changes, and epigenetic modifications. Studies on fireflies and marine diatoms provide insights into the genetic basis of adaptation to different environmental conditions.

Keywords Phenotypic plasticity; Genetic evolution; Gene expression; Aquatic species; Adaptation mechanisms

1 Introduction

Ocean acidification is a critical and pressing issue that affects marine ecosystems worldwide. The phenomenon, primarily driven by the absorption of atmospheric carbon dioxide (CO_2) by the world's oceans, results in a decrease in pH levels, altering the carbonate chemistry of seawater. This process has far-reaching consequences for marine life, particularly for species with calcium carbonate structures, such as corals and shellfish. This review aims to explore the mechanisms of adaptation in aquatic species to ocean acidification, spanning from phenotypic plasticity to genetic evolution.

Ocean acidification refers to the ongoing decrease in the pH of Earth's oceans, caused by the uptake of CO_2 from the atmosphere. Since the industrial revolution, increased CO_2 emissions have led to a significant rise in atmospheric CO_2 levels, with a substantial portion being absorbed by the oceans. This absorption forms carbonic acid, which subsequently dissociates into bicarbonate and hydrogen ions, leading to lower pH and a reduction in carbonate ions available for calcifying organisms (Stillman and Paganini, 2015). The decrease in carbonate ion concentration impairs the ability of marine organisms, such as corals, mollusks, and some plankton species, to produce and maintain their calcium carbonate shells and skeletons (Tagliarolo, 2019).

Understanding ocean acidification is crucial for several reasons. Firstly, it poses a direct threat to marine biodiversity, affecting organisms from the smallest plankton to the largest marine mammals. The disruption of marine food webs can lead to cascading effects on global fisheries, which are vital for food security and economic stability in many regions. Secondly, coral reefs, which are biodiversity hotspots, are particularly vulnerable to acidification. The decline of coral reefs not only affects marine life but also impacts coastal protection, tourism, and fisheries (Tembo, 2017). Moreover, studying the adaptive mechanisms of marine organisms can provide insights into the resilience and future of marine ecosystems in the face of ongoing environmental changes. The primary objective of this review is to identify and describe the physiological and genetic mechanisms that enable aquatic species to adapt to ocean acidification. This involves a comprehensive exploration of phenotypic plasticity and genetic adaptation across different marine organisms. Understanding these mechanisms is essential for elucidating how various species respond to the changing oceanic conditions brought about by increased CO_2 levels.

2 Causes and Mechanisms of Ocean Acidification

2.1 Carbon dioxide absorption

Ocean acidification is a multifaceted phenomenon resulting primarily from human activities, specifically the emission of carbon dioxide (CO_2) into the atmosphere. The mechanisms through which ocean acidification occurs involve the absorption of CO_2 by seawater and subsequent chemical reactions, leading to changes in the ocean's carbonate chemistry. This section details the primary causes and chemical processes involved, as well as historical trends and future projections.

The primary cause of ocean acidification is the absorption of atmospheric CO_2 by the world's oceans. Approximately one-quarter of the CO_2 released by human activities, such as the burning of fossil fuels, deforestation, and cement production, is absorbed by seawater. When CO_2 dissolves in seawater, it reacts with water molecules to form carbonic acid. This weak acid rapidly dissociates into bicarbonate ions and hydrogen ions. The increase in hydrogen ions leads to a reduction in pH, making the water more acidic (Das and Mangwani, 2015). This increase in acidity has far-reaching implications for marine life, particularly those species that rely on calcium carbonate to form their shells and skeletons. The reduction in carbonate ions is particularly detrimental to calcifying organisms, such as corals, mollusks, and some plankton species, which need carbonate ions to build their calcium carbonate structures (Tagliarolo, 2019). Understanding this fundamental process is crucial for grasping the broader impacts of ocean acidification.

2.2 Chemical processes in seawater

Once CO_2 is absorbed by seawater, a series of chemical reactions occur that alter the carbonate chemistry of the ocean. The carbonic acid formed from dissolved CO_2 dissociates into bicarbonate (HCO^{3-}) and hydrogen ions (H+). This increase in H+ ions lowers the pH of seawater, making it more acidic. Additionally, the formation of bicarbonate reduces the concentration of carbonate ions (CO_3^{2-}), which are crucial for the formation of calcium carbonate ($CaCO_3$) used by marine organisms to build shells and skeletons. These chemical processes have significant implications for marine life, particularly calcifying organisms such as corals, mollusks, and some plankton species, which rely on carbonate ions to form their calcium carbonate structures (Doney et al., 2009). The reduction in carbonate ion availability makes it more difficult for these organisms to build and maintain their shells and skeletons, leading to potential declines in their populations and broader impacts on marine ecosystems.

2.3 Historical trends and future projections

Historically, the pH of the world's oceans has remained relatively stable, providing a consistent environment for marine life. However, since the onset of the industrial revolution, there has been a significant increase in atmospheric CO_2 levels due to human activities such as fossil fuel combustion, deforestation, and industrial processes. This rise in CO_2 levels has led to a corresponding increase in the amount of CO_2 absorbed by the oceans, resulting in a measurable decrease in oceanic pH. Data indicate that the average pH of surface ocean waters has decreased by about 0.1 units since the pre-industrial era, which corresponds to a 30% increase in acidity (Mostofa et al., 2015).

Projections based on current CO_2 emission trends suggest that the pH of the oceans could drop by an additional 0.3 to 0.4 units by the end of the 21st century. Such changes would significantly alter marine ecosystems and the organisms that inhabit them. For instance, reduced pH levels and decreased carbonate ion concentrations would severely impact calcifying organisms, leading to weaker shells and skeletons and affecting the overall biodiversity and functionality of marine ecosystems (Zeng et al., 2015). These future projections underscore the urgent need for strategies to mitigate CO_2 emissions and protect marine environments from the adverse effects of ocean acidification.

3 Impacts on Marine Organisms

3.1 Effects on calcifying organisms

Ocean acidification has profound effects on marine organisms, impacting their physiology, behavior, and ecological interactions. This section examines the specific impacts on calcifying organisms, fish and invertebrates, and marine microbes. Calcifying organisms, such as corals, mollusks, and some plankton species, are particularly vulnerable to ocean acidification due to their reliance on calcium carbonate ($CaCO_3$) to form shells and skeletons. The decrease in pH reduces the availability of carbonate ions, essential for calcium carbonate formation.

This reduction leads to weaker and thinner shells, making these organisms more susceptible to predation and environmental stress. Studies have shown that ocean acidification can decrease the calcification rates of corals, leading to slower growth and weaker reef structures (Henry et al., 2020). Additionally, mollusks, such as oysters and mussels, show impaired shell formation, which can reduce their survival and reproductive success (Mostofa et al., 2015). The long-term impact of these changes includes potential declines in populations of calcifying species, which could disrupt marine food webs and ecosystem services, such as coastal protection and biodiversity (Scherer et al., 2022).

3.2 Impacts on fish and invertebrates

Ocean acidification affects fish and invertebrates in multiple ways, including physiological stress, altered behavior, and reproductive challenges. Fish rely on chemoreception for vital functions such as finding food, avoiding predators, and locating mates. Acidified conditions can impair these sensory abilities, leading to disorientation and decreased survival rates (Tembo, 2017).

For instance, studies on juvenile fish, like the European sea bass, have shown that acidification alters their stress response, leading to prolonged recovery times and changes in neurotransmitter levels, which affect behavior and motor activity (Servili et al., 2022). Invertebrates, such as copepods and polychaetes, exhibit varied responses to acidification, often experiencing reduced growth, delayed development, and increased oxidative stress (Lee et al., 2019). These physiological and behavioral changes can impact individual fitness and, over time, lead to shifts in population dynamics and community structure (Wang et al., 2018).

3.3 Consequences for marine microbes

Marine microbes play crucial roles in nutrient cycling and carbon flow within marine ecosystems. Ocean acidification can significantly alter microbial community composition and function, affecting overall ecosystem health. Microbial processes such as photosynthesis and nitrogen fixation are sensitive to changes in pH. For example, studies indicate that acidification can enhance the photosynthetic activity of some phytoplankton species while inhibiting others, leading to shifts in community structure and potential disruptions in primary production (O'Brien et al., 2016) (Figure 1).

The microbial communities associated with marine organisms, such as corals, may shift under acidified conditions, potentially increasing host susceptibility to diseases (Zunino et al., 2021). These changes at the microbial level can have cascading effects throughout the marine food web, influencing the health and stability of larger marine ecosystems.

The image depicts photos taken along a pCO_2/pH gradient in Papua New Guinea (year 2014) and illustrates three potential scenarios for coral reefs under present-day and future (years 2050 and 2100) ocean acidification (OA) conditions if we continue on current predicted CO_2 emissions trajectories. In the present-day scenario, the coral reef is shown to be healthy, with high structural complexity and diversity, likely colonized by beneficial microbial associates, and experiencing a low incidence of disease. As pCO_2 levels increase, the scenarios for the years 2050 and 2100 illustrate the successive degradation of coral reef heterogeneity (structural diversity), destabilization of microbial associations, and an increase in disease. By 2050, the coral reef starts to show signs of degradation, with beneficial microbial associations beginning to destabilize and disease prevalence increasing, leading to a reduction in structural diversity. By 2100, the degradation has progressed further, and the reef transitions to an alternative stable state dominated by competitive species such as sponges, macroalgae, and seagrass, along with sediment/rubble. The arrows from green to red indicate the positive to negative changes a coral reef might experience over time. This transition highlights the severe ecological degradation that coral reefs may face if CO_2 emissions continue on the current trajectory.

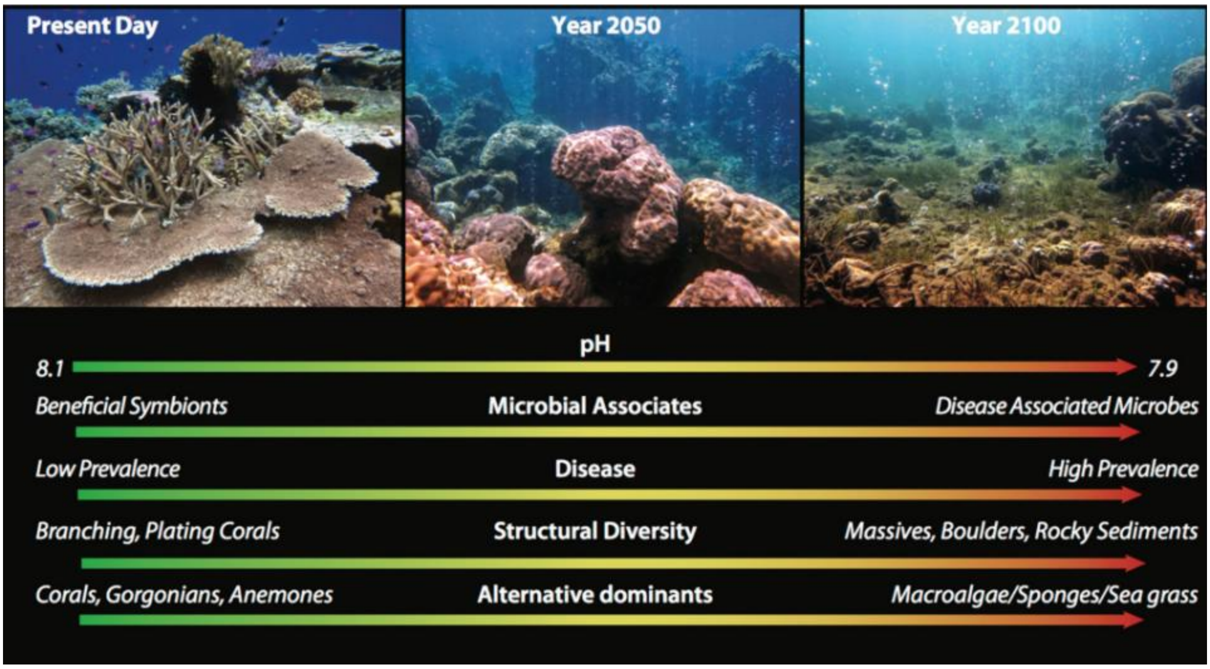

Figure 1 Photos, taken along a pCO_2/pH gradient in Papua New Guinea (year 2014), and text depict three potential scenarios for coral reefs under present day and future (year 2050 and 2100) OA conditions if we continue on current predicted CO_2 emissions trajectories (Adopted from O'Brien et al., 2016)

Image caption: Present Day illustrates a healthy coral reef with high structural complexity and diversity that is likely colonized by beneficial microbial associates and experiences a low incidence of disease. As pCO_2 increases, scenarios for years 2050 and 2100 illustrate the successional degradation of coral reef heterogeneity (structural diversity), destabilization of microbial associations and increase in disease, transitioning to an alternative stable state composed of competitive dominants (e.g., sponges, macroalgae) and/or sediment/rubble. Arrows from green to red indicate the positive to negative changes a coral reef might experience over time (Adopted from O'Brien et al., 2016).

4 Ecosystem-Level Impacts

4.1 Changes in biodiversity

Ocean acidification has profound implications for marine ecosystems, influencing biodiversity, food web dynamics, and ecosystem services. This section explores these impacts in detail. Ocean acidification leads to significant changes in marine biodiversity, primarily by affecting species differently based on their physiological and ecological characteristics. Calcifying organisms, such as corals, mollusks, and certain plankton, are particularly vulnerable due to their reliance on calcium carbonate for their skeletal structures. The reduction in pH decreases the availability of carbonate ions, essential for calcification, leading to weaker shells and skeletons. This vulnerability can result in decreased biodiversity as these organisms struggle to survive and reproduce under more acidic conditions (Zunino et al., 2021). Additionally, acidification can alter species composition and abundance, favoring non-calcifying over calcifying species, and causing shifts in community structure. Studies at CO_2 seeps have shown that areas with lower pH levels have reduced species diversity and are dominated by algae and non-calcifying organisms (Hall-Spencer and Harvey, 2019) (Figure 2).

Figure 2 illustrates the ecosystem properties, functions, and services provided by coastal habitat-forming species and the communities they support. The central part of the diagram shows temperate and tropical habitat-forming species, such as coral reefs and seagrass beds, which provide the foundational structure for ecosystems. Surrounding this central part is a layer labeled "Species," indicating how these habitat-forming species support various ecosystem communities. The outermost layer is divided into three sections: ecosystem properties, ecosystem functions, and ecosystem services. Ecosystem properties include habitat complexity, species richness, and coverage. Ecosystem functions encompass productivity, biodiversity, and nutrient cycling. Ecosystem services involve food provision, recreation, and coastal protection. These properties, functions, and services are interconnected and collectively maintain the health and stability of the ecosystem. Arrows within the diagram illustrate the relationships between ecosystem properties, functions, and services, indicating that the loss of habitat-forming species and the degradation of ecosystem states diminish ecosystem services. Observations from CO_2 seeps worldwide show that ocean acidification leads to reductions in habitat complexity, species richness, and habitat coverage. This reduction impairs ecosystem functions, such as productivity and nutrient cycling, and consequently affects ecosystem services like coastal protection, recreation, and food provision. Overall, the figure emphasizes the importance of protecting habitat-forming species and maintaining ecosystem health. This not only helps preserve ecosystem complexity and diversity but also ensures that humans continue to benefit from the various services ecosystems provide.

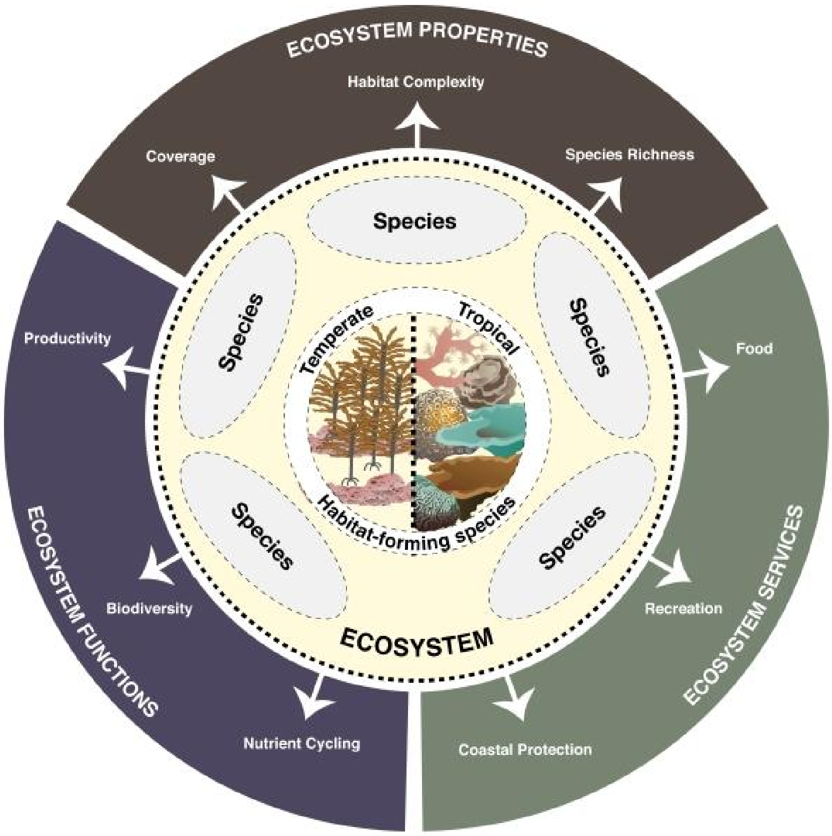

Figure 2 Ecosystem properties, functions and services provided by coastal habitat-forming species and the communities that they support (Adopted from Hall-Spencer and Harvey, 2019)

Image caption: The loss of habitat-forming organisms and degradation of ecosystem state diminishes ecosystem services. Observations at CO_2 seeps worldwide show that ocean acidification results in reductions in habitat complexity, species richness and habitat coverage. This impairs ecosystem function and the goods and services available to society, such as coastal protection, recreation and food provision (Adopted from Hall-Spencer and Harvey, 2019)

4.2 Alterations in food web dynamics

Ocean acidification impacts food web dynamics by affecting the physiological and behavioral responses of marine organisms. For instance, the reduction in calcification rates among shellfish can lead to declines in their populations, which in turn affects the species that rely on them for food. Additionally, changes in the abundance and composition of primary producers can cascade through the food web, impacting secondary consumers and higher trophic levels (Riebesell et al., 2018).

Acidification also affects predator-prey interactions, with some predators experiencing changes in hunting efficiency and prey vulnerability. For example, toxic algal blooms, which may increase under acidified conditions, can disrupt trophic interactions by providing a selective advantage to harmful algal species, thereby altering the food web structure and function (Riebesell et al., 2018).

4.3 Effects on ecosystem services

The impacts of ocean acidification extend to ecosystem services, which are the benefits humans derive from marine ecosystems. Coral reefs, which provide coastal protection, tourism opportunities, and fisheries habitats, are particularly at risk. As acidification weakens coral structures, the associated ecosystem services diminish, leading to increased coastal erosion, reduced fishery yields, and loss of biodiversity (Lemasson et al., 2017). Similarly, the degradation of shellfish populations affects water filtration services, as species like oysters and mussels play crucial roles in maintaining water quality. The economic implications are significant, particularly for communities dependent on marine resources for their livelihoods (Zunino et al., 2021). The cumulative effects of acidification on ecosystem services highlight the urgent need for mitigation and adaptation strategies to preserve the functionality and benefits of marine ecosystems.

5 Socioeconomic Impacts

5.1 Effects on fisheries and aquaculture

Ocean acidification has wide-ranging socioeconomic impacts, affecting fisheries, coastal communities, and the broader economy. This section explores these impacts in detail. Ocean acidification poses a significant threat to fisheries and aquaculture, particularly those dependent on calcifying organisms such as shellfish. Shellfish, including oysters, mussels, and clams, rely on calcium carbonate for their shells. Reduced carbonate ion availability due to acidification makes it harder for these organisms to build and maintain their shells, leading to increased mortality and reduced growth rates. For instance, the oyster industry on the Pacific coast of North America has already experienced substantial economic losses due to increased larval mortality linked to acidified conditions (Clements and Chopin, 2017). This reduction in shellfish populations directly impacts aquaculture operations and wild capture fisheries, leading to decreased yields and significant economic losses.

The Atlantic sea scallop fishery, a high-value industry in the United States, is projected to see a significant decline in biomass under high CO_2 emissions scenarios. Under a high CO_2 emissions scenario (RCP8.5), sea scallop biomass could decline by more than 50% by the end of the century, which would drastically reduce industry landings and revenues (Rheuban et al., 2018) (Figure 3). Similarly, Europe, a significant producer of marine mollusks, could face annual economic impacts exceeding \$1 billion by 2100, with countries like France, Italy, and Spain being the most affected (Narita and Rehdanz, 2017). These economic impacts highlight the need for robust mitigation and adaptation strategies to protect fisheries and aquaculture industries from the adverse effects of ocean acidification.

Figure 3 shows contour plots of biomass at three different time points (2020, 2050, and 2100) for RCP8.5 (left panels) and RCP4.5 (right panels). The X-axes represent increasing management levels from low to high: no set catch limit (None), allowable biological catch limits only (Low), ABC and variable fishing mortality at maximum sustainable yield (YPR, Medium), and ABC, YPR, and an additional 10% closed area (High). The Y-axes represent increasing ocean acidification impacts from no impact to high impacts: no ocean acidification impacts, larval impacts only (L), larvae and growth rate impacts (L+G), and larvae, growth, and predation (L+G+P). Biomass is shown in units of 1000 metric tons (mT). The contour lines in the plots illustrate the distribution of biomass under different management levels and ocean acidification impacts. In the RCP8.5 scenario, biomass gradually decreases over time (from 2020 to 2100), with this trend being more pronounced under low management levels and high ocean acidification impacts. Conversely, in the RCP4.5 scenario, even by 2100, biomass remains at relatively high levels under high management levels and lower ocean acidification impacts. These plots clearly indicate that both management measures and ocean acidification impacts jointly influence future biomass changes. Under no or low management levels, the negative impacts of ocean acidification are more significant, while strengthening management measures (such as increasing closed areas) can mitigate these negative impacts to some extent, particularly in the RCP4.5 scenario.

5.2 Implications for coastal communities

Coastal communities that depend on fisheries and aquaculture are particularly vulnerable to the impacts of ocean acidification. These communities often rely on the marine environment for their livelihoods, food security, and cultural practices. Declines in fishery yields can lead to economic hardship, increased unemployment, and social instability. For example, coastal communities in Atlantic Canada, which heavily depend on shellfish fisheries, are expected to face significant socioeconomic challenges as acidification reduces resource availability (Wilson et al., 2020). In regions where alternative employment opportunities are limited, such as rural and remote areas, the impacts can be especially severe.

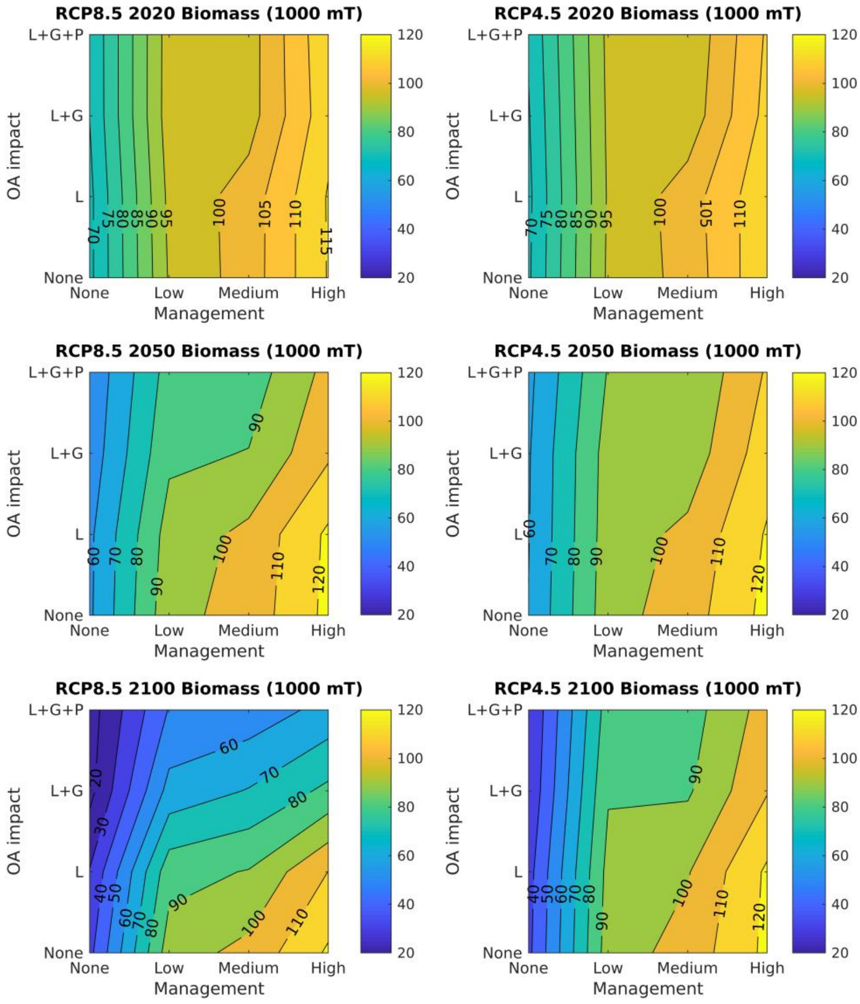

Figure 3 Contour plots of biomass at three different time points (2020, 2050, and 2100) for RCP8.5 (left panels) and RCP4.5 (right panels) (Adopted from Rheuban et al., 2018)

Image caption: X-axes increase management levels from low to high as no set catch limit (None), allowable biological catch limits only (low), ABC and variable fishing mortality at maximum sustainable yield (YPR, medium), and ABC, YPR, and an additional 10% closed area (high). Y-axes increase ocean acidification impacts from no impact to high impacts as no ocean acidification impacts, larval impacts only (L), larvae and growth rate impacts (L+G), and larvae, growth, and predation (L+G+P). Biomass is shown in units of 1000 metric tons (mT) (Adopted from Rheuban et al., 2018).

Beyond economic impacts, ocean acidification can also affect the cultural and social fabric of coastal communities. Many communities have deep cultural connections to the marine environment, with traditional practices and recreational activities being integral parts of their identity. Changes in species composition and ecosystem health due to acidification can disrupt these practices and alter the way communities interact with their natural surroundings. This can lead to a loss of cultural heritage and a decline in community wellbeing (Falkenberg et al., 2020). Moreover, the health impacts on coastal communities cannot be overlooked. Ocean acidification can lead to changes in the availability and quality of seafood, potentially affecting nutrition and food security. It can also increase the prevalence of harmful algal blooms, which pose health risks through the contamination of seafood and water supplies. These combined impacts underscore the need for comprehensive policies and measures to support coastal communities in adapting to the changing marine environment.

5.3 Economic costs of ocean acidification

The economic costs of ocean acidification are substantial and multifaceted. They include direct losses in fisheries and aquaculture revenues, costs associated with mitigating and adapting to its impacts, and broader economic implications for coastal protection, tourism, and ecosystem services. A meta-analysis of economic impacts estimated that the global annual cost of ocean acidification could exceed $1 billion by 2100, with significant regional variations (Moore and Fuller, 2022). In Europe, countries with significant mollusk production, such as France, Italy, and Spain, are expected to experience the highest economic impacts, with annual losses potentially exceeding $1 billion (Narita and Rehdanz, 2017).

The broader economic implications include increased costs for coastal protection due to the weakening of coral reefs. Coral reefs act as natural barriers that protect coastlines from storm surges and erosion. The degradation of these reefs due to acidification can lead to higher costs for artificial coastal defenses and increased damage from coastal storms (Doney et al., 2020). Additionally, the tourism industry, which relies heavily on the health and beauty of marine ecosystems, may suffer as acidification leads to the degradation of coral reefs and other marine habitats. This can result in reduced tourist arrivals and revenue, particularly in regions where marine tourism is a major economic driver.

Furthermore, ocean acidification affects ecosystem services such as water filtration, carbon sequestration, and nutrient cycling. The loss or reduction of these services can have cascading economic effects, impacting industries beyond fisheries and tourism. For instance, reduced water quality can increase the costs of water treatment for coastal municipalities, while changes in nutrient cycling can affect agricultural productivity and food security. Effective management and mitigation strategies are crucial to reducing these costs and protecting the socioeconomic wellbeing of affected communities. Investing in research and monitoring, implementing adaptive management practices, and reducing CO_2 emissions are essential steps to mitigate the impacts of ocean acidification and safeguard the services provided by marine ecosystems (Zunino et al., 2021).

6 Mitigation Strategies

6.1 Reduction of carbon emissions

Mitigating the impacts of ocean acidification requires a multi-faceted approach, incorporating global efforts to reduce carbon emissions, geoengineering techniques, and localized adaptation measures. This section explores these strategies in detail. The most effective strategy for mitigating ocean acidification is the reduction of carbon dioxide (CO_2) emissions. As the primary driver of ocean acidification, CO_2 emissions from the burning of fossil fuels, deforestation, and industrial processes must be curtailed to stabilize and eventually reduce the atmospheric concentration of CO_2. This global effort aligns with the goals of international agreements such as the Paris Agreement, which aims to limit global warming to well below 2 ℃ above pre-industrial levels, and preferably to 1.5 ℃. Achieving these targets would significantly mitigate the extent of ocean acidification (Schlunegger et al., 2021).

Policies promoting renewable energy sources, enhancing energy efficiency, and implementing carbon pricing mechanisms are critical components of emission reduction strategies. Transitioning from fossil fuels to renewable energy sources, such as wind, solar, and hydroelectric power, can reduce CO_2 emissions substantially. Energy efficiency improvements in buildings, transportation, and industry also play a crucial role in reducing overall energy demand and associated emissions (Harrould-Kolieb, 2019). Furthermore, carbon pricing, through mechanisms like carbon taxes or cap-and-trade systems, provides economic incentives for reducing emissions and investing in cleaner technologies.

6.2 Geoengineering approaches

Geoengineering techniques offer potential methods to mitigate ocean acidification by directly manipulating the environment to counteract the effects of increased CO_2 levels. One such approach is ocean alkalinization, which involves adding substances like limestone or olivine to the ocean to increase its alkalinity. This process can enhance the ocean's capacity to absorb CO_2 and reduce acidification locally. For example, studies have shown that adding alkaline materials to coastal regions can help buffer pH changes and protect sensitive marine habitats like coral reefs (Feng et al., 2016). Another geoengineering strategy is the use of seaweed and seagrass cultivation. These marine plants can absorb significant amounts of CO_2 during photosynthesis, potentially mitigating local acidification effects. Research has indicated that strategically located seaweed farms could enhance carbon sequestration and provide a buffer against ocean acidification in specific areas, such as the Great Barrier Reef (Mongin et al., 2016). However, these approaches must be carefully managed to avoid unintended ecological impacts and ensure that they do not shift the problem elsewhere.

6.3 Local adaptation measures

Local adaptation measures are crucial for communities and ecosystems already experiencing the impacts of ocean acidification. These measures include monitoring and early warning systems, habitat restoration, and community engagement. For instance, continuous monitoring of seawater chemistry can help detect changes in pH and carbonate levels, enabling timely responses to mitigate impacts on aquaculture and fisheries (Clements and Chopin, 2017).

Restoration of habitats such as seagrass meadows and mangroves can also play a significant role in local mitigation efforts. These habitats not only sequester carbon but also provide essential services like coastal protection and nursery grounds for marine species. Restoring these ecosystems can enhance their resilience to acidification and other stressors (Luan et al., 2023).

Engaging local communities in adaptation efforts is critical. Education and outreach programs can raise awareness about ocean acidification and its impacts, fostering community support for mitigation actions. Involving stakeholders in decision-making processes ensures that local knowledge and needs are incorporated into adaptation strategies, enhancing their effectiveness and sustainability (Cross et al., 2019).

7 Policy and Regulatory Responses

7.1 International agreements and frameworks

Addressing ocean acidification requires coordinated efforts at international, national, and local levels. This section examines the policy and regulatory frameworks that have been developed to tackle this issue, highlighting international agreements, national and regional policies, and the role of non-governmental organizations (NGOs). International agreements play a crucial role in addressing ocean acidification. However, no single international treaty specifically targets ocean acidification. Instead, a fragmented array of international agreements addresses various aspects of this issue. The United Nations Convention on the Law of the Sea (UNCLOS) provides a broad framework for marine protection, obligating countries to protect and preserve the marine environment. However, it does not specifically mention ocean acidification (Fennel and VanderZwaag, 2015).

The UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement focus on reducing greenhouse gas emissions, which indirectly addresses ocean acidification by aiming to stabilize atmospheric CO_2 levels. The Convention on Biological Diversity (CBD) also includes measures to protect marine biodiversity, which is threatened by ocean acidification. Furthermore, Sustainable Development Goal 14 (Life Below Water) includes a target to minimize and address the impacts of ocean acidification through enhanced scientific cooperation at all levels (Harrould-Kolieb and Hoegh‐Guldberg, 2019).

Despite these efforts, the lack of a unified treaty specifically addressing ocean acidification presents challenges. Thus, integrating ocean acidification into existing frameworks and promoting international cooperation and policy coherence are critical for effective mitigation and adaptation strategies (Harrould-Kolieb, 2017).

7.2 National and regional policies

National and regional policies vary widely in their approach to addressing ocean acidification. In Europe, policies and legislation targeting ocean acidification are generally uncoordinated, with some notable exceptions. For instance, Norway has proactive legislative frameworks and research initiatives aimed at understanding and mitigating ocean acidification. However, most European countries do not adequately address ocean acidification in their Marine Strategy Framework Directive reporting, except for Italy and the Netherlands (Galdies et al., 2020).

In the United States, some states have taken significant steps to address ocean acidification. Washington State, for example, has implemented comprehensive policies and legislative measures to tackle ocean acidification, driven by the severe impacts on its shellfish aquaculture industry. These measures include establishing an Ocean Acidification Center and implementing monitoring programs and mitigation strategies (Ekstrom et al., 2015).

National policies in other regions also reflect varying degrees of commitment. Small Island Developing States (SIDS) are particularly vulnerable to the impacts of ocean acidification and have begun integrating it into broader climate change and environmental policies. These policies often emphasize the importance of local adaptation measures and community resilience (Schmutter et al., 2017).

7.3 Role of non-governmental organizations

Non-governmental organizations (NGOs) play a vital role in advocating for action on ocean acidification, raising public awareness, and supporting research and policy development. NGOs often bridge gaps between scientific research and policy implementation by translating scientific findings into actionable policy recommendations. They also engage in capacity-building activities, helping communities and policymakers understand and respond to the challenges posed by ocean acidification (Falkenberg et al., 2020).

Organizations such as the Ocean Conservancy and the International Union for Conservation of Nature (IUCN) have been instrumental in promoting international and national policies to mitigate ocean acidification. These NGOs work with governments, scientists, and local communities to develop and implement strategies that address both the causes and impacts of ocean acidification. Furthermore, NGOs frequently facilitate international collaborations and partnerships, enhancing global efforts to tackle ocean acidification. By organizing workshops, conferences, and public awareness campaigns, they help to keep ocean acidification on the global environmental agenda and ensure that it receives the attention it deserves (Cooley et al., 2016).

8 Progress and Future Directions

8.1 Advances in research and monitoring

Recent advances in ocean acidification research have improved our understanding of its impacts on marine ecosystems and the underlying mechanisms driving these changes. The use of experimental design improvements has been crucial. For instance, guidelines on designing ocean acidification laboratory experiments emphasize the importance of appropriate replication and rigorous monitoring of carbonate chemistry to ensure accurate detection of biological responses (Cornwall and Hurd, 2016). These advancements have addressed previous methodological limitations, resulting in more reliable and reproducible findings.

Additionally, the integration of IoT-based monitoring systems has revolutionized data collection. These systems employ buoys and fishing boats equipped with sensors to provide near real-time data on seawater pH and other parameters. This approach offers a cost-effective and high-resolution alternative to traditional methods, enhancing our ability to monitor acidification over large spatial and temporal scales (Gopika et al., 2022).

The Global Ocean Acidification Observing Network (GOA-ON) has expanded its efforts to provide comprehensive monitoring data. GOA-ON integrates data from various sources, including autonomous sensors, to support adaptive management and policy decisions. This network's work has been pivotal in advancing our understanding of acidification at both local and global levels (Tilbrook et al., 2019).

8.2 Emerging technologies and innovations

Emerging technologies and innovations are enhancing our ability to study and mitigate ocean acidification. One notable advancement is the development of autonomous pH monitoring instruments, such as the Honeywell Durafet® pH electrode, which provide precise and continuous measurements of seawater pH. These instruments significantly improve the accuracy of time-course documentation in laboratory and field studies, reducing the labor required for monitoring (Kapsenberg et al., 2017). Satellite-based assessments of ocean acidification are becoming more feasible. New space-based salinity measurements enable the development of novel models to assess ocean acidification from space. This method offers a promising way to monitor the ocean surface on a global scale, providing valuable data for understanding large-scale patterns and trends in acidification (Land et al., 2015). Another innovative approach is the use of marine organisms as bioindicators of acidification. Studies have demonstrated that gastropod shells, for example, can effectively monitor acidification in coastal areas. The shell erosion ranking system developed for these organisms provides a cost-effective and easy-to-use method for assessing acidification, potentially involving citizen scientists in monitoring efforts (Marshall et al., 2019).

8.3 Future research needs and priorities

Despite significant progress, several research gaps and priorities remain. Future research should focus on understanding the synergistic effects of multiple stressors, such as warming, deoxygenation, and acidification, on marine ecosystems. Integrating these factors into experimental designs and ecological models will provide a more comprehensive understanding of their combined impacts (Andersson et al., 2015).

There is also a need for long-term monitoring programs that capture the variability in carbonate chemistry and its effects on marine life. Expanding the geographic coverage of monitoring networks, particularly in underrepresented regions, will enhance our ability to detect and respond to changes in ocean chemistry (Goldsmith et al., 2019).

Advancing genomic and transcriptomic studies will shed light on the adaptive potential of marine species to acidification. Identifying genetic traits associated with resilience can inform conservation and management strategies aimed at protecting vulnerable species and ecosystems (Evans et al., 2015). Fostering interdisciplinary collaborations and engaging stakeholders, including policymakers, industry, and local communities, is essential for developing effective mitigation and adaptation strategies. Bridging the gap between science and policy will ensure that research findings translate into actionable measures to address ocean acidification (Cooley et al., 2016).

9 Concluding Remarks

Ocean acidification is a critical environmental issue with profound impacts on marine ecosystems and human societies. This concluding section summarizes the key findings of recent research, emphasizes the importance of continued research and mitigation efforts, and offers recommendations for policy and practice. Recent research has significantly advanced our understanding of ocean acidification and its effects on marine life and ecosystems. Studies have shown that ocean acidification affects a wide range of marine organisms, particularly those that rely on calcium carbonate for their shells and skeletons, such as corals, mollusks, and some plankton species. These organisms experience reduced calcification rates, leading to weaker structures and increased vulnerability. Additionally, changes in ocean chemistry disrupt predator-prey relationships, reproductive success, and community dynamics, leading to shifts in species composition and ecosystem functions. Human activities are also impacted, as coastal communities and industries, particularly fisheries and aquaculture, face significant economic and social challenges due to declines in marine resources. While some species exhibit phenotypic plasticity and potential for genetic adaptation, the overall resilience of marine ecosystems to acidification remains uncertain. Effective mitigation strategies are essential to reduce CO_2 emissions and manage the impacts on marine ecosystems.

The importance of continued research and mitigation efforts cannot be overstated. Long-term monitoring programs are essential for capturing the variability in ocean chemistry and its ecological impacts, providing crucial data for predicting future changes and informing management strategies. Investigating the combined effects of ocean acidification, warming, deoxygenation, and other stressors will provide a more comprehensive understanding of the challenges facing marine ecosystems. Advances in genomic technologies are also vital for identifying genetic traits associated with resilience, guiding conservation efforts and helping to develop breeding programs for aquaculture species. Additionally, assessing the socioeconomic impacts of ocean acidification on coastal communities and industries will inform policy decisions and support the development of targeted adaptation measures.

To effectively address ocean acidification, policymakers and stakeholders should consider several key recommendations. Implementing policies to reduce CO_2 emissions is critical to mitigate ocean acidification. International agreements such as the Paris Agreement should be strengthened and fully implemented. Governments should invest in monitoring networks and support research initiatives to improve understanding and management of ocean acidification. Collaboration between scientists, policymakers, and industry is essential. Developing and implementing adaptation strategies for vulnerable communities and industries is also crucial. This includes habitat restoration, development of acidification-resistant aquaculture species, and community engagement. Finally, increasing public awareness about the impacts of ocean acidification and the importance of mitigation efforts can drive policy changes and encourage individual actions to reduce carbon footprints.

Acknowledgments

The Aqua Publisher thanks the two anonymous peer reviewers for their careful review and helpful suggestions on the manuscript of this study.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Andersson A.J., Kline D.I., Edmunds P.J., Archer S.D., Bednaršek N., Carpenter R., and Zimmerman R.C., 2015, Understanding ocean acidification impacts on organismal to ecological scales, Oceanography, 28(2): 16-27.
https://doi.org/10.5670/OCEANOG.2015.27

Clements J., and Chopin T., 2017, Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies, Reviews in Aquaculture, 9(4): 326-341.
https://doi.org/10.1111/RAQ.12140

Cooley S., Ono C., Melcer S., and Roberson J., 2016, Community-level actions that can address ocean acidification, Frontiers in Marine Science, 2: 128.
https://doi.org/10.3389/fmars.2015.00128

Cornwall C., and Hurd C., 2016, Experimental design in ocean acidification research: problems and solutions, ICES Journal of Marine Science, 73(3): 572-581.
https://doi.org/10.1093/ICESJMS/FSV118

Cross J., Turner J., Cooley S., Newton J., Azetsu-Scott K., Chambers R., and Wickes L., 2019, Building the knowledge-to-action pipeline in north america: connecting ocean acidification research and actionable decision support, Frontiers in Marine Science, 6: 356.
https://doi.org/10.3389/fmars.2019.00356

Das S., and Mangwani N., 2015, Ocean acidification and marine microorganisms: responses and consequences, Oceanologia, 57: 349-361.
https://doi.org/10.1016/J.OCEANO.2015.07.003

Ekstrom J., Suatoni L., Cooley S., Pendleton L., Waldbusser G., Cinner J., and Doherty C., 2015, Vulnerability and adaptation of US shellfisheries to ocean acidification, Nature Climate Change, 5: 207-214.
https://doi.org/10.1038/NCLIMATE2508

Evans T.G., Padilla-Gamiño J., Kelly M., Pespeni M., Chan F., Menge B., and Hofmann G., 2015, Ocean acidification research in the 'post-genomic' era: Roadmaps from the purple sea urchin *Strongylocentrotus purpuratus*, Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology, 185: 33-42.
https://doi.org/10.1016/j.cbpa.2015.03.007

Falkenberg L.J., Bellerby R., Connell S., Fleming L., Maycock B., Russell B., Sullivan F., and Dupont S., 2020, Ocean acidification and human health, International Journal of Environmental Research and Public Health, 17(12): 4563.
https://doi.org/10.3390/ijerph17124563

Feng E.Y., Keller D., Koeve W., and Oschlies A., 2016, Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification, Environmental Research Letters, 11(7): 074008.
https://doi.org/10.1088/1748-9326/11/7/074008

Fennel K., and VanderZwaag D., 2015, Ocean acidification: scientific surges lagging law and policy responses, Routledge Handbook of Maritime Regulation and Enforcement, 342-362.
https://doi.org/10.4324/9781315890241.CH20

Galdies C., Bellerby R., Canu D., Chen W., García-Luque E., Gašparović B., and Guerra R., 2020, European policies and legislation targeting ocean acidification in european waters-Current state, Marine Policy, 118: 103947.
https://doi.org/10.1016/j.marpol.2020.103947

Goldsmith K.A., Lau S., Poach M., Sakowicz G.P., Trice T., Ono C., and Saba G., 2019, Scientific considerations for acidification monitoring in the U.S. in Mid-Atlantic region, Estuarine Coastal and Shelf Science, 225: 106189.
https://doi.org/10.1016/J.ECSS.2019.04.023

Gopika K.V.N.M., and Ramesh M., 2022, IoT based ocean acidification monitoring system with ML based edge analytics, 2022 4th international conference on inventive research in computing applications (ICIRCA), 345-353.
https://doi.org/10.1109/ICIRCA54612.2022.9985728

Hall-Spencer J., and Harvey B.P., 2019, Ocean acidification impacts on coastal ecosystem services due to habitat degradation, Emerging Topics in Life Sciences, 3(2): 197-206.
https://doi.org/10.1042/ETLS20180117

Harrould-Kolieb E., 2017, An orphan problem looking for adoption: responding to ocean acidification utilising existing international institutions, Biogeosciences Discussions, 2017: 1-22.
https://doi.org/10.5194/BG-2017-230

Harrould-Kolieb E.R., 2019, (Re) Framing ocean acidification in the context of the united nations framework convention on climate change (UNFCCC) and paris agreement, Climate Policy, 19(10): 1225-1238.
https://doi.org/10.1080/14693062.2019.1649994

Harrould-Kolieb E., and Hoegh-Guldberg O., 2019, A governing framework for international ocean acidification policy, Marine Policy, 102: 10-20.
https://doi.org/10.1016/J.MARPOL.2019.02.004

Henry J.A., Patterson J.T., and Krimsky L., 2020, Ocean acidification: calcifying marine organisms, University of Florida IFAS Extension, 2020(5): 4.
https://doi.org/10.32473/edis-fa220-2020

Kapsenberg L., Bockmon E., Bresnahan P., Kroeker K., Gattuso J., and Martz T., 2017, Advancing ocean acidification biology using durafet pH electrodes, Frontiers in Marine Science, 4: 321.
https://doi.org/10.3389/fmars.2017.00321

Land P., Shutler J., Findlay H., Girard-Ardhuin F., Sabia R., Reul N., and Bellerby R., 2015, Salinity from space unlocks satellite-based assessment of ocean acidification, Environmental Science and Technology, 49(4): 1987-1994.
https://doi.org/10.1021/es504849s

Lee Y.H., Kang H.M., Kim M.S., Wang M., Kim J.H., Jeong C.B., and Lee J.S., 2019, Effects of ocean acidification on life parameters and antioxidant system in the marine copepod Tigriopus japonicus, Aquatic Toxicology, 212: 186-193.
https://doi.org/10.1016/j.aquatox.2019.05.007

Lemasson A., Fletcher S., Hall-Spencer J., and Knights A., 2017, Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: a review, Journal of Experimental Marine Biology and Ecology, 492: 49-62.
https://doi.org/10.1016/J.JEMBE.2017.01.019

Luan W.Q., Li H., Zhang L., and Liu J.Z., 2023, Enhalus acoroides efficiently alleviate ocean acidification by shifting modes of inorganic carbon uptake and increasing photosynthesis when pH drops, Marine Environmental Research, 186: 105896.
https://doi.org/10.2139/ssrn.4214412

Marshall D., Abdelhady A., Wah D., Mustapha N., Gödeke S.H., and De Silva L.C., 2019, Biomonitoring acidification using marine gastropods, The Science of the Total Environment, 692: 833-843.
https://doi.org/10.1016/J.SCITOTENV.2019.07.041

Mongin M., Baird M., Hadley S., and Lenton A., 2016, Optimising reef-scale CO_2 removal by seaweed to buffer ocean acidification, Environmental Research Letters, 11(3): 034023.
https://doi.org/10.1088/1748-9326/11/3/034023

Moore C., and Fuller J., 2022, Economic impacts of ocean acidification: a meta-analysis, Marine Resource Economics, 37(3): 201-219.
https://doi.org/10.1086/718986

Mostofa K.M., Liu C.Q., Zhai W., Minella M., Vione D., Gao K., and Sakugawa H., 2015, Reviews and Syntheses: Ocean acidification and its potential impacts on marine ecosystems, Biogeosciences, 13: 1767-1786.
https://doi.org/10.5194/BG-13-1767-2016

Narita D., and Rehdanz K., 2017, Economic impact of ocean acidification on shellfish production in Europe, Journal of Environmental Planning and Management, 60(3): 500-518.
https://doi.org/10.1080/09640568.2016.1162705

O'Brien P.A., Morrow K., Willis B., and Bourne D., 2016, Implications of ocean acidification for marine microorganisms from the free-living to the host-associated, Frontiers in Marine Science, 3: 47.
https://doi.org/10.3389/fmars.2016.00047

Rheuban J., Doney S., Cooley S., and Hart D., 2018, Projected impacts of future climate change ocean acidification and management on the US Atlantic sea scallop (Placopecten magellanicus) fishery, PLoS ONE, 13(9): e0203536.
https://doi.org/10.1371/journal.pone.0203536

Riebesell U., Aberle-Malzahn N., Achterberg E., Algueró-Muñíz M., Álvarez-Fernández S., Arístegui J., and Taucher J., 2018, Toxic algal bloom induced by ocean acidification disrupts the pelagic food web, Nature Climate Change, 8(12): 1082-1086.
https://doi.org/10.1038/s41558-018-0344-1

Scherer L., Gürdal İ., and van Bodegom P.V., 2022, Characterization factors for ocean acidification impacts on marine biodiversity, Journal of Industrial Ecology, 26: 2069-2079.
https://doi.org/10.1111/jiec.13274

Schlunegger S., Rodgers K., Hales B., Dunne J., Ishii M., Yamaguchi R., and Slater R., 2021, Climate mitigation averts corrosive acidification in the upper ocean, PREPRINT, Version 1.
https://doi.org/10.21203/RS.3.RS-648059/V1

Schmutter K., Nash M., and Dovey L., 2017, Ocean acidification: assessing the vulnerability of socioeconomic systems in Small Island Developing States, Regional Environmental Change, 17: 973-987.
https://doi.org/10.1007/s10113-016-0949-8

Servili A., Lévêque E., Mouchel O., Devergne J., Lebigre C., Roussel S., and Zambonino-Infante J., 2022, Ocean acidification alters the acute stress response of a marine fish, The Science of the Total Environment, 858(1): 159804.
https://doi.org/10.2139/ssrn.4116088

Stillman J., and Paganini A.W., 2015, Biochemical adaptation to ocean acidification, The Journal of Experimental Biology, 218: 1946-1955.
https://doi.org/10.1242/jeb.115584

Tagliarolo M., 2019, Acidification in aquatic systems, Encyclopedia of Ecology, 16(11): 606A-615A.
https://doi.org/10.1016/B978-0-12-409548-9.10958-3