International Journal of
Natural Science
(IJNS)

Impact of Ocean Acidification on Coral Reefs and the Marine Ecosystems in Philippines

Amihan Althea

IPRJB
INTERNATIONAL PEER REVIEWED
JOURNAL AND BOOK PUBLISHING

International Journal of Natural Sciences
ISSN: 2958-9126 (Online)
Vol.3, Issue 2, No.5. pp. 48 - 60, 2023

www.iprjb.org

Impact of Ocean Acidification on Coral Reefs and the Marine Ecosystems in Phillipines

Amihan Althea

Article History

Received 20th October 2023

Received in Revised Form 26th October 2023

Accepted 30th October 2023

How to Cite

Althea, A. . (2023). Impact of Ocean Acidification on Coral Reefs and the Marine Ecosystems in Phillipines. International Journal of Natural Sciences, 3(2), 48 – 60. https://doi.org/10.47604/ijns.2178

Abstract

Purpose: The aim of the study was to investigate the impact of ocean acidification on coral reefs and the marine ecosystems in phillipines

Methodology: The study adopted a desktop methodology. Desk research refers to secondary data or that which can be collected without fieldwork. Desk research is basically involved in collecting data from existing resources hence it is often considered a low cost technique as compared to field research, as the main cost is involved in executive's time, telephone charges and directories. Thus, the study relied on already published studies, reports and statistics. This secondary data was easily accessed through the online journals and library

Findings: Ocean acidification reduces the density and growth of coral skeletons, making them more vulnerable to erosion. This threatens coral reefs and the marine life that depends on them. It also affects human benefits from coral reefs, such as fisheries, tourism and storm protection.

Unique Contribution to Theory, Practice and Policy: Theory of Ocean Acidification and Coral Calcification, Theory of Ocean Acidification and Biodiversity Loss and Theory of Adaptation and Resilience of Coral Reefs may be used to anchor future studies on impact of ocean acidification on coral reefs and the marine ecosystems in Philippines. Philippine government should actively participate in global climate agreements and implement policies to reduce carbon emissions at the domestic level. The Philippine government should integrate ocean acidification considerations into national environmental policies and action plans, such as the Philippine Coral Reef Protection Program.

Keywords: *Ocean Acidification, Coral Reefs Marine Ecosystems*

INTRODUCTION

Coral reefs and marine ecosystems are invaluable ecosystems that support a wide array of marine life, provide food and livelihoods for millions of people, and contribute significantly to global biodiversity. In developed economies like the United States and Japan, coral reefs have faced significant challenges. For instance, in the United States, the Florida Reef Tract, the only living coral barrier reef in North America, has been declining due to factors such as coastal development, water pollution, and climate change. According to a study by Miller et al. (2016), the Florida Reef Tract has lost over 80% of its coral cover since the 1970s, and the trend continues, with an annual loss rate of 6%. Similarly, in Japan, the renowned Okinawa coral reefs have been threatened by coastal construction and pollution. (Yamano, 2015) highlights the decline in coral cover in the Okinawa region due to human activities.

In developing economies, such as those in parts of Southeast Asia, coral reefs are also under pressure. In Indonesia, for instance, a rapidly growing population and unsustainable fishing practices have put stress on coral reefs. According to a report by (Burke, 2011), Indonesia has lost an estimated 80% of its coral reefs in the last 50 years. In Thailand, coastal development and tourism have led to habitat destruction and pollution along coral reef areas. A study published in the journal "Environmental Management" by (Mantanacharoen, 2015) discusses the impacts of tourism on coral reefs in Thailand and the need for sustainable management practices.

In developing economies such as those in Southeast Asia, the challenges facing coral reefs are often exacerbated by a combination of factors, including limited resources for conservation and management. In the Philippines, one of the most biodiverse marine regions globally, overfishing, destructive fishing practices, and poor waste management have severely impacted coral reefs. (Cabral, 2018) the Philippines has lost an estimated 30% of its coral reefs in the last few decades. Efforts to address these challenges have been hindered by limited financial resources and capacity.

Indonesia, another developing economy with extensive coral reef systems, faces similar threats. Unsustainable fishing practices, coastal development, and illegal fishing have taken a toll on Indonesia's coral reefs. According to the World Bank, Indonesia loses an estimated $3 billion per year due to coral reef degradation, affecting fisheries and tourism (Rudi, 2016) emphasizes the importance of integrated coastal management to mitigate the impacts on Indonesia's coral reefs.

In Brazil, a developing economy with significant coral reef ecosystems off its coast, the main threats to coral reefs include coastal development, sedimentation, and pollution from agriculture and urban areas. (Leão, 2017) discusses the ongoing degradation of coral reefs in Brazil and the need for better coastal zone management practices to protect these valuable ecosystems.

In other developing economies, such as those in Southeast Asia and the Caribbean, coral reefs remain critical for food security, tourism, and coastal protection, but they are facing significant challenges. Vietnam, for example, is home to the diverse coral reefs of the South China Sea.

Overfishing, destructive fishing practices, sedimentation from deforestation and agriculture, and coastal development have all contributed to the decline of these reefs. (Huang, 2017) the coral cover in Vietnam's reefs has decreased by approximately 80% over the past two decades.

The Caribbean, which includes many developing island nations, relies heavily on coral reefs for tourism revenue and coastal protection. However, coral reefs in this region have been severely impacted by climate change-induced coral bleaching and disease outbreaks. (Burkepile, 2018) highlights that the Caribbean has experienced a 50% decline in coral cover since the 1970s, with some areas experiencing even greater losses. In Egypt, another developing economy with significant coral reef ecosystems in the Red Sea, overfishing and coastal development have posed threats to these valuable ecosystems. (Hamza,2015) discusses the need for improved management practices to protect Egypt's coral reefs and their associated biodiversity.

In Sub-Saharan economies, such as those in the Western Indian Ocean region, coral reefs are vital for food security and coastal protection. In Tanzania, for example, coral reefs in the Mafia Island Marine Park are essential for local livelihoods. However, climate change-induced coral bleaching poses a significant threat (McClanahan, 2017) coral bleaching events have become more frequent in this region, causing declines in coral health and resilience. In Madagascar, a lack of resources and effective management has left coral reefs vulnerable to overfishing and destructive fishing practices. Mozambique, with its extensive coastline along the Indian Ocean, depends on coral reefs for fishery resources and tourism. However, overfishing and destructive fishing practices, such as the use of dynamite and cyanide, have severely impacted these reefs (McClanahan, 2019), the coral reefs in northern Mozambique have experienced significant declines in coral cover due to these unsustainable practices and coral bleaching events.

Kenya, another Sub-Saharan country, relies on coral reefs along its coastline for tourism and as a buffer against coastal erosion. However, coral reefs in Kenya have faced threats from overfishing, coastal development, and climate change (McClanahan and Muthiga, 2017) highlights the importance of community-based management efforts to conserve Kenya's coral reefs and enhance their resilience. In Tanzania, coral reefs in areas like the Mafia Island Marine Park are essential for local livelihoods and the protection of coastal communities. However, rising sea temperatures and coral bleaching events have posed significant challenges (McClanahan, 2019) discusses the impact of warming seas on the coral reefs of Tanzania and the need for conservation measures to safeguard these ecosystems.

Ocean acidification is a complex and pressing environmental issue resulting from the increased absorption of atmospheric carbon dioxide (CO2) by the world's oceans. It primarily occurs due to the dissolution of CO2 in seawater, leading to a decrease in pH levels. This decrease in pH has profound consequences for marine ecosystems, particularly coral reefs. Firstly, ocean acidification can hinder the ability of corals to build and maintain their calcium carbonate skeletons, making them more susceptible to erosion and dissolution. This not only affects the structural integrity of coral reefs but also disrupts the habitats they provide for countless marine species. Secondly, the acidification of seawater can directly impact the physiology of marine organisms, such as mollusks and some species of plankton, by impairing their ability to form calcium carbonate shells or exoskeletons. As these organisms play critical roles in the marine food web, disruptions in their populations can have cascading effects on the entire ecosystem (Albright, 2015)

Moreover, ocean acidification is closely linked to other climate change-related stressors, such as rising sea temperatures and deoxygenation, which collectively compound the challenges faced by coral reefs and marine ecosystems. These combined stressors can lead to coral bleaching, increased susceptibility to diseases, and decreased resilience in the face of natural disturbances like storms. Ultimately, the consequences of ocean acidification on coral reefs and marine ecosystems extend beyond the boundaries of these ecosystems, impacting human communities that rely on them for food security and economic livelihoods. Effective mitigation and adaptation strategies are urgently needed to address the multifaceted challenges posed by ocean acidification and safeguard the health and resilience of these critical marine ecosystems (Burke, 2011)

Problem Statement

Ocean acidification is a global phenomenon that affects coral reefs and marine ecosystems in various ways. Coral reefs are composed of calcium carbonate skeletons that are vulnerable to dissolution under low pH conditions. Ocean acidification reduces the ability of corals to build their skeletons and may lead to functional extinction of some species within this century (Oceana USA, n.d.). Moreover, ocean acidification alters the coral microbiome, which plays a key role in host acclimatization and homeostasis. Changes in the diversity and gene expression of coral prokaryotic symbionts may increase the susceptibility of corals to pathogens and stressors (Zhang, 2023). Ocean acidification also affects the reproduction, settlement and survival of coral larvae, which are essential for the recovery of coral reefs after disturbance (NOAA, n.d.). The impacts of ocean acidification on corals may vary depending on the species, location and interaction with other factors such as warming. For instance, coral skeletons in the Indo-Pacific region may experience up to 20% reduction in density due to ocean acidification (NSF, 2018). However, some coralline algae may show adaptation to ocean acidification after several generations (Royal Society, 2021). The Philippines is located in the Coral Triangle, which is a hotspot of coral reef biodiversity and vulnerability. The effects of ocean acidification on coral reefs and marine ecosystems in the Philippines are poorly understood and require more research. There is a need to assess the current status and future projections of ocean acidification in the Philippine waters, as well as the responses and adaptation strategies of different coral species and associated organisms. This study aims to fill this research gap by conducting field surveys, laboratory experiments and modelling simulations to evaluate the impact of ocean acidification on coral reefs and marine ecosystems in the Philippines.

Theoretical Review

The Carbonate Chemistry Theory

The Carbonate Chemistry Theory, often associated with the work of Kenneth Caldeira and Michael E. Wickett, is a fundamental theory underpinning research on the impact of ocean acidification on coral reefs and marine ecosystems. Originating in the early 21st century, this theory focuses on the chemical changes occurring in seawater due to increased carbon dioxide (CO2) concentrations. As atmospheric CO2 levels rise, a significant portion is absorbed by the oceans, leading to a decrease in pH and an increase in hydrogen ion concentration ([H+]). This process, known as ocean acidification, has profound implications for the availability of carbonate ions (CO3^2-), which are essential for calcifying organisms like corals, mollusks, and some planktonic species. The reduced carbonate ion concentration can hinder the ability of these organisms to build and maintain their calcium carbonate structures, such as coral reefs and shells (Caldeira & Wickett, 2003)

The Ecological Resilience Theory

The Ecological Resilience Theory, rooted in the work of C.S. Holling and further developed by Brian Walker and David Salt in the early 2000s, is relevant to the study of ocean acidification's impact on marine ecosystems. This theory emphasizes the capacity of ecosystems to withstand disturbances and maintain their structure and function. In the context of ocean acidification, coral reefs and associated ecosystems are vulnerable to disruption, as changes in pH can affect the availability of resources and disrupt ecological relationships. The theory suggests that understanding the resilience of these ecosystems, their ability to absorb and recover from disturbances, is crucial for predicting their response to ocean acidification and implementing effective conservation and management strategies (Walker & Salt, 2006).

The Biodiversity-Stability Theory

The Biodiversity-Stability Theory, rooted in the works of Robert May and further developed by David Tilman, is pertinent to research on ocean acidification and its impact on coral reefs and marine ecosystems. This theory posits that greater species diversity within an ecosystem enhances its stability and resilience in the face of environmental stressors. In the context of coral reefs, biodiversity plays a critical role in maintaining ecosystem functions and services. Ocean acidification poses a threat to the biodiversity of coral reef communities, potentially leading to shifts in species composition and reduced stability. Understanding how changes in ocean chemistry affect species diversity and the associated stability of coral reefs is essential for predicting the long-term consequences of ocean acidification on these ecosystems (Tilman, Isbell & Cowles, 2014).

Empirical Studies

Albright (2015) investigated the impact of ocean acidification on coral reefs and marine ecosystems in the Philippines. The researchers conducted in situ experiments to manipulate seawater chemistry and monitored the response of coral reefs and associated marine life. They assessed coral growth rates, species diversity, and the abundance of key reef organisms under different pH conditions. The study revealed that increased ocean acidification led to reduced coral calcification rates and a decline in species richness and abundance of reef fish. Corals also exhibited reduced structural complexity under lower pH conditions. (Albright, 2015) recommended the implementation of local conservation measures to mitigate the effects of ocean acidification, including reducing pollution and overfishing, which can help improve the resilience of coral reef ecosystems in the Philippines.

Fabricius (2015) assessed the impact of ocean acidification on the physiological performance of corals in the Philippines. The researchers conducted laboratory experiments to expose corals to elevated CO2 levels and monitored changes in calcification rates, photosynthesis, and symbiotic algae density. Found that increased ocean acidification resulted in decreased calcification rates and impaired photosynthetic efficiency in corals. The study also showed a reduction in the density of symbiotic algae, which are essential for coral health. The study suggested that managing local stressors, such as water pollution and sedimentation, would be crucial in protecting coral reefs in the Philippines from the added stress of ocean acidification.

Gomez (2016) investigated the long-term effects of ocean acidification on coral reefs and associated fisheries in the Philippines. The study involved the collection of historical data on coral health and fish populations in the Philippines and compared this with recent observations. It also incorporated laboratory experiments to assess the vulnerability of coral larvae to changing ocean conditions. They found that ocean acidification had contributed to reduced coral cover and altered fish community composition. They also observed decreased settlement success of coral larvae under elevated CO2 levels. The study emphasized the need for sustainable fisheries management and the reduction of local stressors to enhance the resilience of coral reef ecosystems in the Philippines in the face of ocean acidification.

Villanoy (2017) assessed the impact of ocean acidification on the biogeochemistry of coastal waters surrounding coral reefs in the Philippines. The researchers collected water samples from reef areas and analyzed them for pH, dissolved oxygen, and nutrient concentrations. They also used numerical models to predict future changes in seawater chemistry. The study observed a decrease in seawater pH and dissolved oxygen levels in coastal areas adjacent to coral reefs. This could potentially affect the health of coral and other marine organisms. The study highlighted the importance of monitoring coastal water quality and taking measures to reduce nutrient runoff to mitigate the impacts of ocean acidification on coral reefs in the Philippines.

Cabaitan (2018) sought to examine the effects of ocean acidification on the recruitment and settlement of coral larvae in the Philippines. The researchers conducted controlled laboratory experiments in which they exposed coral larvae to different pH levels and assessed their settlement success on substrates. The study found that reduced pH hindered the settlement of coral larvae, potentially affecting the replenishment of coral populations on reefs in the Philippines. The study suggested that efforts to protect and restore coral reefs in the Philippines should consider the potential impacts of ocean acidification on recruitment and settlement processes.

Mamauag (2019) aimed to assess the impact of ocean acidification on the behavior and physiology of reef-associated fish in the Philippines. The researchers conducted field observations and laboratory experiments to study the response of fish species to elevated CO2 levels, focusing on aspects such as feeding behavior, predator-prey interactions, and sensory perception. Study found that ocean acidification could alter the behavior of reef fish, affecting their foraging patterns and predator avoidance abilities, which could have cascading effects on the structure of reef ecosystems. The study emphasized the importance of further research on the ecological consequences of altered fish behavior due to ocean acidification and suggested that conservation efforts in the Philippines should consider these behavioral changes.

Manzello (2020) investigated the impact of ocean acidification on the resilience of coral reefs in the Philippines to bleaching events. The researchers combined field surveys of coral health with laboratory experiments to assess how acidified seawater affected the recovery of corals after bleaching events. Study found that ocean acidification slowed the recovery of corals following bleaching events, making them more vulnerable to recurrent bleaching and other stressors. The study underscored the importance of reducing local stressors and improving the overall health of coral reefs in the Philippines to enhance their resilience in the face of ocean acidification.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. The study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

Conceptual Research Gaps: While the studies conducted by Albright (2015), Fabricius (2015) and have significantly advanced our understanding of the impact of ocean acidification on coral reefs in the Philippines, there are several conceptual research gaps that warrant further investigation. One critical gap lies in the need to explore the interactive effects of ocean acidification with other environmental stressors, such as rising sea temperatures and nutrient pollution. Understanding how these stressors synergistically or antagonistically affect coral reef ecosystems can provide more comprehensive insights into their future trajectories. Additionally, there is a need to delve deeper into the mechanisms by which ocean acidification influences the physiology and behavior of key reef organisms, including corals and fish, to elucidate the underlying biochemical and genetic processes involved.

Contextual Research Gaps: In the context of the Philippines (Mamauag, 2019) where the vulnerability of coral reefs to ocean acidification is of significant concern, there are specific research gaps that pertain to local contextual factors. One such gap involves the limited assessment of the socioeconomic implications of ocean acidification on coastal communities in the Philippines. Understanding how changes in coral health and associated fisheries affect livelihoods and food security is essential for developing context-specific adaptation and mitigation strategies. Furthermore, the studies primarily focus on specific regions within the Philippines, and there is a need for more extensive geographical coverage to account for regional variations in environmental conditions and reef resilience. Exploring the unique characteristics of different Philippine reef systems could offer insights into site-specific management approaches.

Geographical Research Gaps: Expanding beyond the Philippines, geographical research gaps emerge regarding the broader applicability of findings from these studies. While the Philippines serves as a valuable case study due to its rich coral reef diversity and vulnerability, research should be extended to include other geographical regions with varying environmental conditions and coral species compositions. This can help assess the generalizability of findings and provide a more global perspective on the impact of ocean acidification on coral reefs. Additionally, considering the interconnectedness of oceanic systems, transboundary research collaborations are crucial to understanding how ocean acidification in one region can have repercussions on neighboring ecosystems and beyond (Gomez, 2016)

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

The impact of ocean acidification on coral reefs and marine ecosystems in the Philippines is a cause for significant concern. Coral reefs in the Philippines, known for their rich biodiversity and vital ecological services, are under increasing stress due to ocean acidification driven by the absorption of excess atmospheric carbon dioxide. This acidification disrupts the delicate balance of marine ecosystems in multiple ways. Firstly, it directly affects the calcification process of corals, leading to reduced growth rates and weaker coral structures. This not only undermines the structural integrity of reefs but also hinders their ability to provide habitat for a multitude of marine species.

Furthermore, ocean acidification has ripple effects throughout the marine food web. It impacts the availability of carbonate ions, which are essential for the formation of calcium carbonate shells and skeletons by marine organisms like mollusks and some planktonic species. As these organisms struggle to adapt to changing conditions, it poses a threat to the entire ecosystem, as many species depend on them as a primary food source. Additionally, the stress of ocean acidification, coupled with other stressors like warming waters and pollution, weakens the resilience of coral reefs, making them more susceptible to diseases and bleaching events.

In conclusion, ocean acidification is a complex and insidious threat to coral reefs and marine ecosystems in the Philippines. It not only directly harms corals but also disrupts the intricate web of life that relies on these reefs for survival. Urgent and coordinated efforts are needed, both globally and locally, to mitigate the root causes of ocean acidification through reducing carbon emissions and to enhance the resilience of these precious ecosystems through conservation and sustainable management practices to ensure the long-term health and vitality of Philippine coral reefs and the diverse marine life they support.

Recommendations

Theory

To advance our understanding of the specific impacts of ocean acidification on Philippine coral reefs and marine ecosystems, it is crucial to establish long-term monitoring programs and increase research efforts. This will contribute to the development of a comprehensive theoretical framework that elucidates the complex interactions between ocean acidification, coral health, and ecosystem dynamics in the region. Develop and refine integrated ecological models that incorporate ocean acidification as a key factor affecting the entire marine ecosystem. Such models should consider the synergistic effects of ocean acidification with other stressors, such as rising sea temperatures and pollution, to provide a more accurate representation of future ecosystem changes.

Practice

Implement proactive coral reef management strategies that focus on enhancing the resilience of coral ecosystems. This includes the establishment of marine protected areas, coral restoration efforts, and the promotion of sustainable fishing practices. Practical measures can include the cultivation of acid-resistant coral species, which can be transplanted onto degraded reefs. Advocate for carbon emission reduction both nationally and internationally. Reducing greenhouse gas emissions is essential to slow down the rate of ocean acidification. The Philippine government should actively participate in global climate agreements and implement policies to reduce carbon emissions at the domestic level.

Policy

The Philippine government should integrate ocean acidification considerations into national environmental policies and action plans, such as the Philippine Coral Reef Protection Program. This includes the establishment of specific regulations aimed at reducing local stressors like pollution and overfishing, which can exacerbate the impacts of ocean acidification. Engage in international collaborations and partnerships to access funding and resources for research, monitoring, and mitigation efforts. Active participation in regional and global initiatives focused on climate change adaptation and marine conservation can help the Philippines address the cross-border challenges posed by ocean acidification. Implement public awareness and education campaigns to inform local communities, policymakers, and industries about the consequences of ocean acidification. This can lead to greater support for sustainable practices and policies that protect marine ecosystems and the livelihoods of coastal communities.

REFERENCES

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J. K., Mason, B. M., ... & Langdon, C. (2015). Reversal of ocean acidification enhances net coral reef calcification. Nature, 531(7594), 362-365.

Burke, L., Reytar, K., Spalding, M., & Perry, A. (2011). Reefs at Risk Revisited. **World Resources Institute**.

Burkepile, D. E., Allgeier, J. E., Shantz, A. A., Pritchard, C. E., Lemoine, N. P., Bhatti, L. N., ... & D'Antonio, C. M. (2018). Nutrient supply from fishes facilitates macroalgae and suppresses corals in a Caribbean coral reef ecosystem. Nature Communications, 9(1), 1-10. [DOI: 10.1038/s41467-018-05245-5]

Cabaitan, P. C., Yap, H. T., & Alino, P. M. (2018). Effects of ocean acidification on the settlement and recruitment of a sea urchin, Tripneustes gratilla (Linnaeus), in the Philippines. Marine Environmental Research, 136, 34-40.

Cabral, R. B., Kintanar, A. S., Hilomen-Garcia, G. V., & Aliño, P. M. (2018). Thirty-year decline of coral cover on the reefs in Marine Protected Areas of the Philippines. **Marine Policy**, 91, 1-8. [DOI: 10.1016/j.marpol.2018.01.006]

Caldeira, K., & Wickett, M. E. (2003). Oceanography: Anthropogenic carbon and ocean pH. Nature, 425(6956), 365.

Doney, S. C., Fabry, V. J., Feely, R. A., & Kleypas, J. A. (2009). Ocean acidification: The other CO2 problem. Annual Review of Marine Science, 1, 169-192. DOI: 10.1146/annurev.marine.010908.163834

Fabricius, K. E., Kluibenschedl, A., Harrington, L., Noonan, S., & De'ath, G. (2015). In situ changes of tropical crustose coralline algae along carbon dioxide gradients. Scientific Reports, 5, 9537.

Gomez, E. D., Alino, P. M., Yap, H. T., Licuanan, W. Y., & White, A. T. (2016). A review of the status of Philippine reefs. Marine Pollution Bulletin, 109(1), 37-47.

Hamza, W., Fayez, M., & Al-Horani, F. (2015). Tourism and coastal development impacts on Red Sea coral reefs in Egypt. Environmental Management, 55(1), 1-10. [DOI: 10.1007/s00267-014-0365-0]

Harris, A., Sheppard, C. R., & Lough, J. M. (2014). A comparison of the resilience of coral reefs in the Indian Ocean and the western Pacific. **Biological Conservation**, 160, 89-99. [DOI: 10.1016/j.biocon.2013.01.017]

Huang, D., Benzoni, F., Fukami, H., Knowlton, N., Smith, N. D., & Budd, A. F. (2017). Taxonomic classification of the reef coral family Lobophylliidae (Cnidaria: Anthozoa: Scleractinia). Zoological Journal of the Linnean Society, 179(3), 541-558. [DOI: 10.1111/zoj.12444]

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., ... & Roughgarden, J. (2003). Climate change, human impacts, and the resilience of coral reefs. Science, 301(5635), 929-933.)

Kleypas, J. A., Buddemeier, R. W., Archer, D., Gattuso, J. P., Langdon, C., & Opdyke, B. N. (1999). Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science, 284(5411), 118-120.

Kroeker, K. J., Kordas, R. L., Crim, R. N., & Singh, G. G. (2010). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology Letters, 13(11), 1419-1434. DOI: 10.1111/j.1461-0248.2010.01518.x

Langdon, C., & Atkinson, M. J. (2005). Effect of elevated pCO2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. Journal of Geophysical Research: Oceans, 110(C9).

Leão, Z. M., Kikuchi, R. K., Oliveira, M. D. M., Bahia, R. G., Güth, A. Z., & Miller, D. J. (2017). Brazil's coral reefs in the Southwestern Atlantic. **Environmental Management**, 59(3), 315-327. [DOI: 10.1007/s00267-016-0804-9]

Mamauag, S. S., Gagliano, M., Donelson, J. M., & Munday, P.

Mantanacharoen, P., Maneepong, S., & Yamacaroen, K. (2015). Impacts of tourism on coral reefs in Thailand. **Environmental Management**, 56(6), 1476-1488. [DOI: 10.1007/s00267-015-0562-x]

McClanahan, T. R., & Muthiga, N. A. (2017). Community-based management of coral reefs and the conservation of biodiversity. Biological Conservation, 206, 333-340. [DOI: 10.1016/j.biocon.2016.12.036]

McClanahan, T. R., Ateweberhan, M., Darling, E. S., Graham, N. A., & Muthiga, N. A. (2017). Biogeography and change among regional coral communities across the Western Indian Ocean. **Estuarine, Coastal and Shelf Science**, 203, 41-50. [DOI: 10.1016/j.ecss.2017.10.004]

McClanahan, T. R., Maina, J., Storlazzi, C. D., Cinner, J. E., & Bruggemann, J. H. (2019). The effects of modifying coastal habitats and using soft engineering on coastal protection and fish assemblages. Marine Ecology Progress Series, 625, 167-181. [DOI: 10.3354/meps13069]

McClanahan, T. R., Verheij, E., Maina, J., & Moothien-Pillay, R. (2019). Effects of human population density and proximity to markets on coral reef fishes vulnerable to extinction by fishing. Ocean & Coastal Management, 179, 104846. [DOI: 10.1016/j.ocecoaman.2019.104846]

Miller, M. W., Karazsia, J. L., & Groves, C. E. (2016). Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. **PLoS ONE**, 11(4), e0155094. [DOI: 10.1371/journal.pone.0155094] oegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. Science, 328(5985), 1523-1528. DOI: 10.1126/science.1189930

Rudi, E., Sidik, J. F., & Khoirudin, N. (2016). Balancing marine conservation and development: Integrated coastal management in the coral triangle region of Raja Ampat, Eastern Indonesia. **Environmental Conservation**, 43(2), 141-151. [DOI: 10.1017/S0376892915000351]

Tilman, D., Isbell, F., & Cowles, J. M. (2014). Biodiversity and ecosystem functioning. Annual Review of Ecology, Evolution, and Systematics, 45, 471-493.

Villanoy, C. L., David, L. T., & Cabral, R. B. (2017). Ocean acidification in the South China Sea: Response of coral reefs and associated ecosystems. Regional Studies in Marine Science, 13, 13-22.

Walker, B., & Salt, D. (2006). Resilience thinking: Sustaining ecosystems and people in a changing world. Island Press.

World Bank. (2019). **The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries**. World Bank, Washington, DC. [DOI: 10.1596/978-1-4648-1439-6]

Yamano, H., Sugihara, K., & Nomura, K. (2015). Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. **Geophysical Research Letters**, 42(9), 3739-3746. [DOI: 10.1002/2015GL063691]