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Reef Ecosystem Conservation for the Hawaiian Islands: The Impacts of Ocean Warming and Acidification on Benthic Reef Populations

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Abstract

This paper explores the anthropogenic effects of rapid climate change and ocean acidification on benthic coral populations along the Hawaiian archipelago. Moreover, the reliance of Hawaiian coastal communities on coral reefs for sustenance and economic prosperity is evaluated to determine the importance of reef ecosystem conservation for the prosperity of Hawaii. Chapter 1 introduces the importance of coral and supplies quantitative data on declining coral populations traditional to Hawaii, as a result of ocean warming and acidification. Empirical data from prior, prominent studies, combined with my own, will be discussed. Chapter 2 outlines the ecology of Hawaiian reef ecosystems, the scientific mechanisms behind coral and its essential but fragile relationship with algae, and the impacts of ocean warming and acidification on this relationship. A conceptual understanding of benthic ecology traditional to Hawaii's reef ecosystems is pertinent when understanding the effects of climate change and ocean acidification, and explaining the functioning of coral as the driver of reef ecosystems showcases its importance to Hawaiian communities. Chapter 3 further lays out quantitative and qualitative data; however, regarding the complex relationship between Hawaiian coastal communities and reef ecosystems to effectively convey the importance of benthic coral health to community life. Additionally, the chapter observes the multifaceted anthropogenic factors directly related to the decline of coral health, evaluating the most prominent threats at both global and local levels. Chapter 4 contextualizes notable existing efforts for reef ecosystem conservation in Hawaii and assesses the current state reef conservation policies in both the state and federal government. Finally, chapter 5 presents adaptive and preservative policy recommendations, with an emphasis on adaptive strategies, to effectively identify effective reef ecosystem conservation efforts that will preserve their vitality.

Keywords: benthic coral, reef ecosystem conservation, Hawaiian coastal communities

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Furthermore, I would like to strongly acknowledge Hawaiian coastal communities and native people; their unending perseverance against oppressive forces is an inspiration to all. This project is dedicated to them, in hopes to attempt to unravel some of the systemic issues that so heavily threaten their natural and indubitable right to a healthy environment.

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Introduction: Preserving Paradise: Hawaiian Reef Ecosystem's Importance

Nestled in the heart of the Pacific Ocean, Hawaii's archipelago is renowned for its breathtaking landscapes, unique cultural heritage, and unparalleled biodiversity. At the heart of Hawaii's natural wonder is the fragile and wondrously complex ecosystem that has captured the imagination of scientists, conservationists, and nature enthusiasts alike: the coral reef. Reef ecosystems are the drivers of Hawaii's socioeconomic system and are the guardians of the archipelago. Moreover, these underwater oases, composed of vibrant corals, diverse marine species, and crystal-clear waters, are not just vital to Hawaii's cultural identity, but also to the global ecosystem.

However, within the paradisiacal allure of Hawaii's coral reefs belies a complex and pressing reality. The Hawaiian Islands face multifaceted threats that target the health and stability of their coral reef ecosystems. Global climate change and ocean acidification as well as local anthropogenic stressors such as overfishing, coastal development, and pollution are rapidly diminishing the health of these delicate underwater ecosystems. Accordingly, coral bleaching events, desecrated marine populations, and habitat degradation are accumulating in occurrence, jeopardizing not only the ecological integrity of Hawaiian reefs but also the livelihoods of the local communities dependent on them. The fragility of coral's biology is what makes reef ecosystems so prosperous but also so vulnerable to environmental ramifications. As coral populations become increasingly threatened, their importance is becoming more realized, and their ecosystems more passionately safeguarded.

In response to these challenges, conservation efforts in Hawaii's coral reefs have gained serious momentum. Researchers, policymakers, and community stakeholders have united to better understand, protect, and restore these invaluable ecosystems. Therefore, my thesis attempts to aid the established conservation of Hawaiian reef ecosystems by analyzing the empirical data of benthic populations, current policy initiatives, and community-based approaches, to assess the current state of reef sustainability.

As we venture deeper into this exploration, it becomes evident that the conservation of Hawaiian coral reefs is not only a matter of local importance but also a national imperative. These ecosystems provide unparalleled benefits through their ecosystem services, ranging from sustaining marine biodiversity to acting as natural barriers against storm surges. Moreover, they also play a crucial role in the culture and traditions of Hawaii's native communities, underscoring the profound connection between coral and its surrounding people.

From May to June 2023, I had the invaluable experience of conducting benthic reef population surveys along the Hawaiian archipelago with the abroad program, SEA Education. In addition to intensive scientific data collection, we met with representatives from several leading Hawaiian conservationists. By shedding light on the multifaceted efforts to conserve Hawaii's reef ecosystems, this thesis aims to contribute to the growing body of knowledge surrounding marine conservation and inspire a renewed commitment to preserving these irreplaceable jewels of the Pacific. Chapter 1 presents quantitative data on the general decline of benthic populations within the tropical reef ecosystem. Chapter 2-4 explore coral's ecology, its relationship with Hawaiian culture, the multifaceted anthropogenic factors eliciting decline, and the aptitude of currently established policies. The final chapter, chapter 5, emphasizes policy suggestions that can effectively build upon existing conservation strategies, using the scientific and policy research presented in the previous chapters. Notably, I will be presenting and analyzing the scientific and anthropogenic data collected from my trip with SEA Education in chapters 1 and 3 respectively.

Chapter 1: Decline of Hawaiian Coral Populations

This chapter contextualizes the declining state of Hawaiian coral reef populations using quantitative data collected from prior experiments combined with my own research. Preemptively, I outline coral reefs and explain their context within the Hawaiian Islands. Next, I convey the importance of reef ecosystems by detailing the ecosystem services reefs provide to Hawaii. I then present empirical data showing the significantly worsening condition of coral reefs, which will be used to elucidate the impact declining reefs have on Hawaii's socioeconomic system at large. Finally, I briefly introduce some conservation solutions, emphasizing policy and community-based initiatives. That said, this chapter is intended to focus on *empirical data*; the extent of coral's relationship with Hawaii and effective policy solutions will be discussed in later chapters.

An introduction to Hawaiian Coral Reefs. Ka pae 'aina o Hawai'I nei, the native term for the Hawaiian archipelago, is comprised of 137 islands, with 1,210 km of coastline (Division of Aquatic Resources, 2021). Hawaiian coral reefs, often referred to as the "rainforests of the sea" are among the most biodiverse and productive ecosystems on Earth. While they take up only an estimated 600,000km of space, or 0.1% of the Earth's surface, their ecosystems support upwards of 1 million biotic organisms (Bishop et al., 2011). So, reefs serve as essential habitats, spawning grounds, and nurseries for a multitude of species, many of which are endemic to Hawaii. Reefs are categorized into two distinctive regions, the Main Hawaiian Islands (MHI) and the Northwestern Hawaiian Islands (NWHI). The MHI comprises of large, populated islands whereas NWI are primarily uninhabited atolls and banks (Bishop et al., 2011).

MHI reefs naturally exist in areas with high human activity. Consequently, their services, which are elaborated upon in the subsequent subsection, encompass shoreline protection, beach maintenance, as well as the provision of food products and recreational activities (Bishop et al., 2011). In contrast, NWHI reefs, being older and more isolated than their MHI counterparts, harbor diverse ecosystems supporting a variety of species. Due to NWHI's isolation, biodiversity tends to flourish there. About half of the 7,000 marine species identified in Hawaii are exclusively found in the NWHI. Among vertebrates are monk seals, reef and bottom fish, turtles, birds, and sharks, while invertebrates include coral, anemones, mollusks, shrimp, sea urchins, sea stars, and sea cucumbers (Bishop et al., 2011). Moreover, the average fish biomass is three times greater than that of the MHI. Additionally, ninety percent of nesting for the endangered green sea turtle (*Chelonia mydas*) occurs at a specific site in the NWHI, the French Frigate Shoals (Bishop et al., 2011). Nevertheless, both reef systems offer crucial habitats for an abundance of different species.

Reefs hold profound cultural significance to Hawaii's native communities and are deeply intertwined into the Hawaiian socioeconomic system. Directly upon indigenous settlement in the archipelago, coral manifests in Hawaiian culture. The Kumulipo, a Polynesian creation chant central to Hawaiian culture, portrays coral as the first true life form created (NOAA, 2018). These depictions are merited, as extant coral species date backwards from the Pliocene and have dominated modern reef ecosystems ever since (Hughes et al., 2003). Ultimately, coral's reverence in Hawaiian culture highlights its historically understood significance both anthropogenically and to the natural world.

However, the Anthropocene has caused reef ecosystems to decline at unprecedented rates. While coral reefs are typically resilient following periodic natural disasters, such as storms and temporary shifts in oceanographic conditions, they are extraordinarily vulnerable to persistent environmental disturbances (Bishop et al., 2011). Anthropogenic causes of increased carbon emissions have fostered rapid climate change, prompting the IPCC's evaluation that 70-90% of coral reefs are in grave danger (IPCC, 2022). Specifically, ironclad science has established that 1.5°C of warming will cause irreversible damage to corals (IPCC, 2022). Ocean warming and acidification are the predominant global factors eliciting the current rapid decline of coral health. The effects of each stressor are elaborated on in a later subsection.

Reefs and Ecosystem Services. Despite their declining state, the ecological, economical, and cultural ecosystem services that coral reefs provide to humans and all other relevant species alike are astronomic. For context, ecosystem services are defined as "the benefits people obtain from ecosystems" (Hassan et al. 2005). Ecosystem services are categorized as: *provisioning services*, such as food, water, timber, and fiber; *regulatory services,* affecting climate, floods, disease, wastes, and water quality; *cultural services*, providing recreational, aesthetic, and spiritual benefits; and *supporting services*, such as soil formation, photosynthesis, and nutrient cycling (Hassan et al., 2005). The human species relies on ecosystem services, so any significant change will impact human life. In Hawaii, coral reefs are notable for their regulatory services, such as biodiversity maintenance and coastal protection, cultural services, like tourism and recreation, and provisioning services, such as fisheries (Hassan et al., 2005). These services are essential for supporting Hawaiian human well-being and livelihoods.

Coral reefs serve as biodiversity and ecological reservoirs to their communities, offering invaluable regulatory services. In Hawaii, these reefs act as repositories of biodiversity, housing unique species that contribute to scientific research and pharmaceutical discoveries (Bishop et al., 2011). Seaweeds, sponges, mollusks, soft corals, and sea anemones found in reef ecosystems have played a significant role in the development of various drugs, including those with anti-cancer, AIDS-inhibiting, antimicrobial, anti-inflammatory, and anticoagulant properties (Bishop et al., 2011). Additionally, coral skeletons are used in bone graft, underscoring their medicinal value.

Moreover, microbes inhabiting coral reefs filter waste before it enters the deeper ocean. As such, reefs help detoxify petroleum pollution by converting hydrocarbons into carbon dioxide and water (Bishop et al., 2011). This regulatory service holds relevance for Hawaii, where naval military bases contribute to pollution that often remains inadequately measured.

Nonetheless, other, broader regulatory services reefs provide are at the ecological and biogeochemical levels. For instance, coral sustains nearby habitats by transporting dissolved organic matter and nitrogen, as well as bacterio-, phyto-, and zooplankton (Bishop et al., 2011). Furthermore, the ecological vulnerability of reefs is used as a tool to monitor temperature variations and environmental changes resulting from human activity (Bishop et al., 2011). Additionally, scientists use reef deposits to study the history of seawater contamination and to track historical trends in temperature, salinity, and flooding. Therefore, reefs offer insights into long-term environmental changes.

Another regulatory service reefs offer is serving as natural storm barriers by absorbing wave energy and mitigating the impact coastal erosion. In Hawaii alone, reefs are estimated to provide an impressive $835 million in coastal flood protection annually (Division of Aquatic Resources, 2021). Specifically, reefs act as a bolster to the shoreline, averting damages prompted by hurricanes or dangerous surges. Thus, reefs help safeguard Hawaii’s communities, infrastructure, and beaches from the destructive forces of the ocean (Hassan et al., 2005).

It's crucial to acknowledge that ecosystem degradation exacerbates systemic poverty. Vulnerable and disenfranchised communities face disproportionately greater challenges in compensating for the loss of regulatory services resulting from declining coral reefs (El-Naggar, 2019). Even worse, top-down conservation-management policies that restrict access to reefs prohibit communities from accessing some of the resources still available to them. Consequently, preservation-based policies are often met with noncompliance, and may discourage community participation in reef-ecosystem management (El-Naggar, 2019).

On that note, coral reefs provide cultural services that underpin Hawaii's socioeconomic system. Quantitatively, the cultural services of Hawaiian coral reefs are predicted to generate an economic influx of $364 million annually (Bishop et al., 2011). The vibrancy of reef ecosystems in Hawaii attracts tourists from across the world, contributing significantly to the state's economy. Empirical data estimates Hawaii's ecotourism revenue to be $6.5 billion annually, constituting 8% of the state's gross domestic product (NOAA, 2018). Ultimately, ecotourism ventures such as snorkeling, diving, and marine tourism contribute considerably to Hawaii's revenue, making these ecosystems economically invaluable to the region.

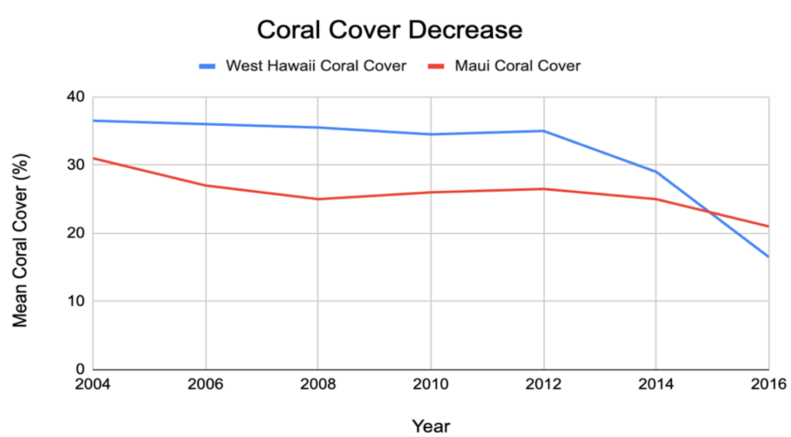
Coral reefs also define Hawaii's economy through their provisioning services of sustaining fisheries. Fish and invertebrates harvested from reef ecosystems are essential for both food security and the state's economy. The commercial fishery harvest value for coral species alone is estimated to exceed $3.2 million annually (NOAA, 2018). When considering the overall annual value, which includes fishing, food, and cultural merits, nearshore fisheries in Hawaii are estimated to contribute between $10.3 to $16. 4 million (NOAA, 2018). Ultimately, Hawaiian reefs support diverse and productive fisheries that provide sustenance and livelihoods to local communities.

In summary, reef ecosystems exhibit a unique interdisciplinary involvement in all four ecosystem services: supporting, regulatory, provisionary, and cultural. The declining health of Hawaiian reef ecosystems presents regulatory and provisioning challenges, but effective solutions for them must also address the issues related to cultural services. Thereby, addressing these challenges will require a national cultural shift to attitudes and practices that recognize the interconnectedness between human-well-being and the health of coral reef ecosystems.

Causes of Reef Ecosystem Degradation. In Hawaii, reef ecosystems face an array of threats that imperil their ecosystem services. These threats can be categorized into three main sectors: climate change, ocean acidification, and direct pollution.

Climate change has led to rising sea temperatures and ocean acidification which trigger widespread coral bleaching events that weaken the resilience of Hawaiian corals. The increasing severity of these events pose a tremendous threat to reef survival. Coral reefs tend to undergo bleaching episodes when sea surface temperatures exceed 0.5°C above their active threshold, exemplifying their vulnerability (Hassan et al., 2005). In Hawaii, the most recent bleaching event, occurring in 2015, resulted in an average coral cover loss of 49.7% (NOAA and DAR 2015). Given that these events are accumulating in both severity and frequency overtime, the state of Hawaiian reef ecosystems are extraordinarily vulnerable. To represent this vulnerability, inserted below is a visual illustrating the decrease in coral cover in West Hawaii and Maui.

Figure 1. Coral Cover Decrease in West Hawaii and Maui from 2004 to 2016 (Joshi et al., 2023).



Indeed, coral's susceptibility to climate change arises from its reliance on a specific and narrow temperature range for essential life processes. This sensitivity is attributed to the intricate, fragile endosymbiotic relationship with algae, a phenomenon that will be discussed in detail in chapter 2. Ultimately, when algal-coral endosymbiosis is pushed out of its temperature threshold, coral undergoes bleaching (Bishop et al., 2011). For instance, research from the University of Hawaii indicates that, of bleached reefs, 50% have perished because of elevated ocean temperatures (Division of Aquatic Resources, 2016). And so, the rapid warming of ocean waters, driven by climate change, pushes tropical Hawaiian coral beyond its temperature capabilities, triggering bleaching events and subsequent degradation.

Furthermore, the substantial release of carbon emissions leads to the absorption of considerable amounts into oceans, a phenomenon deemed ocean acidification. Hawaii, a coastal island located approximately 3,000 miles into the Pacific, is thus largely vulnerable to ocean acidification's ramifications (IPCC, 2022). As carbon dioxide dissolves into seawater, it reacts to form carbonic acid, increasing the acidity levels of the ocean. These elevated acidity levels impede the ability of corals to build their calcium carbonate skeletons, essential for their structure and growth. This impairment weakens coral structures, growth rates, and diminishes reproductive success (Hoegh-Guldberg et al., 2007). Additionally, like climate change, ocean acidification disrupts the balance of the coral-algae symbiosis, exacerbating coral bleaching (Hoegh-Guldberg et al., 2007). Therefore, the overall health and resiliency of Hawaiian reef ecosystems is jeopardized by the global phenomena of climate change and ocean acidification.

However, reefs also face additional threats from local environmental stressors. Research lists the most impactful direct threats to Hawaiian reefs as the following: destructive fishery practices; mining and dredging; sedimentation, pollution, and waste; and non-sustainable tourism, all of which will be elaborated on later (Bishop et al., 2011). Specifically, the most significant threats to the MHI tend to be local, direct environmental disturbances, whereas the NWHI battles with invasive species, and the overarching issues of climate change and ocean acidification (Bishop et al., 2011). Therefore, effective conservation efforts should address the specific and predominate local threats faced by each type of reef. However, many local solutions and initiatives can also effectively mitigate the global issues of ocean warming and acidification, which impact all reefs.

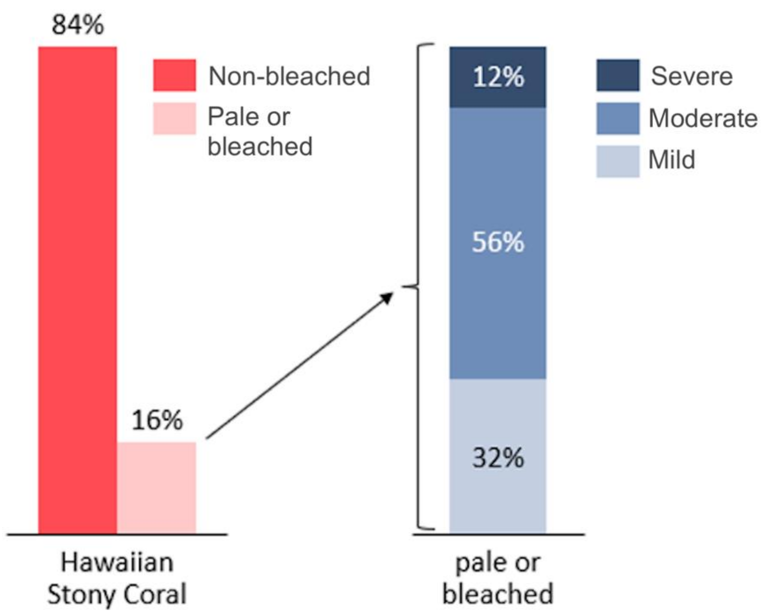
Accordingly, much of the research my team and I conducted in Hawaii centered on coral bleaching and the current state of Hawaiian coral. During a research cruise aboard the SSV *Robert C. Seamans,* we travelled to Oahu, Maui, the Big Island, and Kauai respectively, anchoring near various reef sites at each island. One aspect of our data collection involved analyzing the benthic community composition within each reef. This included measuring coral health and the coverage of coral and macroalgae, utilizing standard photo-quadrant sampling methodologies.

The photo-quadrat data collection process was conducted during a reef survey following a structured protocol. At each reef site, we laid out four 10-meter transects. At every meter interval along each transect, a reef surveyor dove to the ocean floor, equipped with a 1m x 1m photo-quadrat to capture an image of the ocean floor. This process resulted in a total of 10 images per transect and 40 images overall. The photographs were taken alternately to the right and left of the transect at each meter.

Subsequently, the images were uploaded to the CPC data processing program, which randomly stratified points of the alphabet across each image. At each designated point, we identified the type of benthic organism present and assessed its state of health. This systemic approach ensured comprehensive documentation and analysis of the benthic community composition at each surveyed reef site.

Inserted below is a visual representation illustrating the ratio of bleached coral observed to non-bleached coral. It should be noted that the visual focuses on stony coral, as its regenerative capabilities predominately influences the health of the entire reef ecosystem; however, a more detailed explanation of this phenomenon will be provided in chapter 2. Furthermore, within the bleached category, we delineate the extent of bleaching into three different classifications: mild (5-19%), moderate (20-49%), and severe (50-90%).

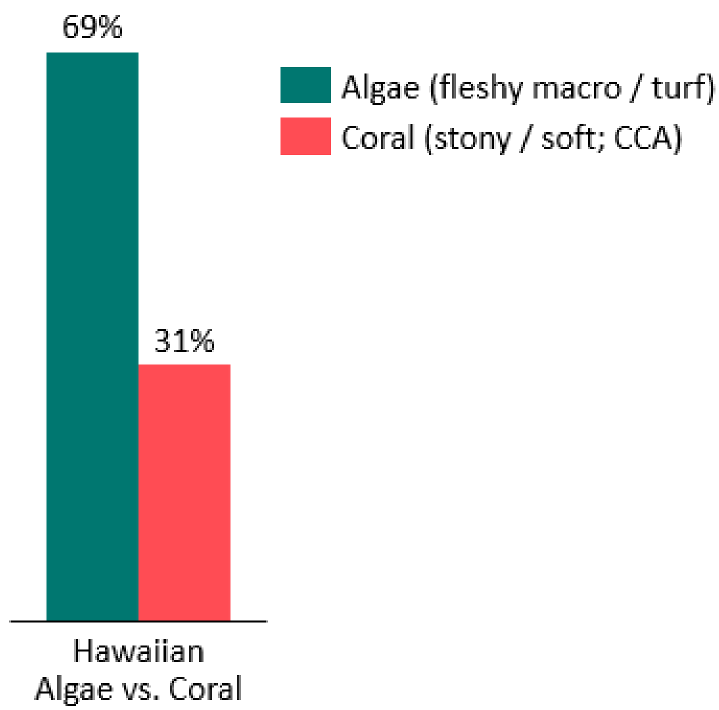
Figure 2. Ratio of Bleached to Non-Bleached Stony Coral Observed in Hawaiian Reefs.



Although 16% may appear to be an insignificant proportion of bleached coral compared to the majority of non-bleached coral at 84%, these numbers are quite concerning. With an average of 16% of coral bleached per reef, this indicates a substantial impact on reef health. Furthermore, within the bleached category, the majority, 56%, of coral exhibited moderate bleaching, suggesting a significant level of stress on these coral communities.

Moreover, non-bleached coral does not necessarily indicate healthy coral. Many of the reefs surveyed were overrun by algae, which is indicative of a disruption to coral-algae endosymbiosis (El-Naggar, 2019). This phenomenon often occurs in response to direct environmental stressors such as pollution, overfishing, and nutrient runoff, but is overarchingly caused by climate change and ocean acidification (El-Naggar, 2019). As a result, even non-bleached coral may be experiencing significant stress and may be at risk of further decline if reef conditions are not improved. Inserted below is a visual comparison depicting the average abundance of algae compared to coral observed at each reef site curing our research cruise.

Figure 3. Comparison of Average Algae to Coral Cover at Hawaiian Reef Sites



Notably, the proportion of algae, constituting 69% of the observed benthic cover, greatly outweighs the presence of coral, accounting for only 31%. This stark contrast underscores the concerning trend of declining coral health across Hawaiian reefs, even in areas where coral bleaching is not prevalent. Indeed, our research highlights the declining state of reef ecosystems along the archipelago.

However, some notable limitations of the study include the need for a larger sample size and the fact that we only conducted surveys at one cite per island. A larger sample size would provide a more comprehensive representation of the overall reef health across each MHI. Additionally, conducting surveys at only one cite per island, and none in the NWI, does not fully capture the variability of each island's reef ecosystems. Hence, increasing the number of survey sites per island and expanding the study to encompass more of the archipelago would enhance the robustness and generalizability of our findings; but, of course, would require extensive resources.

Nonetheless, while our study offers insight into the current condition of Hawaiian coral reefs, their health is influenced by various factors beyond coral bleaching alone. As aforementioned, the proliferation of algae on many of the surveyed reefs highlight broader ecosystem degradation (El-Naggar, 2019). Indeed, this degradation is linked to the effects of climate change on weather patterns, as well as the impacts of direct pollution.

For instance, greenhouse gas emissions have contributed to increased storm activity and altered changes in precipitation patterns, posing threats to Hawaiian coastlines (Jokiel, 2006). Historically, Hawaiian coastlines have endured numerous surf events of high magnitude per year, typically originating from the northwest. However, anthropogenic carbon emissions have disrupted these traditional precipitation patterns, leading to storms originating from unexpected directions (Jokiel, 2006). Storms of significant magnitude from unprecedented directions can result in substantial damage to coastlines. For instance, a 2003 storm coming from the northeast of Kauai reduced coral cover in the area from 14% to 6% (Jokiel 2006). Additional research indicates that maximum wave height is strongly correlated with a negative impact on coral cover, diversity, and species richness (Jokiel, 2006). As such, the impact of high surf on coral cover is one of the most immediately destructive forces on reef ecosystems.

The advancement of technology has significantly enhanced scientists' understanding of the effects of storm activity on coral health. For instance, the establishment of meteorological satellites has illustrated that hurricanes have become increasingly prevalent in the central Pacific compared to previous records (Jokiel, 2006). Hurricanes, per definition are tropical storms that produce high surf and storm surges along coastlines, threatening winds, waterspouts, tornadoes, heavy rain, and flooding (Jokiel, 2006). In Hawaii, Hurricane Iniki in 1992 wreaked havoc in Oahu and Kauai, causing upwards of $2.2 billion dollars of water and wind damage. Its waves desecrated coral throughout much of Kauai, as well as damaging homes, appliances, trees, and other objects (Jokiel, 2006).

Additionally, tsunamis, a series of immense waves triggered by a violent movement of the sea floor, typically resulting from earthquakes, underwater landslides, or volcanic eruptions, also threaten reef ecosystems (Jokiel, 2006). Moreover, in Hawaiian communities, tsunamis notably account for more deaths than all other local natural disasters (Jokiel, 2006). While damages to reefs from tsunamis are less extensively documented, assessments are often based on the destruction observed along shorelines and to communities. Overall, increasing storm activity prompted by climate change poses a clear and present danger to both Hawaiian reef ecosystems and the community at large.

Furthermore, direct anthropogenic stressors such as land-based runoff and overfishing significantly impact the health of coral. Reefs are often exposed to harmful sediments from sewage, nutrients, freshwater, and oil exposures (Fabricius, 2011). This exposure can either suspend in water, reducing the reef's light exposure, or smother the coral by impacting its symbiosis with algae. Currently, nitrate concentrations off the coast of Hawaii are 50 times greater than the standard (USGS, 2018).

Overfishing in coastal communities is another significant direct factor threatening reef ecosystems, specifically in respect to biodiversity. The National Oceanic and Atmospheric Administration has identified overfishing on virtually every inshore reef near the MHI (NOAA, 2022). Cross analytical research reveals that in the MHI, 40% of fish species had an estimated 25% lower biomass than the same fish species in the non-populated NWHI. (Friedlander et al. 2017).

Ship strikes also pose a notable stressor against coral reefs. While the Coast Guard affirms that ship damage to MHI reefs varies each year, NOAA scientists approximate that, on average, 5 acres of reefs are damaged each year (Bishop et al., 2011). Moreover, studies in Florida discern that reefs seriously damaged by ship strikes can take a minimum of 50 years to grow back if unmanaged. While Florida is indeed not Hawaii, the amount of immediate destruction ship strikes have on reefs is thematically apparent. That said, active restoration efforts can revitalize reefs in about a decade. These restoration efforts include propagating new coral from coral farms and rehabilitating existing coral damaged by ship strikes (Bishop et al., 2011).

Coral reefs exhibit high resilience against natural disturbances, but this resilience diminishes in the presence of high pollution. Generally, anthropogenic effects like increased sedimentation plague environments where wave forces are minimal, like bays or lagoons that do not receive powerful enough wave energy to flush sediments from the ecosystem (Jokiel, 2006). Major causes of erosion, runoff, and rapid accumulation of sedimentation is overgrazing on watersheds in the mainland. Presently, feral pigs, goats, and deer, are severely impacting watersheds in Molokai, Lanai, west Maui, and the north coast of Kauai (Jokiel, 2006).

Despite the extensive environmental forces accumulating against reef ecosystems, coral has prevailed. Direct pollution is suspected to accumulate destruction of coral ecosystems at a rapid rate compared to gradual ocean warming and acidification effects (USGS, 2018). However, these sources can be minimized or addressed in a more feasible manner than climate change and ocean acidification, which necessitate global solutions.

Effects of Reef Ecosystem Degradation. Hawaiian reef ecosystems are incredibly valuable and provide a wide range of ecosystem services to both the environment and communities; therefore, their degradation has drastic impacts on the archipelago. For instance, economically, coral reefs are estimated to value about $364 million annually, and potential reef areas are estimated to value nearly $10 billion (NOAA, 2013). In this subsection, I overview the effects of the declining health of reef ecosystems from the context of supporting, provisionary, and cultural services. However, in later chapters I will expand on the multifaceted complexity of the consequences of reef degradation.

The effects of regulatory services provided by coral reefs are most notably observed in biodiversity and nutrient cycling. For context, coral reefs are among the most biodiverse ecosystems globally. Therefore, elevated water temperatures contribute to species loss, impacting the stability and resilience of the entire marine ecosystem. For example, the highest recorded marine heatwave occurred in 2015, resulting in over 50% coral loss in the most affected (NOAA, 2022). Moreover, if climate change persists at its current rate, severe bleaching events, like those witnessed in 2015, are projected to occur annually by 2048 (Jokiel et al., 2011).

Furthermore, reefs play a role in nutrient cycling, which influences the productivity of coastal waters. As such, coral degradation disrupts these natural processes. Mentioned previously, coral has a symbiotic relationship with algae, which is particularly vulnerable during periods of nutrient loading and coral bleaching. An EPA experiment conducted in captivity revealed that during episodes of ocean acidification, coral's ability to spawn decreased by 78%, while fleshy algae increased cover by 52% on reefs (Jokiel et al., 2011).

Additionally, changes in coral reef's provisionary service capabilities severely impacts fisheries, tourism, and medicinal resources. The degradation of reef ecosystems leads to reduced fish populations, affecting seafood availability for local consumption and impacting the livelihoods of fishermen. Recent data indicates a 31% reduction in reported commercial fish catches (NOAA, 2022). Furthermore, healthy coral reefs serve as major tourist attractions, so their decline can deter visitors, reducing revenue from the tourism industry, which is arguably the most significant economic driver in Hawaii. Presently, approximately 85% of the value of Hawaiian reefs is dependent on tourism (NOAA, 2013).

The cultural services provided by reefs means that their degradation severely impacts Hawaiian culture, particularly cultural identity and daily livelihood. The degradation of reefs can erode the cultural identity of indigenous communities and impact traditional practices and knowledge. Local communities are acutely aware of their connection to coral. A survey shows that 94% of Hawaiian residents acknowledge the importance of reefs to Hawaiian culture (NOAA, 2018). In terms of livelihood, water activities are extremely popular in Hawaii; therefore, degrading reefs reduce opportunities for such activities, affecting residents as well as tourists. The recreation value of reef ecosystems is estimated to benefit Hawaii's economy $304 million annually (NOAA, 2013).

Finally, regulatory services of storm protection and water quality are significantly due to anthropogenically induced climate change. As aforementioned, coral reefs act as natural barriers that reduce the impact of waves and storm surges, protecting coastal communities from erosion and damage during storms (Jokiel, 2006). Additionally, reefs filter pollutants and help maintain water quality. Their degradation results increased sedimentation and nutrient runoff, perpetuating water quality issues.

Ultimately, the degradation of reef ecosystems has far-reaching consequences, affective biodiversity, fisheries, tourism, medicinal resources, cultural identity, storm protection, and water quality. These impacts are caused by climate change, ocean acidification, and direct pollution. Accordingly, efforts to mitigate these effects and preserve reef ecosystems are crucial for maintaining their valuable ecosystem services and ensuring their long-term resilience.

Various conservation and restoration efforts are currently in place to reduce the degradation of Hawaiian reef ecosystems and protect their ecosystem services. These include marine protected areas, sustainable fisheries management, coral restoration projects, and efforts to reduce land-based pollution (NOAA, 2022). Moreover, the resilience of these ecosystems can be improved through science-based approached, community involvement, and sustainable practices, helping to maintain their valuable ecosystem services long-term. These strategies will be illustrated and assessed in chapters 4 and 5, respectively.

Chapter 2: Ecology of Coral Reefs

Rapid, anthropogenic climate change has resulted in the accumulative decline of Hawaiian reef ecosystems. Additionally, coastal communities reliant on reefs for subsidence and financial gain are increasingly threatened as reef ecosystems deteriorate. Coral itself is the foundation for Hawaiian coastal communities' sustainability. So, to preserve both the biodiversity and the communities that live within and depend upon Hawaiian reef ecosystems, we must understand the science behind why coral is dying off. Thus, this chapter will address the ecology of coral, how it drives the reef ecosystem, the effects of climate change and ocean acidification, and the local effects related to declining populations. Ultimately, such analyses will help mobilize sustainable conservation movements to effectively preserve Hawaiian reef ecosystems and associated communities.

Regenerative Coral and its Impact on the Reef Ecosystem. My voyage in Hawaii taught me that there is a specific type of coral, scleractinian coral, colloquially known as stony corals, that are primarily responsible for the generation of reefs. Early scleractinian corals were not reef builders, but small solitary polyps. However, evolution prompted stony coral to obtain specialized reproductive strategies and resiliency to stress that extended their lifespans to centuries (Bhattacharya et al., 2022). Hawaiian reefs are now comprised of approximately 55 species of stony coral, 25% to 50% which are endemic to Hawaii, because of the archipelago's geographic isolation (Bishop et al., 2011).

That said, up until recently, little research has been conducted on regenerative coral and its impacts on reef ecosystems. Technological hinderances, combined with lack of awareness were mostly to blame. The extent of scleractinian coral's ecological importance was stunted by the complexities and limitations of oceanography research methods (Montano, 2020). Notably, limitations of SUCBA research methods have inhibited the study of scleractinian coral below a depth of 30m (Rooney et al., 2010). Therefore, it is likely that the true capacity of regenerative coral is not yet fully conceptualized.

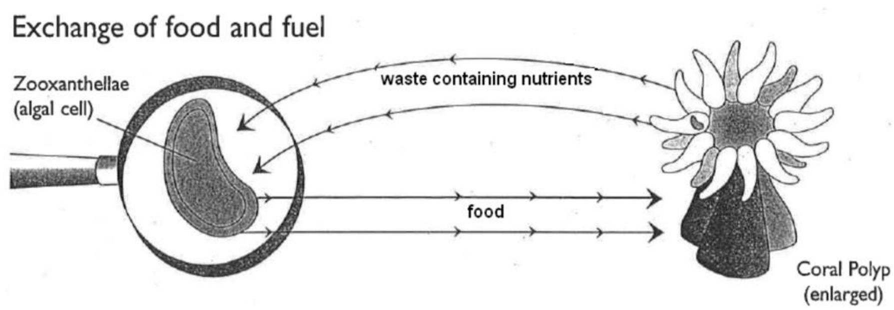
Nonetheless, the technology revolution has increased the accessibility and thus incentive to map Hawaiian coral reef ecosystems. Such advances have expanded the knowledge about scleractinian coral; specifically, its presence at a depth range of 30-130+ m. Newfound research methods such as cameras, underwater sleds, and refined SCUBA technology, have optimized coral mapping and, thus, data collection (Rooney et al., 2010). Study results reveal that scleractinian coral are reoccurring and significant to all reef ecosystems of the Hawaiian archipelago (Rooney et al., 2010). Furthermore, studies determine that scleractinian coral and other regenerative types possess functional behavior variations tied to the performance of reef ecosystem (Stat & Gates 2010). Ultimately, understanding the significance of scleractinian coral relative to the Hawaiian reef ecosystem is essential to outline successful conservation methods for both reef and Hawaiian coastal communities.

For a bit of ecological history, Hawaiian reefs contain only three primary genera of coral: *porities, montipora,* and *pocillopora*. While the genera diversity of coral species is relatively low, Hawaii's geographic isolation has prompted genome growth and adaptation. For instance, in high wave environments, *Pocillopora meandrina and Porites lobata* thrive, but in low wave environments, *Montipora capitata or Porites compressa* excel (Jokiel, 2006). The predominant natural factors that influence the structure of coral reefs are depth, wave regime, and rugosity, or surface roughness (Rodgers et al., 2009). The species of coral that dominates a particular reef is determined based on these natural factors, and then adapt to anthropogenic stressors from there. For instance, *Montipora capitata* assumes encrusting, plate-like or branching growth forms depending on the amount of light and surf.

Coral's cyclic relationship with its surrounding environment upholds the reef ecosystem. Through an extraordinary process called coral endosymbiosis, algae called dinoflagellates, or zooxanthellae, provide organic carbon to the host coral and receive inorganic waste in return

(Stat & Gates 2010). Below is a simplistic visual of the symbiosis process between zooxanthellae and coral to aid in its understanding.

Figure 4. Coral Polyp and Zooxanthellae Exchange of Nutrients For Their Symbiotic Relationship (Molloy, 2012).



Furthermore, in coral endosymbiosis, nutrients are recycled back into the ecosystem, coral regenerates and provides new habitats to other reef creatures, and, ultimately, the reef ecosystem is maintained. This symbiotic ecological process is most commonly referred to as the *Symbiodinium* and is as aforementioned, conducted by *all* coral species. However, the *Symbiodinium* requires specialized conditions and can only operate within a short range of temperatures (Stat & Gates 2010). Scleractinian coral is grouped with coral species that have the highest *Symbiodinium* temperature threshold; therefore, it is arguably one of the most important coral species to study as rapid climate change surges sea temperatures upward.

To serve as an exemplar, the scleractinian *Montipora* coral species' resiliency to short-term thermal stress is what makes it one of the most populous corals in Hawaiian reefs. Additionally, *Montipora* contains a perforate, or holed, skeleton that can sequester zooxanthellae in deeper tissues, mitigating its vulnerability to bleaching events (Bhattacharya et al., 2022). Mass spawning events occur approximately three times annually, during the New Moon phases in June, July, and August, although this can widely vary. Moreover, within the *Montipora* genera, there is great diversity amongst species, indicating their adaptability to different local environmental conditions (Bhattacharya et al., 2022). All these traits are a testament to the resiliency of scleractinian coral. So forth, studying scleractinian coral is integral to obtain a deeper understanding about the Anthropocene's effects on reef ecosystems.

Nonetheless, the ecological significance of scleractinian coral and, perhaps, the premises of this paper is largely intertwined with the *Symbiodinium.* While all types of coral practice *Symbiodinium* to stimulate their ecosystems, regenerative coral, categorized under clade D *Symbiodinium*, is deemed more thermally tolerant (Stat & Gates 2010). Specifically, clade D *Symbiodinium* coral can withstand a temperature rise of 1-1.5°C (Stat & Gates 2010). Hence, conceptually speaking, scleractinian coral is more evolutionary resilient than other coral species. Because scleractinian coral can function at a higher temperature threshold, it has a stronger capacity of survival as temperatures continually increase. Even more, clade D *Symbiodinium* behavior can be translated to other types of coral, in the event that coral bleaching diminishes the latter of its endosymbionts—i.e., its required nutrients (Stat & Gates 2010). Meaning, other corals may mimic scleractinian coral's behavior as a final act of survival. Accordingly, new evidence suggests that clade D *Symbiodinium* increases amongst coral following a period of bleaching (Stat & Gates 2010). Thus, scleractinian coral can be expected to increase and/or significantly affect overall coral evolution during the Anthropocene.

Additionally, the *Symbiodinium* supports reef ecosystems by catalyzing calcium carbonate deposition. Coral is primarily comprised of calcium carbonate; therefore, coral calcification ultimately facilitates the structure of the reef. Ultimately, as the base of the reef ecosystem, coral calcification is vital for reef biodiversity, shoreline protection, and, thus, coastal communities' cultures (Stat & Gates 2010). Scleractinian coral is especially fascinating in that it can extract dissolved inorganic carbon from seawater for *Symbiodinium*. Typically, corals receive required nutrients from dinoflagellates or other related organisms for endosymbiosis. Therefore, scleractinian coral's endosymbiosis can effectively reduce carbon dioxide levels in the sea by mobilizing dissolved, liquiform carbon into calcium carbonate to build reef infrastructure (McCulloch et al., 2017). Relatedly, anthropogenic factors have led to the release of monumental amounts of carbon dioxide, 30% of which is retained by the ocean (Anthony et al., 2008). Therefore, scleractinian coral may be highly beneficial to conservation studies and reef ecosystem regeneration because of its unique capacity to extract dissolved carbon from seawater.

Alongside stony corals, crustose coralline algae (CCA), also contribute significantly to the health of a reef. CCA are solid calcareous red algae that facilitate reef calcification and provide crucial services for benthic larval settlement, essential processes for reef development and maintenance ("Crustose Coralline Algae and Sedimentation," n.d.). Their calcified encrustations recycle dead coral and fill cracks in reef substratum, contributing to a reef's formation, maintenance, and erosion prevention ("Crustose Coralline Algae and Sedimentation," n.d.). In fact, the generative effects of CCA place them on par with stony coral in terms of importance within reef ecosystems. Furthermore, many benthic organisms, including coral, prefer CCA for propagation.

Overall, the dynamic of Hawaiian reef ecosystems are extraordinarily intricate, and are particularly dependent on scleractinian (stony) coral and crustose algae (CCA). Both types of coral and algae are integral to a reef's formation, maintenance, and resilience. However, despite their importance, these reefs face significant challenges in the face of climate change, ocean acidification, and direct pollution.

Impacts of Climate Change and other Anthropogenic Stressors. Anthropogenic effects are decreasing the health of scleractinian, regenerative coral; progressively threatening Hawaiian reef ecosystems. Both global stresses such as elevated water temperatures and ocean acidification as well as local stresses such as nutrient overloading and pollution are regarded as the main causes for reef ecosystem degradation (Stat & Gates 2010). Corals already live at the brink of their thermal maxima, thus, increasing ocean temperatures expedites the vulnerability of reef ecosystems. Specifically, the *Symbiodinium* ecological process between regenerative coral and dinoflagellates necessitates specialized, unchanging environmental conditions (Stat & Gates 2010). If temperatures exceed thermal maxima, dinoflagellates become lost from the host coral's tissues, which then turn pale; a phenomenon colloquially known as 'coral bleaching' (Stat & Gates 2010). Notably, the thermal tolerance threshold of clade D *Symbiodinium* coral will continually be challenged as rapid anthropogenic climate change accumulates.

Additionally, ocean acidification combines with climate change to accumulate scleractinian coral decline. More than 30% of anthropogenically released carbon dioxide is absorbed by the ocean, decreasing pH surface level waters to an increasingly vulnerable state (Anthony et al., 2008). Calcium carbonate accretion, i.e., coral growth, cannot occur in an overly acidic environment. Casually, the dissipation of atmospheric carbon into the ocean hinders coral calcification (Stat & Gates 2010). Therefore, ocean acidification is tied to the dissolution of scleractinian coral and, thus, to the decreased performance of the reef. Indeed, ocean acidification is also tied to coral bleaching. While no theory has been unanimously proven, scientists conceptually agree that ultimately changes in the carbon-concentrating mechanisms of coral endosymbiosis disrupt the *Symbiodinium* function. Such disruption is universal to all coral; even clade D *Symbiodinium* dramatically decreases in productivity with elevated carbon dioxide levels, and worsen with warming (Anthony et al., 2008). Therefore, while scleractinian coral can withstand higher temperatures, it cannot withstand high carbon dioxide levels prompted by ocean acidification.

Furthermore, both increasing sea temperatures and ocean acidification combine to perpetually decrease coral productivity. In an experiment that manipulated both temperature and pH variables on clade D *Symbiodinium* coral, at the highest carbon dioxide and temperature exposures, productivity rates regressed 160% (Anthony et al., 2008). Therefore, while scleractinian coral indeed has an evolutionary edge by functioning at high ocean temperatures, it cannot withstand against the ecological conditions wrought by rapid climate change combined with ocean acidification --regardless of its ability to extract carbon from sea water.

Moreover, scleractinian coral is directly threatened by point and nonpoint pollution runoff, overfishing, bacterial infections, and abnormal salinity changes prompted by local anthropogenic activities (Stat & Gates 2010). Notably, however, the local issues aforementioned are general to reef ecosystems across the world, and not just Hawaii. Specifically, direct, land-based pollution can lead to coral sedimentation, eutrophication, and increased toxins (National Ocean Service, 2018). Such issues directly disrupt reef ecosystems by harming and/or killing coral, and dysregulating critical ecological functions (National Ocean Service, 2018).

To summarize, generally, scleractinian coral supports the bulk of habitat diversity and symbiotic relationships within a reef ecosystem. They are a monumental facilitator of the reef ecological cycle. As a regenerative coral, their ecological processes nurtures relationships of upwards of a thousand different micro and macro-organisms within the reef (Montano, 2020). Moreover, their symbiotic relationship with unicellular dinoflagellates ultimately drives the productivity of the reef ecosystem. Additionally, scleractinian coral possess a remarkable ability to capture dissolved carbon from sea water, to use for its endosymbiosis. However, the studies on scleractinian coral, and of clade D *Symbiodinium* coral in entirety, is immature. While conclusions seem promising, no studies have been done from the majority of the world's reefs (Stat & Gates 2010). Thus, to effectively outline reef conservation policies that focus on regenerative coral, further testing, data, and information must be facilitated.

Ecological Community's Dependance on Regenerative Coral: Ultimately, reef ecosystems are not static communities, but dynamic and profound systems that can adapt to several, natural environmental disturbances. The impact of the Anthropocene compounded with natural disturbances is cause for concern, as it is unknown if reefs will have the resiliency to handle such unprecedented amounts of stress (Jokiel, 2006). Therefore, as scleractinian coral is vital for coral reef production, their decline has significant impacts on the rest of the ecological community. This subsection explores the notable impacts that coral degradation has on the biodiversity of the entire reef ecosystem.

Coral reefs, akin to tropical rainforests, harbor immense biodiversity and form complex ecosystems beneath the ocean surface (Bhattacharya et al., 2022). One of the key characteristics of reef ecosystems that foster such high levels of biodiversity is regenerative coral's three-dimensional structure (Hoegh-Guldberg et al., 2019). Therefore, the decline in these coral species, specifically *porites, montipora,* and *pocillopora* has led to an increased threat to biodiversity (Joshi et al., 2023). Species like turtles, reef fish, and marine mammals rely on coral for both protection and food, making them vulnerable to habitat loss and food scarcity due to degraded coral cover (Joshi et al., 2023)

Hawaiian sea turtles, such like the like zooxanthellae algae that inhabit coral polyps, share a symbiotic relationship with coral reefs. Turtles use reefs as nesting sites, finding protection from predators and suitable conditions for egg deposition (Joshi et al., 2023). In return, coral benefits from the grazing activities of turtles, which help control algae growth. So, a reduction in coral cover disrupts their symbiosis. With fewer coral structures to provide shelter turtles become exposed to predators and have difficulty finding areas for nesting. Consequently, coral degradation contributes significantly to the current threat status of Hawaiian turtles, a factor prompting their classification on the IUCN Red list (Joshi et al., 2023).

The loss of coral cover also has significant implications for fish biodiversity within reef ecosystems. While some smaller species of Hawaiian fish demonstrate a degree of resilience to coral degradation, larger fish such as rays and sharks are more vulnerable (Joshi et al., 2023). This vulnerability stems from the relationship between fish and coral; coral also serves as a critical habitat for fish, providing shelter, breeding grounds, and food sources. Moreover, as key predator-prey relationships are disrupted because of coral loss, the reef is further destabilized (Joshi et al., 2023).

Among all species threatened by degrading reefs, the Hawaiian Monk Seal ranks first for being the most vulnerable to extinction. The 2023 updated version of the IUCN Red List has established them as critically endangered (Joshi et al., 2023). This dire status is directly linked to the decline in coral cover, as Hawaiian Monk Seals exclusively inhabit reef ecosystems. The decline in their population can be attributed to two primary factors: food availability and anthropogenic activity (Joshi et al., 2023).

The specialized diet of Hawaiian Monk Seals consists of fish, squids, octopuses, eels, and crustaceans, all of which rely on a healthy reef ecosystem for their abundance. is dependent on a healthy reef ecosystem (Joshi et al., 2023). As coral cover diminishes, the availability of food sources for these seals decreases, leading to nutritional stress and reduced reproductive success.

However, while many species within the ecological community of reef ecosystems are declining due to coral loss, a few species are paradoxically thriving. One notable example is the proliferation of turf algae, which becomes dominant when coral reefs experience disruptions in the symbiotic relationship between coral and algae (Jouffray et al., 2015). This phenomenon has been observed across reefs throughout the archipelago. The expansion of turf algae is compounded by the loss of biodiversity, like turtles and reef fish, which traditionally control algae populations by grazing on them (Jouffray et al., 2015).

Turf algae proliferation can quickly overgrow and outcompete coral for space and resources, which is an extraordinary cause for concern. In one study in Hawaii, turf algae was found to dominate over half of the surveyed reefs, indicating a widespread and concerning trend (Jouffray et al., 2015). Notably, in my own research cruise, most of the reefs we observed were predominately composed of turf algae. This observation was depicted in the visual inserted in chapter 1.

The dominance of turf algae represents a critical juncture for coral reef ecosystems. If left unaddressed, turf algae could exacerbate coral decline by smothering coral larvae, inhibiting their germination and growth (Jouffray et al., 2015). The overtaking of turf algae could result in a reef turning to macroalgae in extreme cases. This shift would exacerbate the declining health and biodiversity of the reef, jeopardizing the reef entirely.

Thus, the impacts of coral degradation reverberate throughout the entire reef ecosystem, affecting biodiversity on multiple fronts (Joshi et al., 2023). Ultimately, coral’s survival and maintenance could rehabilitate and conserve native ecosystems and the coastal communities that depend on them. And so, scleractinian coral must be prioritized when outlining effective conservation methods, as it is, arguably, the most performative and resistant coral in the reef ecosystem. Particularly, effective reef conservation strategies should consider both the health status of clade D *Symbiodinium* coral and the potential benefits that such coral can provide for reef ecosystem regeneration. The consecutive chapters will explore the depth of the relationship between reef ecosystems and Hawaiian culture and how coral should be prioritized in conservation policy for Hawaii.

Chapter 3: Reef Ecosystems and Hawaiian Culture

The Hawaiian archipelago is viewed by Native peoples as an ancestral environment, embodying the kinship between people and their natural world, and as a place where life both originates and spirits return after death (Lubchenco & Haugan, 2023). Hence, beyond their natural beauty and ecological importance, reef ecosystems have woven into the very fabric of Hawaiian identity, representing a unique heritage that holds valuable lessons for both environmental conservation and cultural preservation. This chapter highlights the intricate and enduring bond between Hawaii's culture and its coral reefs and illustrates how anthropogenic induced climate change and ocean acidification jeopardize this relationship. In exploring the synergy between Hawaii's unique coral ecosystems and cultural reverence for them, we gain insight into the symbiotic relationship that exists between nature and society, and the challenges and opportunities that this presents for our future in the Anthropocene.

Overview of Hawaii's Cultural Connection to Coral. By the time westerners entered the Pacific Ocean in the 16th century, Polynesian culture had already flourished on the islands for centuries. Ancient peoples had complex, emotional, spiritual, artistic, as well as material and transactional relationships with the ocean (Lubchenco & Haugan, 2023). Therefore, Native Hawaiians occupied the archipelago thousands of years before Western colonialization and developed complex resource management systems that emphasized their connection with the ocean (NOS, 2022).

The relationship between Hawaiian peoples and their surrounding environment stems from the unique ecology of the islands. An estimated 15,000 endemic species thrive in Hawaii; the island's ecoregions support more life forms than any other place on the planet (Gregg et al., 2015). As a result of the islands biodiversity, Hawaiian culture is wholistically intertwined with its environment. Their ideology perceives all things in the natural world as spiritual beings that demand respect, a phenomenon often referred to as ecocentrism.

In Hawaiian culture, knowledge is primarily transmitted kupuna, the grandparents and ancestors who are the keepers of cultural wisdom (Gregg et al., 2015). Traditionally, cultural heritage is shared through *oli* (chants), *mo 'oku' auhau* (geneology), *hula* (dance), as well as through dreams and thoughts. Hence, Hawaiian culture embodies physicality, both through the spread of knowledge and in relationship to the natural world.

Coral holds a significant place in Hawaiian ethnobiology, and is often depicted as an ancestor, a provider of life and death, and as possessing spirituality (Gregg et al., 2015). For instance, the Kumulipo, a Hawaiian creation chant, depicts coral as the first organism of the universe, representing its cultural significance. Additionally, it recognizes that both humans and coral are composed of calcium carbonate, which is used as evidentiary support for our kinship (Gregg et al., 2015).

The Kumulipo also depicts the scientific mechanisms behind coral spawning, highlighting Polynesian's advanced understanding of nature (Gregg et al., 2015). As described in chapter 2, coral germinates as a microscopic larva that compound together to form reefs, a complex science that requires advanced technology to study. Western science did not acquire the same understanding about coral germination until the 1950s, whereas Native Hawaiians were aware of it for centuries. (Gregg et al., 2015).

Numerous other proverbs illustrate Native Hawaiian's respect for coral, referencing its ability to withstand fierce storms and ocean conditions as qualities of resiliency and strength. There is a female ancestor, Hinaʻōpūhalakoʻa, who is portrayed as the "woman of the coral" (Gregg et al., 2015). She is often depicted in proverbs or stories as a figure of respect. However, pragmatically, traditional uses of coral ranged from polishing canoes, to making dye bowls, poisons, and to build the heiau, or sacred temples (Gregg et al., 2015). In summary, the cultural emphasis on coral shows Native Hawaiian's appreciation and reliance on coral for their way of life.

It's worth noting that the delay in Westerners' pace to keep up with Polynesia's ecological understanding may have accelerated colonization and its impacts on Hawaiian culture. This notion finds validation in President Bush's issuance of the "Apology Resolution" (U.S. Public Law 103-150), which Congress signed in 1993 (NOS, 2022). The resolution acknowledges the repercussions of the overthrow of the Kingdom of Hawaii, including the "deprivation of the rights of native Hawaiians to self-determination." Additionally, it highlights that the "health and well-being of the Native Hawaiian people is intrinsically tied to their deep feelings and attachment to the land" (U.S. Public Law 103-150). This recognition underscores the shared understanding of the importance of ecology, particularly coral reefs, among Native Hawaiians and those who interact with them.

Socio-economic Influence of Hawaiian Reef Ecosystems. Transitioning from the discussion on Hawaiian cultural reverence for coral to the socio-economic influence of Hawaiian reef ecosystems, it becomes evident that coral holds a deeply rooted significance in the Hawaiian way of life. Beyond its cultural heritage, coral provides a multitude of socio-economic benefits, as touched upon briefly in chapter 1. While the ecological benefits of reefs were conveyed in chapter 2, reefs are also are essential to human well-being. Their socio-economic benefits to people range from sustenance, employment, and cultural identity to shoreline protection and support for the tourism and research sectors of the Hawaiian economy (Rodgers et al., 2009).

However, the relationship between human livelihoods and reef ecosystems in Hawaii is mirrored by the reciprocal impact of human activities on reefs. Factors such as population growth, sedimentation, and organic inputs exert direct influences on the structure of reefs (Rodgers et al., 2009). This interconnectedness highlights the importance of implementing sustainable practices and conservation measures to mitigate the degradation of reefs, preserving the future generations of both humans and reef organisms alike. Accordingly, this subsection will present empirical data that proves the socio-economic significance of reef ecosystems in Hawaii.

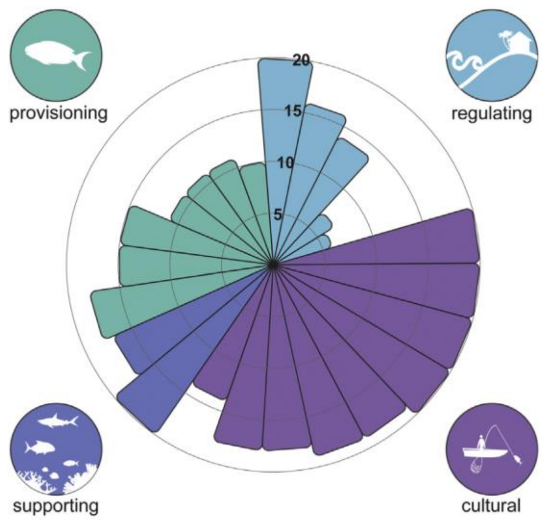
When evaluating the socio-economic importance of coral reef ecosystems, it is best to convey their worth in terms universally understood by all humans: economic value. A 2011 seminal case study conducted by the National Oceanographic and Atmospheric Administration (NOAA) aimed to calculate the total value of coral reef ecosystems in Hawaii. This was the first major economic evaluation of reef ecosystems and established a global framework for all coastal communities when quantifying the economic worth of their reef ecosystems. NOAA's study used formulas and estimates from the publication, Cesar et al. (2002) as a model to determine the total economic value of the MHI (Bishop et al., 2011). This total economic value encompasses not only the profits generated directly by reef ecosystems but also the positive externalities they indirectly contribute to. Specifically, Cesar and his colleagues categorized reef values into recreational, amenity, fisheries, and biodiversity sectors, estimating each value separately. These estimates where then aggregated to approximate the total economic value of Hawaiian coral at $364 million annually (Bishop et al., 2011).

Among the reef value categories, fisheries and tourism stand out as the two largest generators of income of Hawaiian reef ecosystems. Quantitatively, the net annual value of Hawaiian fisheries exceeds $10 million, while the tourism industry projects a staggering $6.5 billion U.S. dollars per year, accounting for 8% of Hawaii's gross domestic product (NOS, 2018). Their specific evaluations are expanded on below.

Demographically, over eight million tourists visit Hawaii per year. Out-of-state Americans spend an average $182 per day, while Japanese tourists average $257 per day (Peng & Oleson, 2017). Given that most tourists visit Hawaii for its beaches, they inevitably engage with nearshore, typically MHI, reef ecosystems. A 2011 survey revealed that over 50% of Hawaiian tourists partake in snorkeling and diving activities, illustrating the importance of coral reefs to the tourism industry (Peng and Oleson, 2017). Clearly, the profits gained from the tourism industry are invaluable to the Hawaiian economy and are dependent on the health of the reef ecosystem. In that vein, this is why sustainable eco-tourism is essential, as tourists interacting with reefs irresponsibly directly impacts reefs; however, this concept will be elaborated upon in chapter 5.

All cultural services provided by reefs, particularly tourism and recreation, are considered to hold the most fiscal value in comparison to the other ecosystem services (Fezzi et al., 2023). To visualize the economic contribution of each ecosystem service, the figure below provides a comprehensive representation. This illustration, resulting from a community-based workshop involving local Hawaiian residents conducted by scientists, highlights the significance of cultural services in the overall economic evaluation of reefs. The spiral nature of the diagram illustrates the varying "effect strength" of each ecosystem service, with weaker effects toward the center and increasing strength as they increase outwards (Ingram et al., 2018).

Figure 5. Evaluated Effect Strength of Each Ecosystem Service (Ingram et al., 2018).



Indeed, the socio-economic value of cultural services provided by reef ecosystems is undeniably high. Although, this may be due to cultural services being easier to quantify in economic terms than other types of ecosystem services. For example, the economic value of tourism and recreation are much easier to quantify in Hawaii than fisheries (Fezzi et al., 2023). This might explain why cultural services receive greater attention in policymaking circles. That said, cultural services can be difficult to evaluate due to their intangible nature and the tendency for individuals to ascribe values subjectively (Ingram et al., 2018). Nonetheless, polices dedicated to the cultural services of Hawaiian reefs can serve as highly effective conservation strategies, as explored further in chapter 5 (Fezzi et al., 2023). However, the worth of other ecosystem services should not be understated, even if they are not as easily measurable in economic terms.

Ultimately, quantifying the economic value of reefs presents immense challenges due to their complex ecological influence, which often exceeds the scope of capitalism and is difficult to translate into pragmatic terms. For example, while small-scale fisheries provide sustenance to hundreds of families, their value to local economies is often underestimated due to data deficiencies. Nonetheless, the estimated total annual value of nearshore coral reef fisheries ranges from $10.3-16.4 million (Peng & Olsen, 2017). When combining commercial and recreational fisheries, Hawaiian reef ecosystems contribute, quantifiably, $200 million annually (Grafeld et al., 2017). Thus, the significance of coral reef fisheries to the Hawaiian economy is another predominate socio-economic value.

As outlined in the preceding subsection, the lives of local Hawaiian residents are deeply entwined with their coastal water zones. Throughout centuries, Native Hawaiians have used nearshore fisheries to sustain themselves and their families. This practice holds true for many families today, particularly in lower-income communities. Non-commercial fisheries alone provide 70% of the meals eaten in rural or economically vulnerable communities (Grafeld et al., 2017). This underscores the socio-economic value fisheries have in supporting livelihoods and ensuring food security among local and more vulnerable populations.

Moreover, beyond mere sustenance, fisheries serve as a conduit for cultural preservation and social cohesion. Since 2011, over 1,000 children and families have been attracted to lawai'a 'ohana camps that teach sustainable fishing practices. Attendees of these camps emphasize the cultural significance of fisheries, regarding activities like transporting and sharing fish as culturally important practices that strengthen community bonds and foster a greater sense of well-being (Grafeld et al., 2017).

Additionally, a 2014 survey of local beach recreationalists revealed an almost surprising and enduring interest in maintaining a minimum level of water clarity of at least medium. Respondents cited that they were willing to contribute financially, albeit in small amounts, to enhance conditions beyond this standard. Therefore, the socio-economic worth of reefs extends beyond the scope of capitalism, as, collectively, people are willing to pay for reef-viability for merely aesthetic purposes. Moreover, impressively, over 95% of survey participants advocated for the protection of coastal resources and remote areas to ensure recreational opportunities for future generations (Peng & Oleson, 2017). These collective sentiments illustrate that Hawaiian cultural bonds remain strong in the face of declining reef ecosystems.

Socio-economic Impacts of Declining Hawaiian Reef Ecosystems. However, the resilience of Hawaiian cultural bonds to coral reefs faces significant challenges amidst the backdrop of declining reef health. Moreover, these challenges extend beyond cultural considerations to encompass profound socio-economic impacts, which necessitate urgent attention and effective management strategies.

Particularly, Hawaiian reefs are under threat by both overarching environmental issues, climate change and ocean acidification, and local stressors, as outlined in chapter 1, in the subsection: *Causes of Reef Ecosystem Degradation*. As these ecosystems dwindle, so too do the socio-economic fabrics interwoven with their existence. Accordingly, this sub-section delves into the multifaceted repercussions of diminishing reef ecosystems in Hawaii, specifically highlighting the impacts to provisioning and cultural ecosystem services.

Among the array of negative impacts affecting provisioning services, overfishing stands out as the most violent threat to reef ecosystems in the MHI. The exponential growth in global population has led to a notable increase in Hawaii’s population density, driven by people drawn to the islands. This surge in density, coupled with the heightened global demand for fish, has significantly impacted Hawaiian fisheries (Bishop et al., 2011). Furthermore, technological advancements have increased fish yields, often surpassing sustainable limits, resulting in habitat degradation (Bishop et al., 2011). Consequently, fish populations have been depleted and reef ecosystems are increasingly vulnerable.

In addition to local stressors such as overfishing, the rising in ocean temperatures and the intensification of heatwaves driven by climate change poses it as of the most formidable threats to reef health (Fezzi et al., 2023). As explained in chapter 2, when corals are put under too much heat stress, the coral polyp expels its algal symbiont and dies, in a process called coral bleaching (Donovan et al., 2021). The socio-economic impact of coral bleaching is severe. For instance, in 2014-2015, coral bleaching events in Hawaii caused economic losses of $25 million per year in Maui alone, averaging out to $235 per adult resident (Fezzi et al., 2023). Given coral's slow recovery from bleaching events, the economic losses are protected. Furthermore, if declining reef conditions drive tourists to seek alternative destinations, reductions in consumer spending, tax receipts, revenue for local businesses, and overall employment are all at risk (Peng & Oleson, 2017).

Other factors to consider in the context of socioeconomic impacts on provisioning services are coastal water quality issues, which are common in Hawaii. Poor water quality not only poses a public health risk but also detracts from the aesthetics and environmental quality of coastal areas (Peng & Oleson, 2017). Algae and brown water blooms reduce the visibility of reefs and can take-away from the scenic views of coastal homes, hotels, and businesses (Peng & Oleson, 2017). Consequently, the economic losses generated by contaminated water issues are profound. For instance, if the 84 days of water quality events reported in Honolulu alone were eliminated, recreationalists could have gained a $550 million consumer surplus (Peng & Oleson, 2017).

As aforementioned, contaminated is a public health issue as well as an economic one. For instance, in 2009, there were 302 bacterial exceedances across the archipelago; exceedances being a term applied when bacteria levels are considered unsafe per US EPA guidelines (Peng & Oleson, 2017). The effects of exceedances result in swimming and fishing prohibitions, the contamination of shellfish, and a decline in nearby marine populations. For context, water contamination of often categorized as point and nonpoint source pollution. Point source pollution, such as sewage discharge and cesspools, and non-point source pollution, like agricultural runoff, are the primary sociological contributors to diminishing coastal water quality (Peng & Oleson, 2017). Their impact on public and ecological health is described below.

The accumulation of nutrients in nearby waters threatens human health due to infections caused by pathogens in untreated sewage (Ingram et al., 2018). Often, this is an example of point source pollution. People who encounter point sources can develop gastrointestinal, raspatory and eye, nose, ear, and skin infections (Ingram et al., 2018). Moreover, inadequate wastewater disposal can infiltrate coastal waters further downstream, exposing these contaminants directly to coral reefs. Hawaii currently leads the nation in cesspools, and presently, any policies that encourage progressive sewage development are feeble (Peng & Oleson, 2017).

Non-point sources contribute to the introduction of toxic chemicals such as lead, zinc, copper, arsenic, and cadmium in nearshore environments, exacerbating the challenges faced by Hawaii’s coastal ecosystems (Peng & Oleson, 2017). Furthermore, poor agricultural and land use practices worsen the situation, leading to sediment plumes after storms that can devastate nearshore coral reefs. These sediments often carry chemicals and pathogens which endanger the reef ecosystem (Peng & Oleson, 2017). For instance, storm floods that trigger sewage spills carry nutrients and toxic materials onto reefs, causing beach closures and widespread ecological ramifications. A notable example of this occurred in January 2004 when flooding caused 14 sewage spills along Oahu, leading to the closure of several high-income beaches along Oahu, in Honolulu, Kailua, and Waimanalo (Jokiel, 2006).

Additionally, both point and nonpoint source pollutants prompts coral disease and impairs their endosymbiosis with algae, reducing the amount of coral cover in a reef ecosystem (Peng & Oleson, 2017). The impacts of reduced coral cover can lead to algae-overgrowth. Additionally, the decline in coral cover diminishes the available habitat for fish populations, compounding the impacts of overfishing (Peng & Oleson, 2017). Consequently, the socioeconomic repercussions of declining reefs in Hawaii are worsened by the interconnected nature of these threats.

In summary, the socioeconomic ramifications of declining reefs in Hawaii are profound and far-reaching, given the state's reliance on its reef ecosystems. By unraveling these variables, we gain a deeper understanding of how the decline of Hawaiian reefs resonates across societal and economic sectors. Moreover, as cultural identity is tied to anthropogenic well-being, the diminishing cultural services of reefs correspondingly impacts mental health. And so, clearly, the socio-economic worth of coral reefs is unfathomable.

What the Future Entails. In the absence of efforts to mitigate the environmental stressors impacting Hawaiian reefs, the future socio-economic relationship of the islands and its community could face profound challenges. Accordingly, this sub-section explores the socio-economic benefits of improving the state of reef ecosystems and illustrates what the future could look like if conservation measures are not put into place.

With continued overfishing and unchecked algae overgrowth, the cultural services provided by coral ecosystems will continue to decline, jeopardizing the state's tourism industry and housing market. Therefore, there is exceptional potential for socio-economic gains through the improvement of coastal water conditions, given the profound impact of water quality on coral reef health (Peng, Oleson, 2017). For example, even a modest increase in coral cover, from 10% to 25%, could result in a substantial improvement in consumer surplus, amounting to $274 million. Moreover, a further increase of coral cover, from 25% to 45%, could add an additional $88 million to the consumer surplus (Peng & Oleson, 2017). Additionally, the implementation of a coral restoration project in Maui is projected to generate $2.9 million in recreation value alone (Fezzi et al., 2023). It is important to note that these estimates only consider tourist ecosystem services and do not account for biodiversity, storm prevention, and other regulatory and provisioning services. Nonetheless, the economic incentives for improving reef conditions, for the tourism and housing industries, are unmistakable.

Moreover, as the economic worth of coral becomes more apparent, reef ecosystem conservation has garnered more political attention. Assigning monetary value estimates to reefs provides them with a stronger voice in politics, as favorable numbers can be leveraged to enhance conservation efforts and justify the need for increased policy budgets (Peng & Oleson, 2017). The study conducted by Carlo Fezzi identified areas where coral reef restoration would maximize welfare gains and illustrates how access fees and/or green taxes can fundraise such restoration endeavors (Fezzi et al., 2023). While the scope of Hawaiian reef ecosystem policy will be examined in the next chapter, it is important to acknowledge how coral's economic significance is becoming increasingly aware as reefs continue to decline.

As more people inhabit both the world and the Hawaiian archipelago, human dependance on the ecosystem services reef ecosystems provide is escalating (Hoegh-Guldberg et al., 2019). As a result, scientists are growing increasingly apprehensive about the shifting relationship between human societies and reef ecosystems amidst their degradation. As more people place increasing expectations on reef ecosystems for food, storm protection, and recreation, the pressure on these delicate ecosystems is mounting (Hoegh-Guldberg et al., 2019). Yet, envisioning a future either devoid of coral reefs or one where societies have adapted to their diminished ecosystem services is difficult (Hoegh-Guldberg et al., 2019). Ultimately, coral reefs are deeply entwined with cultural identity and societal well-being, making their preservation imperative for the sustainability of both natural and human communities.

Chapter 4: The Current State of Reef Ecosystem Conservation

After outlining the economic significance of reef ecosystems, this next chapter assesses the current state of reef ecosystem conservation in Hawaii. After establishing the ecological, cultural, and economic importance of coral reefs, it is pertinent to evaluate the effectiveness of existing conservation policies. This chapter outlines and reviews the existing governmental policies, while addressing any challenges that impede their success. Furthermore, it explores the role of community engagement and the integration of indigenous practices as essential components in successful conservation efforts. Lastly, the chapter highlights the importance of scientific research in informing effective policymaking. By contextualizing the various aspects of Hawaiian reef conservation, this chapter sets the stage for the analysis of effective strategies and proposed reforms in the final chapter.

Conservation Efforts and Initiatives. This subsection delves into the existing pragmatic conservation policies, initiatives, and strategies implemented in and for Hawaii. It outlines governmental regulations, marine protected areas, and collaborations between governmental bodies, NGOs, and local communities. A case study of a successful partnership between multiple entities and the local community is outlined and assessed. Additionally, any recent policy changes or emerging conservation approaches will also be touched upon.

Preemptively, the Department of Aquatic Resources (DAR), is the overarching agency responsible for the nation's reef ecosystems. In Hawaii, a branch within the DAR, named the Hawaii Department Land and Natural Resources (DLNR) oversees reef conditions. Within the DLNR, there is a Coral Reef Working Group, comprised of state and federal partners that manage reefs. Their management goals are listed as the following: (1) protect undamaged coral reefs from pollution, invasive species, marine construction, and marine debris; (2) facilitate productive and sustainable reef fisheries and habitats; and (3) increase public stewardship of coral reef ecosystems (Department of Aquatic Resources, n.d.). The regenerative type of coral mentioned in chapter 2, stony coral, is singled-out in their policy, and deemed "unlawful to take, break or damage." Additionally, the DLNR also mobilizes Marine Managed Areas (MMAs), which are areas designated by administration on behalf of conservation. A subset of MMAs is Marine Protected Areas (MPAs), which emphasize ecosystem protection, enhancement, and sustainability. Categorized areas ultimately may have as few or as many restrictions depending on the site's vulnerability (Department of Aquatic Resources, n.d.).

Indeed, there has also been other federal efforts to address national coral reef decline. Former President Bill Clinton issued the U.S. Coral Reef Task Force, (CRTF) [Executive Order (EO) 13089], during his leadership in 1998 (Bishop et al., 2011). Like the DLNR Coral Reef Working Group, CRTF is also partnership between state and federal agencies, but also includes territorial and commonwealth governments; the scientific community; the private sector; and other related organizations. The primary goal of the CRTF is to cleanup and elevate existing reef ecosystem conservation efforts and management systems (Bishop et al., 2011). Such duties include coral mapping and monitoring, climate change research, reef restoration projects, and promoting sustainable reef practices internationally (Bishop et al., 2011).

Moreover, the National Oceanic and Atmospheric Administration (NOAA) is a co-chair of the CRTF and is mostly responsible for managing U.S. coral reefs and any related research. NOAA also manages three National Marine Sanctuaries (NMS); coral reef resources under the National Marine Sanctuaries Act (NMSA, 16 U.S.C. 1431, et seq). In addition to these oversights, NOAA is also authorized to conduct research in any Marine Protected Areas (MPAs) under EO 13158 (Bishop et al., 2011).

In addition to government agencies, many private entities are addressing the coral crisis. A prominent example is the 501©3 nonprofit organization called Kuleana, which is dedicated solely to Hawaiian coral reef restoration and resiliency, establishing local solutions to systemic problems. Relying on donations for support, Kuleana's top three priorities are: (1) coral restoration; (2) reef monitoring and mapping; and (3) Kuleana education and outreach (Kuleana Coral, n.d.). The nonprofit is headed by a combined team of Native Hawaiians, scientists, and related ocean advocates. Moreover, Kuleana has partnerships with the Hawaii Institute of Marine Biology, NOAA, Hawaii Department of Aquatic Resources, and the for-profit organization, Malama Maunalua (Kuleana Coral, n.d.). The work that Kuleana does for reef restoration is effective and is based off local participation and empowerment. Accordingly, the interactive collaboration between public and private agencies is essential for effective and action-based efforts.

Local environmental restoration projects are excellent ways to enact progressive change on the condition of reefs. Additionally, while these projects can have extraordinary ecological benefits, they also should be regarded for their positive socioeconomic and cultural impacts on local communities (Kittinger et al., 2013). Below is a description and analysis of a case study of an effective restoration project conducted in Maunalua Bay, O'ahu.

The restoration effort in Maunalua bay was yearlong project dedicated to the removal of an invasive algae overtaking the reef, called *A. amadelpha* (Kittinger et al., 2013). In all, the large-scale coral restoration project removed 1.32 million kg of invasive algae from 23 acres of coral reefs. However, the ecosystem services generated simultaneously related to public health and mental well-being, Native Hawaiian cultural empowerment, and recreational benefits for ocean users (Kittinger et al., 2013).

The initiative created more than 60+ jobs, benefitting more than 250 individuals and 81 households. Crew members noted that the wages compared favorably with the current minimum wage in Hawaii and aided household financial stability. They also mentioned the importance of the medical benefits the employment provided. Additionally, other socio-economic benefits included employing Native Hawaiian cultural practices as well as using harvested invasive algae as compost for local farmers (Kittinger et al., 2013). Local farmers are estimated to have saved "hundreds of dollars per month" on compost during the extent of the project (Kittinger et al., 2013). Thus, socioeconomic benefits and ecological success of the project is clear.

Moreover, in terms of health and well-being, over 80% of crew members reported that their work made them physically healthier and more fit, over 97% reported a greater sense of accomplishment, and over 96% stated that the project granted them more personal gratification (Kittinger et al., 2013). Native Hawaiian concepts and practices were shared within the crew by kupuna, such as the history of the bay and its ecosystems, the cultural practices of land-to-sea stewardship, and the importance of the giving-back relationship to the bay (Kittinger et al., 2013). Crew respondents directly connected Native Hawaiian culture to the restoration project, suggesting that these efforts are intertwined with the uplifting of holistic practices. Therefore, the locality of the project clearly fostered a community-orientated environment, producing socio-economic benefits.

Additionally, the Maunalua Bay restoration effort is also a primary example of effective collaboration between governmental nongovernmental industries. The Nature Conservancy (TNC) in partnership with a community organization, Malama Maunalua, and the for-profit restoration firm Pono Pacific, organized the project together. Furthermore, the project was funded by a $3.4 million USD grant from the American Recovery and Reinvestment Act (ARRA) of 1990 (Kittinger et al., 2013). The grant's role in the production of this project cannot be understated. For instance, because of the grant, Malama Maunalua cultivated relationships with greater than 30 partner organizations, businesses, and local, state, and federal agencies (Kittinger et al., 2013).

Additionally, the project engaged with community organizations through educational programs, research and scientific inquiries, community events, and recreational activities, etc. (Kittinger et al., 2013). As a result, over 94% of survey respondents agreed that the project stimulated a greater understanding of the bay's heritage, 82% stated that they have an increased sense of personal ownership for the bay, and 84% testified the project's facilitation of a closer-knit community (Kittinger et al., 2013). Hence, the services community-based restoration projects have to the community are worthwhile.

As for the tourism sector, all ocean users in Maunalua Bay experienced increased water quality conditions. Additionally, surfers made use of cleared channels for access to surf spots and local fishers remarked that the conditions of the bay are comparable to how it looked decades prior, noting a 40% increase in catches (Kittinger et al., 2013). Overall, community-orientated restoration projects prompted by the collaboration between governing and nongoverning agencies are an effective form of holistic conservation policy.

That said, as mentioned at the beginning of this subsection, the federal government is the primary institution responsible for mitigating environmental issues, including reef ecosystems. Ultimately, the federal government has the largest bandwidth and number of resources to address reef degradation. Numerous pieces of national legislation pertain to coral reefs; however, they are often feebly constructed and underenforced (Carson et al., 2022). For instance, the Clean Water Act (CWA) is the most comprehensive piece of federal legislation regarding water pollution and contamination. The criterion of the CWA provides a strong legal basis to reduce point and nonpoint pollution on Hawaiian reefs (Carson et al., 2022). But it is rarely used to protect reefs, as discussed in chapter 3.

In summary, the existing pragmatic conservation policies and initiatives in Hawaii encompass a range of governmental regulations, marine protected areas, and collaborations between governmental bodies, NGOs, and local communities. These efforts, including successful restoration projects like the one in Maunalua Bay, highlight the importance of both public and private sector involvement in reef conservation. Socio-economic benefits, ecological successes, and community engagement are key factors leading to the success of these initiatives.

Limitations and Challenges of Existing Policies. While these existing conservation policies and efforts are commendable, they face significant challenges and threats that hinder their success. This subsection explores the obstacles confronting existing policies and initiatives aimed at reef ecosystem conservation in Hawaii. From regulatory shortcomings to limited enforcement, understanding these challenges is essential for devising strategies to overcome them and pave the way for better conservation measures.

Firstly, while partnerships between public and private entities are essential for successful conservation initiatives, many groups have vastly different agendas pertaining to reef conservation, making collaboration difficult. For example, many industries, lobbyists, and other stakeholders that profit off practices that are damage coral hold significant power in both government and private enterprises. Indeed, the identified barriers prevent effective co-management are: (1) lack of consistent political support and leadership; (2) inadequate funding; (3) vague and difficult co-management strategies (Ayers & Kittinger, 2014).

Furthermore, as mentioned in chapter 3, the environmental impacts of reefs are incredibly complex and intertwined, so addressing a specific conservation issue is often difficult in practice. For example, also mentioned in chapter 3, one of the more prominent threats to coral reefs is nutrient overloading (Fezzi et al., 2023). As a result, reducing the impacts of land-based pollution, such as nutrient fertilizers and agricultural chemicals, as well as erosion of sediment on coral reefs, is now the principal concern among conservationists (Lubchenco & Haugan, 2023). A government plan called the "Sustainable Hawaii Initiative" established a well-intended goal to "effectively manage 30% if nearshore areas" in Hawaii by 2030 (Fezzi et al., 2023). However, to do so effectively, conservationists must consider the potential tradeoffs to the reef ecosystem at large.

For instance, while reef ecosystems are vulnerable to too much sediment, depositional coastal areas, such as mangrove and saltmarsh habitats, require a certain amount of sediment from upstream (Lubchenco & Haugan, 2023). To balance these ecological complexities, effective policy includes regulating the amount of water used upstream, sediment management in reservoirs, and the upkeep of natural environmental hydrological flows that reach the coast unimpeded (Lubchenco & Haugan, 2023). If conservationists were to ignore or overlook the difference in nutrient requirements, they might have enacted a strategy that had unintended consequences to other ecological environments. Therefore, even well-intended conservation strategies must proceed with caution, and use local knowledge to investigate every potential tradeoff.

There are many other occurrences where single sector strategies result in "unforeseen impacts" on other elements within the ecosystem (Ingram et al., 2018). For instance, Marine Resource Management policies (MRM), focus only on one species/demographic, and thus overlook how the entire ecosystem may be affected. As a result, these policies increase the propensity for system collapses and non-ideal management consequences. Related failures in top-down, centralized natural resource governance approaches have prompted a shift toward community-based approaches and co-management (Ayers and Kittinger 2014).

Ultimately, top-down, government oversight often lacks the ecological foresight and about reef ecosystems that is required for successful conservation. Therefore, a major challenge to regulating direct pollution that harm reefs are seen through the context of the state and federal government (Carlson et al., 2022). Many states are hesitant to evoke federal policy because of bureaucratic roadblocks, lack of intersectoral coordination, inadequate resources to identify proper criteria and monitoring programs, and/or the general lack of political will (Carlson et al., 2022).

Additionally, policies often lack the funding or sufficient research necessary to reach the root of their targeted issue. The lack of sufficient information to expedite policy priorities, management budgets, or create impactful conservation finance, downplays the necessity for effective reef conservation. For example, the federal BEACH Act of 2000 facilitated new pathogen control and reporting requirements for nearshore waters. However, the detailed research that Hawaii reef ecosystems need is lacking; studies are too underfunded or surface-level to depict the full extent of coastal water quality problems (Peng & Oleson, 2017).

In conclusion, while commendable, existing conservation policies and efforts in Hawaii have many notable limitations and challenges. These obstacles include regulatory shortcomings, limited enforcement, and complex ecological tradeoffs. Understanding these challenges is crucial for devising strategies to overcome them and pave the way for more effective conservation measures.

Community Engagement and Indigenous Practices. Despite these challenges, community engagement emerges as a promising approach to address reef conservation in Hawaii. By involving communities in the decision-making processes and management efforts, a more holistic and sustainable approach to conservation can be achieved. This sub-section discusses the significance of traditional knowledge, community-based management approaches, and the involvement of local stakeholders in conservation efforts. It highlights successful community-driven initiatives, educational programs, and partnerships that actively engage communities in reef conservation.

Community-centric approaches are being increasingly recognized as pivotal for effective reef conservation strategies. Many communities across Hawaii, numbering up to 50, have already intensified local involvement in marine resource management, with a significant portion implementing co-management policies (Ayer & Kittinger, 2014). This trend highlights a growing convergence between state institutions and local organizations regarding the urgency of addressing the depletion of reef ecosystem services.

Communities encompass a wide range of stakeholders; in the context of Hawaiian reef conservation, they generally include groups of fishers, local leaders, and resource appropriators

(Ayers & Kittinger, 2014). These local stakeholders possess invaluable knowledge and insights into regional conservation goals and needs that may be overlooked in pragmatic policies (Ingram et al., 2018). Indigenous cultures, like Native Hawaiians, have long practiced sustainable reef conservation through traditional ecological knowledge. Western governments are increasingly recognizing the importance of incorporating indigenous knowledge and practices into conservation efforts, leading to the implementation of initiatives such as Community-Based Subsistence Fishing Areas (CBSFAs) (Lubchenco & Haugan, 2023). CBSFAs empower communities to manage nearshore fisheries for subsistence purposes, fostering co-management partnerships between communities and state institutions while empowering Native Hawaiian cultural practices (Ayers & Kittinger, 2014).

Furthermore, there is a growing recognition of indigenous rights and ownership of coastal areas, strengthening their voice in marine governance and conservation (Lubchenco & Haugan, 2023). Despite the barriers mentioned in the previous subsection, community-engaged efforts are gaining popularity as effective means to gather local knowledge, facilitate democratic communication, and build trust between local communities and management (Ingram et al., 2018). These initiatives, often defined as co-management governance, involve shared responsibilities between local communities and state institutions (Ayers & Kittinger, 2014). The strengths of a co-management style of governance are that policies are active rather than strategized, and adaptive rather than linear (Ayer & Kittinger, 2014).

A golden example of effective co-management governance was depicted in the case study of Maunalua Bay in the preceding subsection. While coral reef restoration projects are a relatively new phenomenon, recent literature has focused primarily on its ecological benefits. Moreover, aside from their ecological benefits, these community-based restoration efforts are beneficial to the local economy, maritime industries, and empower Native Hawaiian sociocultural values within their community (Kittinger et al., 2013). Therefore, reef restoration projects that prioritize community-based awareness, involvement, and shared responsibility may provide the foundation for long-term sustainable stewardship programs (Kittinger et al., 2013).

Another successful example of community-based, co-management governance is Ecosystem-Based Management (EBM). EBM, founded by a diverse array of stakeholders including scientists, policymakers, conservationists, and resource managers, emerged as a response to the recognition that traditional management approaches often fail to account for the complexity and interconnectedness of ecosystems and human activities (Ingram et al., 2018). EBM seeks to address this by adopting a “holistic” approach that considers all facets of an ecosystem: social, economic, and ecological (Ingram et al., 2018).

In support of the EBM and all co-management endeavors, the National Oceanographic ad Atmospheric Administration (NOAA) initiated the Integrated Ecosystem Assessment (IEA) Program to facilitate Ecosystem-Based Management (EBM). IEAs employ conceptual ecosystem models (CEMs) to delineate the interplay between social and ecological element within a given system (Ingram et al., 2018). CEMs work by identifying and addressing knowledge gaps and hypothesizing about the relationships between people and their environment, and thus serve as great tools for mobilizing participatory approaches to conservation. Workshops involving scientists, resource managers, and community members foster the exchange of place-based knowledge, identifying regionally specific needs, building trust, and promoting social cohesion (Ingram et al., 2018). Ultimately, these approaches exemplify a model of democratic decision-making that empowers local communities and enhances the effectiveness of conservation efforts.

For example, although ecosystem services are not traditionally accounted for in top-down conservation policies because of regulator's limited understanding of the socio-economic relationship between Hawaii and its reef ecosystems, they are central components within EBM framework (Ingram et al., 2018). Indeed, the importance for EBM is clear, but application has been slow moving because of challenges like limited data, conflicting government agencies, and timeline or financial restraints (Ingram et al., 2018). Despite these challenges, EBM holds promise for promoting sustainable ocean governance and conserving marine biodiversity.

Building upon the holistic approach of Ecosystem-Based-Management (EBM), it's essential to acknowledge that while many governance frameworks prioritize the economic aspects of conservation, other realms should be explored, too. Indeed, community-based efforts empower the non-material benefits of reef conservation. A historical example is UNSECO's 1972 Convention Concerning the Protection of the World's Cultural and Natural Heritage (Lubchenco & Haugan, 2023). The program advocates for ocean governance from the perspective of cultural preservation. By emphasizing the cultural significance of marine environments, UNSECO, and any related imitative, empower marginalized coastal communities in the policymaking process (Lubchenco & Haugan, 202). This underscores the importance of integrating cultural values into conservation strategies, as evidenced by the outcomes of community-based conservation workshops where participants exhibited heightened awareness of ecosystem dynamics and management strategies (Ingram et al., 2018).

However, the success of community-based approaches hinges on meticulous planning and execution. Co-management groups must navigate various tasks, such as defining the affected community, implementing effective stakeholder engagement strategies, and synthesizing different stakeholder perspectives (Ayers & Kittinger et al., 2014). Failure to unify stakeholders around a common goal can jeopardize the effectiveness of conservation efforts (Ayers & Kittinger et al., 2014). Thus, community-based approaches serve as a litmus test for the relationship between governing institutions and the communities they serve. They highlight the need for collaborative, inclusive, and professionally executed initiatives.

On another note, empirical data underscores substantial public endorsement for reef conservation endeavors, extending beyond coastal communities, to encompass a considerable proportion of the mainland population (NOAA, 2022). These findings illustrate a willingness among individuals to invest financially in the restoration and preservation of reef ecosystems. For instance, a survey found that 92.5% of the mainland population expressed readiness to contribute up to $407.29 towards achieving the most significant possible reef enhancement, while an overwhelming 97% indicated a willingness to allocate $109.82 for the same level of improvement (NOAA, 2022). This robust support from the broader population highlights the widespread recognition of the importance of coral reef conservation. Moreover, it illustrates the potential for leveraging public backing to propel community-based policy initiative’s forward.

Ultimately, in this subsection, the major thematic points revolve around the role of the community in effective reef conservation. These approaches emphasize the importance of local involvement and collaboration between state and federal institutions and local communities. Overall, community-centric approaches represent a promising avenue for addressing the depletion of ecosystem services provided by coral reefs and mitigating the impacts of reef degradation.

Chapter 5: Policy Recommendations for Hawaiian Reef Ecosystems

In the previous chapter we gathered a vast understanding about the current policies and conservation efforts Hawaii and related enterprises have evoked and explored their effectivity.

Now, it is time to make knowledgeable and meaningful suggestions to reef ecosystem conservation strategies.

Climate Change Adaptation Strategies. This subsection delves into the pivotal role of adaptive policy frameworks in safeguarding the sustainability of Hawaiian reef ecosystems. By examining the interplay between policy innovation and ecological resilience, I unravel the mechanisms essential for preserving coral reefs for future generations.

Preemptively, adaptive conservation policies differ significantly from traditional approaches, particularly in the context of Hawaiian coral reefs, due to their dynamic, flexible, and responsive nature. Traditional conservation policies often rely on static regulations and fixed management plans, which often struggle to address rapid changes and uncertainties faced by reef ecosystems in the wake of climate change and human impacts (Gillson et al., 2019). Adaptive policies, however, emphasize flexibility, learning, and iterative adjustments (Gillson et al., 2019). They acknowledge the complexity of ecological systems and can evolve with changing circumstances. Ultimately, adaptive approaches are crucial in dealing with the uncertainties and multifaceted challenges that Hawaiian reefs face, providing a more nuanced and responsive way to safeguard coral (Gillson et al., 2019).

The Hawaii Coral Reef Strategy 2030 report, published by the Department of Land and Natural Resources Division of Aquatic Resources, outlines adaptive strategies for Hawaiian coral reef conservation, emphasizing the importance of collaboration, innovation, and resilience-building. While the report is a government publication, it underscores the importance of holistic, science-based approaches and collaborative efforts to sustainably manage and conserve Hawaiian coral reefs. Thus, I align with its suggestions, and elaborate on the more notable ones below.

Firstly, the report advocates to enhance reef resilience through habitat restoration and protection. Particularly, restoration efforts include coral gardening, where corals are grown into nurseries and then transplanted onto degraded reefs to promote their recovery (DAR, 2020). Additionally, establishing marine protected areas (MPAs) and implementing zoning regulations can help safeguard critical reef habitats from destructive activities such as overfishing, pollution, and coastal development (DAR, 2020).

Next, the report discusses the implementation of sustainable fishing practices, which I believe to be a key component of reef conservation. Sustainable fishing practices are essential for maintaining healthy reef ecosystems and supporting the long-term viability of fish populations. This adaptive strategy involves measures such as size and catch limits, seasonal closures, and gear restrictions to prevent overexploitation of fish stocks (DAR, 2020). Moreover, promoting sustainable fishing preserves biodiversity and supports the livelihoods of local fishing communities (DAR, 2020).

Finally, the Hawaii Reef Conservation Strategy 2030 report supports fighting the overarching issues of climate change and ocean acidification through adaptive conservation strategies (DAR, 2020). As established, rising sea temperatures, ocean acidification, and more frequent and severe storms contribute to coral bleaching, disease outbreaks, and habitat degradation. Successful adaptive strategies involve implementing measures such as coral reef monitoring and early warning systems, heat-tolerant coral breeding programs, and ecosystem-based approaches to climate resilience (DAR, 2020). By proactively addressing the impacts of climate change, adaptive strategies can minimize the extent of damage caused by changing environmental conditions.

However, like other types of conservation policies, adaptive strategies have limitations. That said, most of the barriers to the implementation of Adaptive Management (AM) in conservation efforts are experienced in other types of efforts as well (Gillson et al., 2019). Common obstacles include risk-averse behavior due to uncertainty in outcomes, difficulties in integrating diverse stakeholder perspectives, and contrasting scientific conceptions amongst stakeholders. Ultimately, in all facets, group work is difficult. Moreover, as adaptive strategies typically involve a democratic approach to problem-solving, the need for multiple cycles of management intervention presents practical, financial, and logistical constraints (Gillson et al., 2019).

Additionally, assessing the success of AM poses another challenge as conventional metrics may not capture the uncertain outcomes inherent in complex conservation programs. To address these challenges, an alternative approach called Ecosystem-Based Conservation (EBC) offers a systemic review-based method to compile evidence on conservation management outcomes (Gillson et al., 2019). Thus, EBC has the capability to predict the effects of management actions more effectively and efficiently, facilitating better-informed decision-making in conservation practices (Gillson et al., 2019).

Overall, the exploration of adaptive policy frameworks in Hawaiian reef conservation highlights the importance of flexibility, collaboration, and innovation in addressing the multifaceted challenges faced by coral reef ecosystems. While the Hawaiian Coral Reef Strategy 2030 report outlines promising adaptive strategies, the limitations inherent in such strategies must be accounted for. Despite these challenges, approaches like Ecosystem-Based Conservation offer promising methods to address the limitations of AM. Nonetheless, by embracing adaptive strategies, there is hope for sustaining and protecting Hawaiian coral reefs for future generations.

Successful Top-Down Conservation Strategies. The preservation of coral reefs demands a multifaceted approach that extends beyond local initiatives, necessitating the integration of national policies to fortify conservation efforts. This section delves into the strategic utilization of key national policies, elucidating their pivotal role in bolstering adaptive conservation strategies aimed at safeguarding Hawaiian coral reef ecosystems. Through an exploration of legislative frameworks such as the Clean Water Act (CWA), the Safe Drinking Water Act (SDWA), the National Flood Insurance Program (NFIP), and the Coastal Zone Management Act (CZMA), this discussion unveils the mechanisms through which top-down approaches can be harnessed to mitigate the adverse impacts of human activities and climate change on reef ecosystems.

Leveraging current national policy is essential in fortifying efforts to safeguard reefs. For example, the Clean Water Act stands as a pivotal legal instrument, offering a framework to curb the influx of harmful chemicals and pollutants into water bodies, thereby mitigating the downstream impact on nearby reef ecosystems (Carlson et al., 2022). Additionally, the authority bestowed upon states to establish their own Water Quality Standards, subject to EPA approval, presents a prime opportunity for tailored conservation measures. In this vein, the State of Hawaii can take proactive steps to limit the discharge of land-based pollutants by instituting coral-specific threshold values (Carlson et al., 2022). By aligning these standards with the unique needs of reef ecosystems, Hawaii can bolster its adaptive conservation strategy, ensuring targeted protection for vulnerable coral habitats. Furthermore, implementing robust monitoring and enforcement mechanisms can hold accountable any entity exceeding these thresholds, thereby reinforcing the integrity of reef preservation efforts through legal recourse.

Additionally, the Safe Drinking Water Act (SDWA) can contribute to coral reef protection indirectly, by regulating pollution levels and saline intrusion in aquifers that supply both drinking water and coastal ecosystems (Carlson et al., 2022). By leveraging data on water quality and aquifer connectivity, coral conservationists can anticipate changes in coastal water conditions and identify potential threats to reefs. Moreover, partnerships between water utilities and conservation advocates can facilitate pollution control measures that benefit both human health and reef resilience (Carlson et al., 2022).

Moreover, coral reef conservation can be integrated in disaster management programs, such as the National Flood Insurance Program (NFIP) administered by FEMA (Carlson et al., 2022). By recognizing coral reefs as natural infrastructure that reduces wave energy and protects coastal communities, FEMA could incentivize coral conservation through reduced flood insurance rates and funding for shoreline stabilization projects (Carlson et al., 2022).

Additionally, the Coastal Zone Management Act (CZMA) can be mobilized to address nonpoint source pollution in Hawaiian reef ecosystems (Carlson et al., 2022). This legislation employs a multifaceted approach to incentivize the mitigation of nonpoint pollution. States with federally approved Coastal Zone Management Programs can access federal grants under CZMA Section 396, specifically designated for the preservation and restoration of priority coastal areas such as coral reefs (Carlson et al., 2022). Moreover, the Coastal Zone Act Reauthorization Amendments of 1990 require coastal zone management programs to develop and implement Coastal Nonpoint Pollution Control Programs, failure of which may result in the loss of federal funding under the CZMA Section 306 and the Clean Water Act (CWA) Section 319 (Carlson et al., 2022). Therefore, these programs can be effective to target sources of pollution like agriculture and urban runoff, that are presently contaminating reefs.

Furthermore, the significant influx of tourists and the consequent environmental footprint they leave behind prompt a critical examination of policies directed specifically at visitors rather than residents. One such approach involves the implementation of green taxes and access fees, which are solely borne by tourists (Fezzi et al., 2023). This strategy not only helps mitigate the adverse effects of tourism but also avoids exacerbating the economic disparities faced by local communities (Fezzi et al., 2023). By designating these fees as retribution for the environmental strain caused by tourism, policymakers can align economic incentives with conservation goals. This ensures that those who directly contribute to reef degradation bear a proportionate share of the responsibility for its preservation, fostering a more equitable distribution of environmental costs. Moreover, earmarking these funds for reef restoration and conservation initiatives can further enhance the sustainability of tourism while simultaneously supporting the protection of reef ecosystems (Fezzi et al., 2023).

In conclusion, the integration of top-down conservation strategies, guided by national policy frameworks, presents a multifaceted approach to safeguarding coral reef ecosystems. By leveraging legal instruments like the Clean Water Act and Safe Drinking Water Act, Hawaii can enact tailored conservation measures to mitigate the influx of pollutants and enhance reef resilience. Additionally, policies targeting tourists, such as green taxes and access fees, provide a mechanism to ensure equitable distribution of environmental costs and support reef restoration initiatives, ultimately fostering the sustainability of tourism while preserving reef ecosystems.

Successful From the Ground-Up Conservation Strategies. As anthropogenic stressors and global climate change continue to threaten reef health, the efficacy of conservation efforts hinges on strategic partnerships between local communities and federal or secular entities. This section explores successful bottom-up conservation strategies that harness the power of grassroots initiatives to address direct anthropogenic impacts and mitigate the challenges posed by climate change and ocean acidification. Through a comprehensive analysis of locally manageable pressures and non-locally manageable pressures on reefs, this discussion aims to delineate the roles and responsibilities of different stakeholders in optimizing conservation efforts and enhancing the resilience of coral ecosystems.

Because the causes of reef ecosystem degradation are categorized as anthropogenic stressors and global climate change, I firmly believe that effective conservation efforts will be a combination of local and federal/secular partnerships with the community (Ingram et al., 2018). Local endeavors are well-suited to address direct anthropogenic impacts, while broader government interventions can tackle challenges related to climate change and ocean acidification.

Particularly, ground-up initiatives in Hawaii target direct anthropogenic impacts of pollution on reefs through community engagement, local regulations, and habitat restoration (Ingram, et al., 2018). These efforts involve raising awareness among residents, establishing local regulations for pollution control, and implementing habitat restoration projects. Additionally, promoting sustainable practices and fostering partnerships among community organizations, government agencies, and non-profits are other key strategies of successful ground up initiatives (Ingram, et al., 2018). By empowering local communities and fostering collaboration, these initiatives aim to mitigate pollution and enhance the resilience of Hawaiian reefs.

Below is a comprehensive table delineating all the major identified pressures on reefs, distinguishing between “Locally Manageable Pressures” between “Non-locally Manageable Pressures.” The visual aid serves to clarify which issues are best addressed at the local level and which necessitate overarching governmental action. By strategically allocating responsibilities, we can optimize conservation efforts and maximize the resilience of reef ecosystems in the face of multifaceted challenges.

Figure 6. Locally Manageable Pressures v. Non-locally Manageable Pressures (Ingram et al., 2018).

Ecosystem Pressures → Ecosystem State Components	Corals	Reef Fishes	Pelagic Fishes	Water Quality	Cumulative Effect Strength
Extraction of Fish	5	5	5	3	18
Ocean Temperature	5	3	5	4	17
Nutrient Input	5	4	3	5	17
Habitat Destruction	5	5	4	3	17
Extreme Weather Events	4	3	2	5	14
Pesticides	5	0	3	5	13
Sediments	3	4	2	3	12
Ocean pH	2	2	4	3	11
Marine Debris	4	1	3	3	11
Freshwater Input	1	2	2	5	10
Human Disturbance to Animals	5	1	3	1	10
Hydrocarbons	3	0	1	5	9
Algal Overgrowth	5	2	1	0	8
Non-native Invasive Species	3	1	1	3	8
Coral Disease	5	1	1	0	7
Pathogens	0	1	1	5	7
Flooding	3	3	0	0	6
Pharmaceuticals	0	0	1	5	6
Wave Forcing	5	0	0	0	5
Other Contaminants	1	0	1	3	5
Wind	2	0	2	0	4
Sea Level Rise	1	0	0	2	3
Precipitation	0	0	0	2	2
Lava	0	0	0	1	1
Locally Manageable Pressures	20	15	19	19	TOTAL PRESSURES
Non-locally Manageable Pressures	72	38	45	66	CUMULATIVE IMPACT

However, in addition to addressing direct pollution, local initiatives possess significant potential to mitigate the impacts of climate change on coral reefs. For instance, Hawaii is actively implementing statewide plans aimed at increasing coral reef resilience in the face of ocean warming (Ingram et al., 2018). These plans often involve measures such as marine protected areas, habitat restoration projects, and community engagement efforts to reduce stressors on coral ecosystems and promote their recovery.

Moreover, Hawaii can leverage local approaches to address its pervasive overfishing issue, which poses a significant threat to reef health (Ingram et al., 2018). By implementing sustainable fisheries management practices, such as size and catch limits, gear restrictions, and marine protected areas, local authorities can help restore fish populations and alleviate pressure on coral reef ecosystems. Community-based initiatives that involve fishers in decision-making processes and promote responsible fishing practices can also play a large role in fostering long-term conservation efforts (Ingram et al., 2018).

Furthermore, in my opinion, colleges and universities in Hawaii offer exceptional opportunities for students to engage in scientific research focused on reef ecosystems. These schools provide access to cutting-edge facilities, expert faculty members, and diverse marine environments, allowing students to gain formative experiences in studying coral reefs. Through fieldwork, laboratory experiments, and data analysis, students can contribute to the understanding of reef dynamics, biodiversity, and resilience.

The research conducted by students has the potential to inform conservation efforts not only locally but also on a broader scale. By applying their findings to real-world challenges, such as declining coral cover, students can contribute to the development of effective management strategies and policy decisions. Additionally, the collaborative nature of scientific research often involves partnerships between academia, government agencies, and community organizations, fostering interdisciplinary approaches to reef conservation.

In conclusion, successful coral reef conservation requires a bottom-up approach that harnesses the collective efforts of local communities, governmental entities, and academic institutions. By leveraging grassroots initiatives and scientific expertise, stakeholders can address both direct anthropogenic impacts and the complex challenges posed by climate change and ocean acidification. Strategic partnerships and interdisciplinary collaboration are essential in optimizing conservation efforts and enhancing the resilience of coral ecosystems for future generations.

A Carbon Tax. As climate change impacts, such as sea level rise and coral bleaching, continue to threaten Hawaii's coral reefs, the urgency to reduce greenhouse gas emissions becomes increasingly evident. Carbon pricing emerges as a promising strategy to mitigate these impacts by incentivizing emission reductions across various sectors (Coffman et al., 2021). However, the implementation of a carbon tax raises concerns about potential tradeoffs, particularly regarding its impact on lower-income individuals. In navigating these complexities, policymakers must carefully consider the design and implementation of carbon pricing to ensure equitable outcomes and effective reef conservation efforts (Coffman et al., 2021). This subsection explores the positives and negatives of implementing a carbon tax, ultimately for the greater purpose of preserving reef ecosystems.

The "Carbon Pricing Assessment for Hawaiʻi" report, commissioned by the State Energy Office, provides a comprehensive analysis of the economic and environmental implications of implementing carbon pricing mechanisms in the state (Coffman et al., 2021). Carbon pricing is increasingly recognized as a crucial tool in addressing climate change by internalizing the costs of carbon emissions and incentivizing the transition to cleaner, low-carbon technologies.

One of the key findings of the report is the potential effectiveness of carbon pricing in reducing greenhouse gas emissions. By placing a price on carbon emissions, either through a carbon tax or a cap-and-trade system, businesses and individuals are incentivized to reduce their carbon footprint (Coffman et al., 2021). This can lead to significant reductions in emissions across various sectors, including transportation, energy production, and industry (Coffman et al., 2021). In Hawaii, where the impacts of climate change, such as sea level rise and coral bleaching, are already being felt, reducing emissions is critical to protecting the state's fragile ecosystems, including coral reefs.

Moreover, the report evaluates the economic impacts of carbon pricing, considering factors such as revenue generation, distributional effects, and impacts on industry competitiveness (Coffman et al., 2021). While carbon pricing may lead to higher costs for fossil fuel-intensive industries initially, it also presents opportunities for revenue generation that can be reinvested in clean energy infrastructure, environmental conservation efforts, and economic diversification. Additionally, by internalizing the social cost of carbon, carbon pricing can spur innovation and investment in renewable energy technologies, creating new job opportunities and driving economic growth in the long term (Coffman et al., 2021).

In the context of Hawaiian reef ecosystem degradation, carbon pricing emerges as a promising strategy to mitigate the impacts of climate change on coral reefs. By reducing greenhouse gas emissions, carbon pricing helps alleviate ocean acidification and coral bleaching, which are exacerbated by rising sea temperatures and carbon dioxide levels. Moreover, protecting coral reefs is not only crucial for biodiversity conservation but also for supporting the state's tourism industry, coastal protection, and cultural heritage.

However, when examining the impacts of implementing a carbon tax, it becomes evident that there are many tradeoffs, particularly regarding how it may disproportionately affect lower-income individuals (Eagle, 2019). Higher taxes on carbon emissions could translate to higher electricity bills, increased prices for gasoline and public transportation, and potentially elevate costs for consumer goods, all of which may burden households with lower incomes to a greater extent (Eagle, 2019).

Moreover, the tradeoffs associated with implementing a carbon tax in Hawaii extend to the delicate balance between environmental protection and economic sustainability, especially concerning reef ecosystems. On one hand, a carbon tax could serve as a significant tool in reducing greenhouse gas emissions, thereby mitigating the impacts of climate change on coral reefs. By incentivizing individuals and businesses to reduce their carbon footprint, such a policy could contribute to the preservation of reef ecosystems by addressing one of the primary drivers of their degradation (Coffman et al., 2021).

Additionally, there are concerns about the potential economic repercussions of a carbon tax, particularly for industries heavily reliant on fossil fuels, such as transportation, tourism, and energy production (Eagle, 2019). Higher costs associated with carbon emissions could lead to increased operational expenses for these industries, potentially impacting employment rates, business profitability, and overall economic growth in Hawaii (Eagle, 2019). Furthermore, there is a risk of carbon leakage, where businesses relocate to areas with less stringent carbon pricing policies, potentially exacerbating environmental degradation elsewhere (Eagle, 2019).

In navigating these complexities, policymakers must carefully consider the design and implementation of a carbon tax to ensure equitable outcomes and effective reef conservation efforts. This may involve implementing measures to mitigate the potential regressive impacts of carbon pricing on lower-income households, such as targeted rebates or subsidies (Coffman et al., 2021). Additionally, policymakers should explore complementary policies and initiatives aimed at fostering renewable energy development, promoting energy efficiency, and supporting sustainable practices in key industries to facilitate a smooth transition towards a low-carbon economy while safeguarding the health of Hawaii's reef ecosystems (Eagle, 2019).

Ultimately, I agree that carbon pricing poses as a viable strategy for combating reef ecosystem degradation and addressing the broader challenges of climate change in the state (Coffman et al., 2021). By incentivizing emission reductions and promoting the transition to cleaner, low-carbon technologies, carbon pricing can help mitigate the primary drivers of reef degradation, such as ocean acidification and coral bleaching.

However, the implementation of a carbon tax must be approached with careful consideration of its potential tradeoffs, particularly concerning its impact on lower-income individuals and fossil fuel-dependent industries (Eagle, 2019). Policymakers must prioritize equitable outcomes and ensure that measures are in place to mitigate any adverse effects on vulnerable communities. Additionally, complementary policies and initiatives aimed at fostering renewable energy development and promoting sustainable practices in key industries can further support reef conservation efforts. Ultimately, a well-designed and effectively implemented carbon tax can contribute to the preservation of Hawaiian coral reefs for future generations while advancing the broader goals of climate action and sustainable development.

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