TRANSLATING RESILIENCE-BASED MANAGEMENT FROM THEORY TO PRACTICE IN HAWAIʻI

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Anne Elizabeth Chung

Dissertation Committee:

Cynthia Hunter (chairperson)
Mark Hixon
Robert Toonen
Zac Forsman
Michael Hamnett

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ABSTRACT

The effects of climate change are beginning to be observed more frequently worldwide, including bleaching events, or the loss of mutualistic dinoflagellates called zooxanthellae, which can result in extensive mortality. Coral mortality resulting from bleaching events can trigger regime shifts, depending on a reef's resilience, meaning the ability to both resist and recover from disturbances. Recently, managers have been working under a new paradigm to promote resilience: resilience-based management. However, there is a gap in our understanding of how to translate resilience-based management at a local scale considering site-specific ecological characteristics. In Hawai'i, extensive mortality due to back-to-back bleaching events has urged managers to seek resilience-building strategies. The goals of this study are to 1) better understand the intervention options available to coral reef managers and develop a way to prioritize resilience-based interventions, 2) focusing on a top-ranked intervention, tailor the intervention to be applied in the main Hawaiian Islands, and 3) investigate where resilience-based strategies could be implemented to provide the best chance of success.

Through a systematic literature review, twelve potential management interventions to promote coral resilience were scored and ranked, revealing Herbivore Management Areas (HMAs) as the top-ranked intervention in Hawai'i. Although HMAs are a highly recommended intervention and have been shown to be effective, there is currently a lack of design guidance on how to implement a network of HMAs addressing local traits. I developed a set of design principles specifically for HMAs incorporating Hawai'i-specific considerations of habitats, critical areas, connectivity, climate, and local threats. Lastly, I applied the design principles to identify areas within West Hawai'i and Maui Nui where HMAs would be most effective. Using Marxan, I identified multiple resilience hotspots, some of which overlap with the existing network of Marine Managed Areas (MMAs).

These results demonstrate a method to translate resilience-based management concepts from theory to practical and site-specific guidance that is actionable by Hawai'i's coral reef managers. Since the global bleaching event 2013-2017, managers in multiple locations have pursued collaborative initiatives to apply resilience-based management and change their strategy to promote recovery. Despite an ever-increasing threat of frequent and severe bleaching events in

Hawaiʻi and around the world, this study provides actions that could be taken at a local scale to maintain and re-build herbivory in priority reef sites.

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CHAPTER 1. INTRODUCTION

Coral Reef Resilience

The effects of climate change are beginning to be observed more frequently worldwide. In coral reef ecosystems, climate change has several effects, including increased ocean acidification (Anthony et al. 2011), storm intensity (Emanuel 2013), and frequent and severe bleaching events (van Hooidonk et al. 2016). Coral bleaching, or the loss of mutualistic dinoflagellates called zooxanthellae, can be triggered by a number of factors, namely high temperature anomalies associated with a changing climate. Bleaching events cause corals to become weakened, and if conditions persist, can result in extensive mortality. A bleaching event is a type of ecological disturbance, or change in environmental condition, which can result in regime shifts from a coral to a macroalgal dominated ecosystem (Done 1992; Scheffer et al. 2001). Coral mortality caused by coral bleaching events can lead to systematic changes in the structure of tropical ecosystems (Bellwood et al. 2006; Hughes et al. 2007; Graham et al. 2013; Ainsworth and Mumby 2015).

A regime shift can be temporary or permanent based on the resilience of the ecosystem. Resilience refers to the ability of an ecosystem to “absorb or withstand perturbations such that the system remains within the same regime, maintaining its structure and functions” (Holling 1973; Walker et al. 2004). Resilience has two main components: the ability to resist, or prevent change from disturbances and recovery, or the ability to regain function following a disturbance (Nyström et al. 2008). A lack of resilience can increase a coral reef’s risk of reaching a tipping point, or a point at which recovery to its original state will be almost impossible (Ateweberhan et al. 2013; N. A. Graham et al. 2013; Selkoe et al. 2015; Hoegh-Guldberg et al. 2017).

A New Management Paradigm

In recent years, a new coral reef management paradigm has emerged which aims to increase resilience to disturbance including bleaching events. Resilience-based management presents a strategy to target the fundamental ecosystem functions and processes that may increase both resistance and recovery (Chapin et al. 2009; Anthony et al. 2015). This new paradigm is a departure from conventional management, which emphasizes the preservation of a singular, optimal stable state, to a focus on absorbing disturbance and retaining function, structure, and feedbacks (Walker et al. 2004). To accomplish this, managers are recommended to identify resilience 'levers' or interventions that will directly lessen pressures that reduce ecosystem resilience (Anthony et al. 2015).

Making Resilience-based Management Operational

Despite the emergence of resilience-based management theory, practitioners struggle to operationalize its concepts due to competing definitions, lack of operational examples of adaptation principles, guidance on the selection and integration of science recommendations, implementation of management strategies supporting resilience, and the pairing of science recommendations with ecological evidence (Hughes 2003; Heller and Zavaleta 2009). Applications of resilience concepts to date have mainly focused on identifying ways to evaluate and map indicators of existing resilience (Maynard et al. 2010) and incorporate these indicators into monitoring activities (Green et al. 2009; Lam et al. 2017; Ford et al. 2018).

Interventions following a global mass bleaching event in 2008 were limited and consisted of decreasing direct human damage from anchors and trampling (Tun et al. 2010; Yeemin et al. 2012; Beeden et al. 2014) and coral transplantation experiments (Gomez et al. 2014). These efforts are examples of reef resilience being the explicit motivation for local-scale management; however, resulting ecological impacts from these efforts are unclear. Several questions remain as to how managers can promote ecological resilience and implement effective interventions (Graham et al. 2015; Dudney et al. 2018).

The Need for Resilience-based Management in Hawai'i

Deemed the third global mass bleaching event to date, high sea surface temperatures triggered mass bleaching events in every ocean basin between 2014 and 2017 (NOAA 2015). High temperatures across the Hawaiian archipelago resulted in consecutive bleaching events in 2014 and 2015 and extensive mortality. Along the Kona coast of Hawai'i Island, an average of 50% mortality was reported at regularly visited monitoring sites (Kramer et al. 2016). The event spurred urgency to explore how resilience-based management could be applied in Hawai'i to promote recovery from the bleaching event as well as long-term resilience to future climate impacts.

Dissertation Goals

This dissertation addresses questions about the application of resilience-based management and specifically how the concept could be applied in Hawai‘i to promote recovery and improve long-term resilience. The goals of this study are to 1) better understand the intervention options available to coral reef managers and develop a way to prioritize resilience-based interventions, 2) focusing on a top-ranked intervention, tailor the intervention to be applied in the main Hawaiian Islands, and 3) investigate where resilience-based strategies could be implemented to provide the best chance of success.

This study focused on a case study of applying resilience-based management in Hawai‘i; however, the process could be replicated in other coral reef regions and therefore has applicability globally.

Dissertation Outline

In Chapter 2, I discuss a method to score and rank intervention options to promote coral reef resilience using a systematic review of scientific literature. The scoring system involved a method to weight papers based on their scale, location, and type of data collected and was developed to target evidence relevant to coral reef management in Hawai‘i.

In Chapter 3, I tailor the use of herbivore management areas, a top-ranked intervention highlighted in Chapter 2, for use in Hawai‘i through the development of design principles. This chapter used guidance from networks of no-take areas and explored how the ecological context of the main Hawaiian Islands would drive the creation of a network of herbivore management areas as a resilience-building tool.

In Chapter 4, I apply the design principles from Chapter 3 using Marxan, a spatial design ArcGIS tool, to identify areas around West Hawai‘i and Maui Nui where herbivore management areas may have the greatest chance of building resilience. This chapter overlays these results with the existing network of marine managed areas along the West Hawai‘i coastline and discusses potential next steps for managers.

In Chapter 5, I draw conclusions from the preceding chapters as well as discuss potential future directions for resilience-based management in Hawai‘i and globally.

References

Ainsworth, C., and P. Mumby. 2015. "Coral-Algal Phase Shifts Alter Fish Communities and Reduce Fisheries Production." *Global Change Biology* 21 (1): 165–72. https://doi.org/10.1111/gcb.12667.

Anthony, K., J. Maynard, G. Diaz-Pulido, P. Mumby, P. Marshall, L. Cao, and O. Hoegh-Guldberg. 2011. "Ocean Acidification and Warming Will Lower Coral Reef Resilience: CO^2 and Coral Reef Resilience." *Global Change Biology* 17 (5): 1798–1808. https://doi.org/10.1111/j.1365-2486.2010.02364.x.

Anthony, K., P. Marshall, A. Abdulla, R. Beeden, C. Bergh, R. Black, M. Eakin, et al. 2015. "Operationalizing Resilience for Adaptive Coral Reef Management under Global Environmental Change." *Global Change Biology* 21 (1): 48–61. https://doi.org/10.1111/gcb.12700.

Ateweberhan, M., D. Feary, S. Keshavmurthy, A. Chen, M. Schleyer, and C. Sheppard. 2013. "Climate Change Impacts on Coral Reefs: Synergies with Local Effects, Possibilities for Acclimation, and Management Implications." *Marine Pollution Bulletin* 74 (2): 526–39. https://doi.org/10.1016/j.marpolbul.2013.06.011.

Beeden, R., J. Maynard, J. Johnson, J. Dryden, S. Kininmonth, and P. Marshall. 2014. "No-Anchoring Areas Reduce Coral Damage in an Effort to Build Resilience in Keppel Bay, Southern Great Barrier Reef." *Australasian Journal of Environmental Management* 21 (3): 311–19. https://doi.org/10.1080/14486563.2014.881307.

Bellwood, D., A. Hoey, J. Ackerman, and M. Depczynski. 2006. "Coral Bleaching, Reef Fish Community Phase Shifts and the Resilience of Coral Reefs." *Global Change Biology* 12 (9): 1587–94. https://doi.org/10.1111/j.1365-2486.2006.01204.x.

Chapin, S. and G. Kofinas. 2009. "A Framework for Understanding Change." *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*. Pages 3-28. New York, New York: *Springer*.

Done, T. 1992. "Phase Shifts in Coral Reef Communities and Their Ecological Significance." Hydrobiologia.

Dudney, J., R. Hobbs, R. Heilmayr, J. Battles, and K. Suding. 2018. "Navigating Novelty and Risk in Resilience Management." *Trends in Ecology & Evolution*, September. https://doi.org/10.1016/j.tree.2018.08.012.

Emanuel, K. 2013. "Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity over the 21st Century." *Proceedings of the National Academy of Sciences* 110 (30): 12219–24. https://doi.org/10.1073/pnas.1301293110.

Ford, A., A. Eich, R. McAndrews, S. Mangubhai, M. Nugues, S. Bejarano, B. Moore, C. Rico, C. Wild, and S. Ferse. 2018. "Evaluation of Coral Reef Management Effectiveness Using Conventional versus Resilience-Based Metrics." *Ecological Indicators* 85 (February): 308–17. https://doi.org/10.1016/j.ecolind.2017.10.002.

Gomez, E., P. Cabaitan, H. Yap, and R. Dizon. 2014. "Can Coral Cover Be Restored in the Absence of Natural Recruitment and Reef Recovery?: Restoring Coral Cover." *Restoration Ecology* 22 (2): 142–50. https://doi.org/10.1111/rec.12041.

Graham, N., S. Jennings, M. MacNeil, D. Mouillot, and S. Wilson. 2015. "Predicting Climate-Driven Regime Shifts versus Rebound Potential in Coral Reefs." *Nature* 518 (7537): 1–17. https://doi.org/10.1038/nature14140.

Graham, N., D. Bellwood, J. Cinner, T. Hughes, A. Norström, and M. Nyström. 2013. "Managing Resilience to Reverse Phase Shifts in Coral Reefs." *Frontiers in Ecology and the Environment* 11 (10): 541–48. https://doi.org/10.1890/120305.

Green, A., D. Bellwood, and International Union for Conservation of Nature. 2009. *Monitoring Functional Groups of Herbivorous Reef Fishes as Indicators of Coral Reef Resilience: A Practical Guide for Coral Reef Managers in the Asia Pacific Region*. http://docs.lib.noaa.gov/noaa_documents/CoRIS/IUCN_herbivorous_reef-fishes_2009.pdf.

Heller, N., and E. Zavaleta. 2009. "Biodiversity Management in the Face of Climate Change: A Review of 22 Years of Recommendations." *Biological Conservation* 142 (1): 14–32. https://doi.org/10.1016/j.biocon.2008.10.006.

Hoegh-Guldberg, O., E. Poloczanska, W. Skirving, and S. Dove. 2017. "Coral Reef Ecosystems under Climate Change and Ocean Acidification." *Frontiers in Marine Science* 4 (May). https://doi.org/10.3389/fmars.2017.00158.

Holling, C. 1973. "Resilience and the Stability of Ecological Systems."

Hooidonk, R. van, J. Maynard, J. Tamelander, J. Gove, G. Ahmadia, L. Raymundo, G. Williams, S. Heron, and S. Planes. 2016. "Local-Scale Projections of Coral Reef Futures and Implications of the Paris Agreement." *Scientific Reports* 6 (December): 39666. https://doi.org/10.1038/srep39666.

Hughes, T. 2003. "Climate Change, Human Impacts, and the Resilience of Coral Reefs." *Science* 301 (5635): 929–33. https://doi.org/10.1126/science.1085046.

Hughes, T., M. Rodrigues, D. Bellwood, D. Ceccarelli, O. Hoegh-Guldberg, L. McCook, N. Moltschaniwskyj, M. Pratchett, R. Steneck, and B. Willis. 2007. "Phase Shifts, Herbivory, and the Resilience of Coral Reefs to Climate Change." *Current Biology* 17 (4): 360–65. https://doi.org/10.1016/j.cub.2006.12.049.

Kramer, K., S. Cotton, M. Lamson, and W. Walsh. 2016. "Coral Bleaching: Monitoring, Management Responses and Resilience." http://coralreefs.org/wp-content/uploads/2016/12/Session-30-Kramer_etal_ICRS_Final-1-2.pdf.

Lam, V., C. Doropoulos, and P. Mumby. 2017. "The Influence of Resilience-Based Management on Coral Reef Monitoring: A Systematic Review." Edited by Chaolun Allen Chen. *PLOS ONE* 12 (2): e0172064. https://doi.org/10.1371/journal.pone.0172064.

Maynard, J., P. Marshall, J. Johnson, and S. Harman. 2010. "Building Resilience into Practical Conservation: Identifying Local Management Responses to Global Climate Change in the Southern Great Barrier Reef." *Coral Reefs* 29 (2): 381–91. https://doi.org/10.1007/s00338-010-0603-8.

National Oceanic and Atmospheric Administration (NOAA). 2015. NOAA Declares Third Ever Global Coral Bleaching Event. https://www.noaa.gov/media-release/noaa-declares-third-ever-global-coral-bleaching-event.

Nyström, M., N. Graham, J. Lokrantz, and A. Norström. 2008. "Capturing the Cornerstones of Coral Reef Resilience: Linking Theory to Practice." *Coral Reefs* 27 (4): 795–809. https://doi.org/10.1007/s00338-008-0426-z.

Scheffer, M., S. Carpenter, J. Foley, C. Folke, and B. Walker. 2001. "Catastrophic Shifts in Ecosystems." *Nature* 413 (6856): 591–96. https://doi.org/10.1038/35098000.

Selkoe, K., T. Blenckner, M. Caldwell, L. Crowder, A. Erickson, T. Essington, J. Estes, et al. 2015. "Principles for Managing Marine Ecosystems Prone to Tipping Points." *Ecosystem Health and Sustainability* 1 (5): 1–18. https://doi.org/10.1890/EHS14-0024.1.

Tun, K., L. Ming Chou, J. Low, T. Yeemin, N. Phongsuwan, N. Setiasih, J. Wilson, et al. 2010. "A Regional Overview on the 2010 Coral Bleaching Event in Southeast Asia." *Status of Coral Reefs in East Asian Seas Region*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Center, Townsville, Australia.

Walker, B., C. Holling, S. Carpenter, and A. Kinzig. 2004. "Resilience, Adaptability and Transformability in Social–Ecological Systems." *Ecology and Society* 9 (2): 5.

Yeemin, T., V. Mantachitra, S. Plathong, P. Nuclear, W. Klinthong, and M. Sutthacheep. 2012. "Impacts of Coral Bleaching, Recovery and Management in Thailand." In *Proc. 12th Int. Coral Reef Symp., Cairns, Australia*. http://www.icrs2012.com/proceedings/manuscripts/ICRS2012_17D_5.pdf.

CHAPTER 2. TRANSLATING RESILIENCE-BASED MANAGEMENT THEORY TO PRACTICE FOR CORAL BLEACHING RECOVERY IN HAWAI‘I

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Abstract

More frequent and severe coral bleaching events are prompting managers to seek practical interventions to promote ecosystem resilience. Although resilience-based management is now well established theoretically, there have been few examples of implementation. In Hawai‘i, back-to-back bleaching events in 2014 and 2015 caused significant damage, motivating the state to seek guidance on next steps for recovery. Hawai‘i is a unique case study in distilling global recommendations to place-based action because of its ecological and social diversity. This study conducted a systematic review of literature using a weighted point system to evaluate and rank twelve potential Hawai‘i-specific interventions to promote coral recovery following a bleaching event. Papers were scored based on their ability to achieve their management objective as well as their ability to directly affect coral recovery. A total of 100 papers were included in the review which varied in their scale (multi-site or case study), location (inside or outside of Hawai‘i), and type of data collected (theoretical or empirical). Establishing a network of herbivore management areas ranked the highest followed by parrotfish size limits for action that could promote recovery in Hawai‘i. Establishing a network of no-take Marine Protected Areas (MPAs) was the intervention with the most literature and ranked third. This method provided a systematic way to compare the effectiveness of management interventions, a system that could be adapted to other regions. This type of evidence-based approach can lead to more fair and transparent decision-making processes, assisting reef managers in navigating the translation of resilience-based management from theory to practice.

Introduction

Climate change is affecting coral reefs worldwide in several ways, including more frequent and severe bleaching events, where corals expel zooxanthellae in response to environmental disturbance, in many cases from increased ocean temperatures. The capacity of the coral ecosystem to respond to these disturbances is known as resilience, which commonly has two components: resistance, the ability to maintain function, and recovery, the ability to regain function following a disturbance (Holling 1973). Ultimately, there is less chance of phase shifts from one dominant state to the other in resilient ecosystems and a greater likelihood that ecosystem services will be maintained after major disturbances (Nyström et al. 2008). Resilience-based management as a theoretical approach attempts to maintain or increase the resilience of ecosystems as a means to cope with global climate change. Broadly, resilience-based management suggests reducing local human threats while simultaneously managing processes that encourage resistance and recovery (Graham et al. 2013). Specific to coral reefs, resilience-based management emphasizes the maintenance of specific processes to maintain ecosystem function in the face of repeated bleaching events (Graham et al. 2013; Anthony et al. 2015; Hughes et al. 2017). Resilience-based management is an approach to refine focus to interventions that will aid in the persistence of coral reefs in a changing climate.

Challenges and Gaps in Implementing Resilience-based Management

Despite several studies describing how resilience-based management might be applied, there have been few examples of the practical translation from a broad concept to implementation action. Recently, an explicit resilience-based framework was proposed, which integrates resilience theory into coral reef management through the identification of management 'levers' (Anthony et al. 2015). Levers are actions that will have a direct impact on resilience or reduce reef vulnerability. This process identifies broad approaches (e.g. 'reduce fishing of herbivores') but does not a) identify specific actions (e.g. bag limits versus size limits, etc.) or b) prioritize these actions. Additionally, although global indicators of resilience have been prioritized that could be incorporated into spatial planning or monitoring, ways to enhance these indicators were not discussed (McClanahan et al. 2012). Heller and Zavaleta (2009) determined that interventions to promote resilience may be limited by several factors including the uncertainty of future conditions, the lack of a planning process to select and integrate recommendations into existing policies, and the narrowness of recommendations to removing ocean users are restricting resilience interventions. Additional information is required to develop standard planning processes and broadening the spectrum of potential interventions to provide more support when integrating reef resilience into management frameworks.

There is also currently little guidance on how to interpret resilience theory to regional actions, considering site-specific ecological and social differences. It is widely understood that several ecological factors vary between regions (e.g. the Caribbean versus the Indo-Pacific) and because of these differences, there may also be regional differences in resistance and recovery potential. Place-based management emphasizes appropriateness of spatial and temporal conditions, developing procedures that can accommodate multiple uses and emphasizing stakeholder involvement (Young et al. 2007). Social factors including engagement in management and dependence on marine resources may also influence whether a site is doing better or worse than anticipated (Cinner et al. 2016). In addition, individual coral reef areas may have different legal and policy capacity and requirements, making resilience intervention more or less practical. It is critical to evaluate the relevancy of resilience recommendations to local ecological and social conditions in order to tailor resilience-based interventions and maximize their effectiveness.

Hawai‘i as a Case Study for the Application of Resilience-based Management

This study assesses the ecological effectiveness of site-specific strategies in the main Hawaiian Islands to improve ecological resilience following a severe coral bleaching event. The Hawai‘i Department of Land and Natural Resources (DLNR), Division of Aquatic Resources (DAR) sought out means to promote recovery following the bleaching events in 2014 and 2015 that resulted in an average 50% decline in coral cover in select regions (Kramer et al. 2016). Although the need for resilience-based management was recognized, it was unclear how to prioritize intervention options and evaluate the chance of success given Hawai‘i's unique ecological features. This gap provided an opportunity to develop a method that could determine which existing management tools used in Hawai‘i best aligned with global resilience-based management strategies and would be most relevant for local coral reef recovery.

Hawai‘i is a unique region for a case study of the relevancy of global management recommendations at local scale. Geographic and evolutionary factors including the isolation of the Hawaiian Islands have resulted in a high level of endemism, e.g. 30% of nearshore fish species. Ecological patterns within the island chain are strongly influenced by oceanographic conditions, including wave action and current patterns (Friedlander et al. 2003; Rodgers et al. 2012) Several distinct ecological regimes have been identified, varying in community structure and coral-algal composition (Jouffray et al. 2014). Socially, there is a diversity in Hawai‘i’s fisheries from subsistence to commercial and high participation in fishing for cultural, recreational, and food value (Kittinger 2013; Friedlander et al. 2013). The main Hawaiian Islands present a unique opportunity to consider how resilience-based management interventions could be applied considering site-specific ecological and social conditions.

This study uses a systematic review to analyze a list of interventions that are currently in the management portfolio in Hawai‘i. The review tests the relevancy of each management intervention based on their documented effectiveness in past applications (management effectiveness) and demonstrated ability to promote coral recovery. The method also integrates place-based considerations through a weighted scoring system, allowing comparison between global resilience recommendations and Hawai‘i ecological characteristics. The ability to systematically evaluate coral reef recovery interventions can improve the decision-making process in marine resource management and support coral reef managers in identifying and implementing resilience-based management in a systematic and replicable way.

Methods

Identifying Hawai‘i-relevant Management Interventions

First, a list of twelve interventions was created that managers in Hawai‘i could implement to promote coral recovery following a bleaching event. The list was derived from a preliminary review of the literature, suggestions from Hawai‘i’s coral reef managers, interventions previously prioritized in a management response workshop with Hawai‘i-based researchers and coral experts, interventions already in use in Hawai‘i, and suggestions from ocean stakeholders received informally by DAR. These twelve actions fell into six basic categories: 1) spatial planning, 2) fisheries rules, 3) gear rules, 4) aquaculture, 5) land-based pollution mitigation and 6) enforcement (Table 2.1). The list was narrowed down from an initial 33 interventions through an online survey of coral bleaching experts. For each intervention, specific metrics were identified to guide the search for relevant literature. Studies were included if they described the ability of the intervention to achieve its particular metrics.

Table 2.1. Hawai‘i-specific interventions describing potential actions to promote coral bleaching recovery.

		Metric		
Category	**Intervention**	**Ability to achieve management objective**	**Ability to promote coral recovery**	**Source**
Spatial Planning	Establish a network of permanent, fully protected no-take MPAs.	Increase of fish biomass within and around areas closed to take of marine resources.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
	Establish a network of permanent Herbivore Fishery management Areas.	Increase in herbivore biomass within and around areas closed to take of marine resources.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
Fisheries Rules	Prohibit all take (commercial and non-commercial) of herbivorous fish.	Increase in herbivorous fish.	Increase in coral cover, increase in coral reef ecosystem health	Literature review, management response workshop, existing intervention
	Prohibit all take (commercial and non-commercial) of parrotfishes.	Increase in parrotfish abundance.	Increase in coral cover, increase in coral reef ecosystem health	Literature review
	Establish size limits to protect parrotfishes.	Increase in parrotfish biomass.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
	Establish bag limits to protect parrotfishes.	Increase in parrotfish biomass.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
Gear Rules	Prohibit laynets.	Increase in herbivorous fish targeted by laynets.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
	Prohibit SCUBA spearfishing.	Increase in biomass of herbivorous fish targeted by SCUBA spearfishing.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
Aquaculture	Identify, collect, propagate, and replant bleaching-resistant corals.	Increase in percent cover of bleaching-resistant corals.	Increase in coral cover, increase in coral reef ecosystem health	Stakeholder suggestion, management response workshop
Land-based Pollution Mitigation	Implement sediment mitigation in adjacent watersheds.	Decrease in sediment levels because of land-based mitigation.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
	Institute nutrient/chemical mitigation in adjacent watersheds.	Decrease in nutrient levels because of land-based mitigation.	Increase in coral cover, increase in coral reef ecosystem health	Existing intervention
Enforcement	Concentrate marine enforcement efforts on	Increase in compliance to coral reef-related rules.	Increase in coral cover, increase in coral reef	Stakeholder suggestion

	rules relating to coral reef recovery.		ecosystem health	

Determining the Inclusion of Studies in the Systematic Review

This study developed a place-based systematic review methodology to evaluate each bleaching recovery intervention option (Figure 2.1). Studies were sought out that described the ecological outcomes of implementing various types of management interventions. A study was included in the analysis if it described the outcome of using an intervention and the ability of that intervention to achieve its management objective and/or its ability to promote coral recovery. For example, if a study described the use of a parrotfish bag limit, it would be included if it contained information on whether that approach was effective at increasing parrotfish biomass (its management objective), and/or if it provided information on whether increased parrotfish biomass promoted coral recovery (ability to promote coral recovery). This included interventions used after a bleaching event but was not limited to only bleaching recovery measures. Studies were excluded if they did not fit these systematic review components.

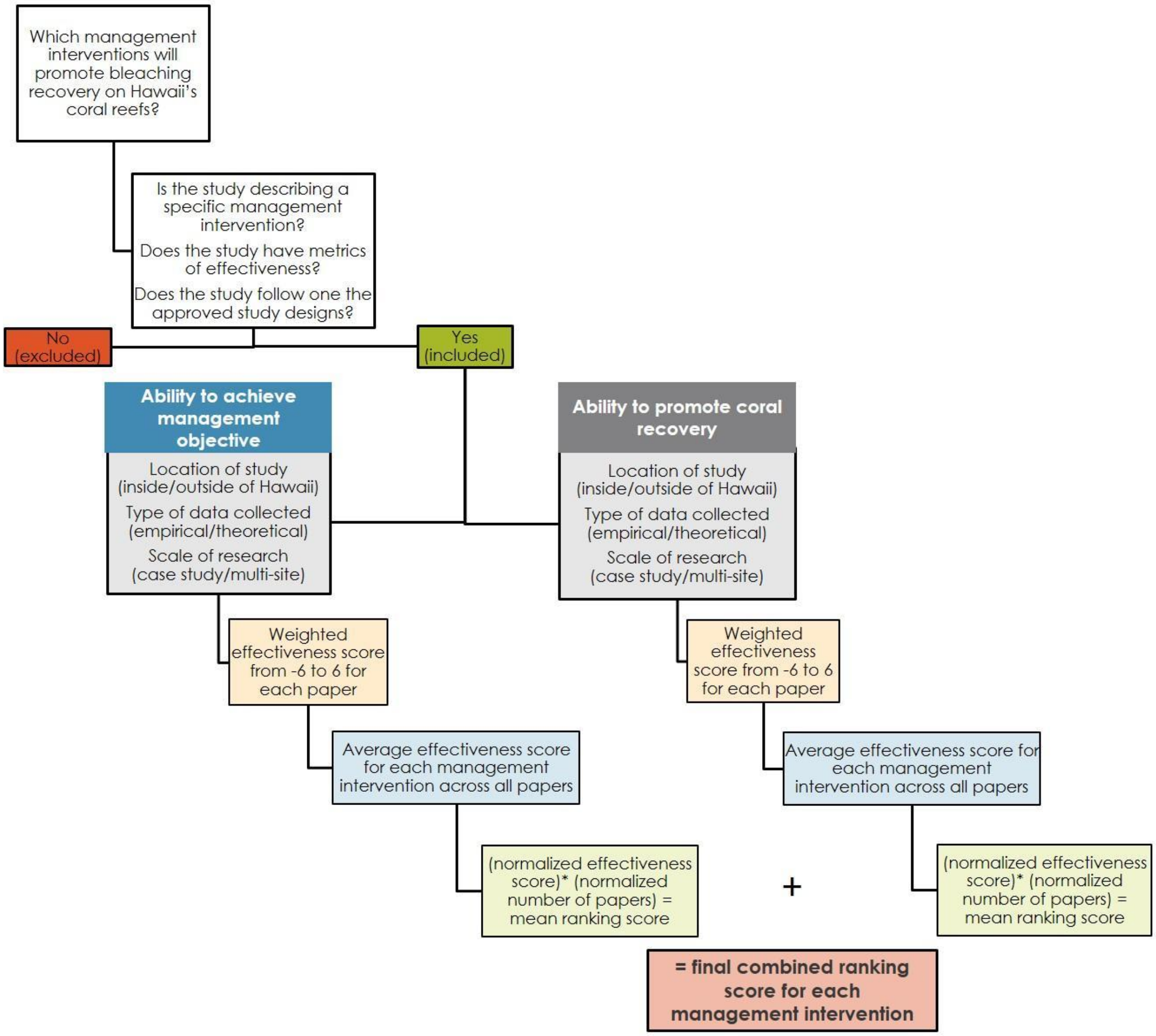


Figure 2.1. A conceptual diagram of the place-based systematic review framework used to evaluate the ecological effectiveness of each management action in the context of coral bleaching recovery in Hawai‘i. The framework begins with a central question, then literature was filtered through three guiding questions. Literature evidence was then organized into evidence describing the ability of an intervention to achieve its management objective and the ability of the intervention to promote coral recovery. Effectiveness scores were calculated for each paper based on a weighted ranking system, then averaged, then normalized. The normalized scores were multiplied by the normalized number of papers collected for a given intervention to give a mean ranking score. Finally, the mean ranking scores were summed to calculate the final combined ranking score for each management intervention.

Next, specific search terms were used to search the Web of Science database and Google Scholar. To search for relevant papers, the name of each intervention (e.g. "no-take Marine Protected Area", "parrotfish size limit") was used along with the phrase "[intervention] AND management effectiveness" and "[intervention] AND coral recovery". Gray literature, including technical and final scientific reports, were included from the Reef Resilience Network (http://www.reefresilience.org/). Academic dissertations were also collected from corresponding institutions and included if their contents had not been published.

Creating a Weighted Scoring Scheme with an Evidence Hierarchy

To organize the literature, papers were scored based on categories of evidence quality and weighted based on criteria, or through an evidence 'hierarchy'. This study adapted the evidence hierarchy first used in the medical field (Stevens and Milne 1997) and then modified for conservation use (Pullin and Knight 2003). Three unique criteria were used to evaluate each paper: the a) location and b) scale of the research, as well as c) the type of data collected. The location of the research was determined to be either inside or outside the Hawai'i. The type of data collected was either empirical (based on direct observation) or theoretical (based on hypotheses or models). The scale of the study was either 'local' scale (single site/region, case study) or 'global' scale (multiple sites, meta-analyses).

A score was assigned to each unique combination of the criteria described above, valuing empirical evidence over theoretical, research from the case study location over research from outside of it, and global studies over local-scale studies. Studies that found a particular intervention to be effective were positively weighted, while those that found the intervention to be ineffective were negatively weighted. This resulted in twelve categories with corresponding point values based on these criteria and weighting (Figure 2.2). Each paper included in the systematic review was assigned a point value ranging from -6 to 6 based on this evidence hierarchy.

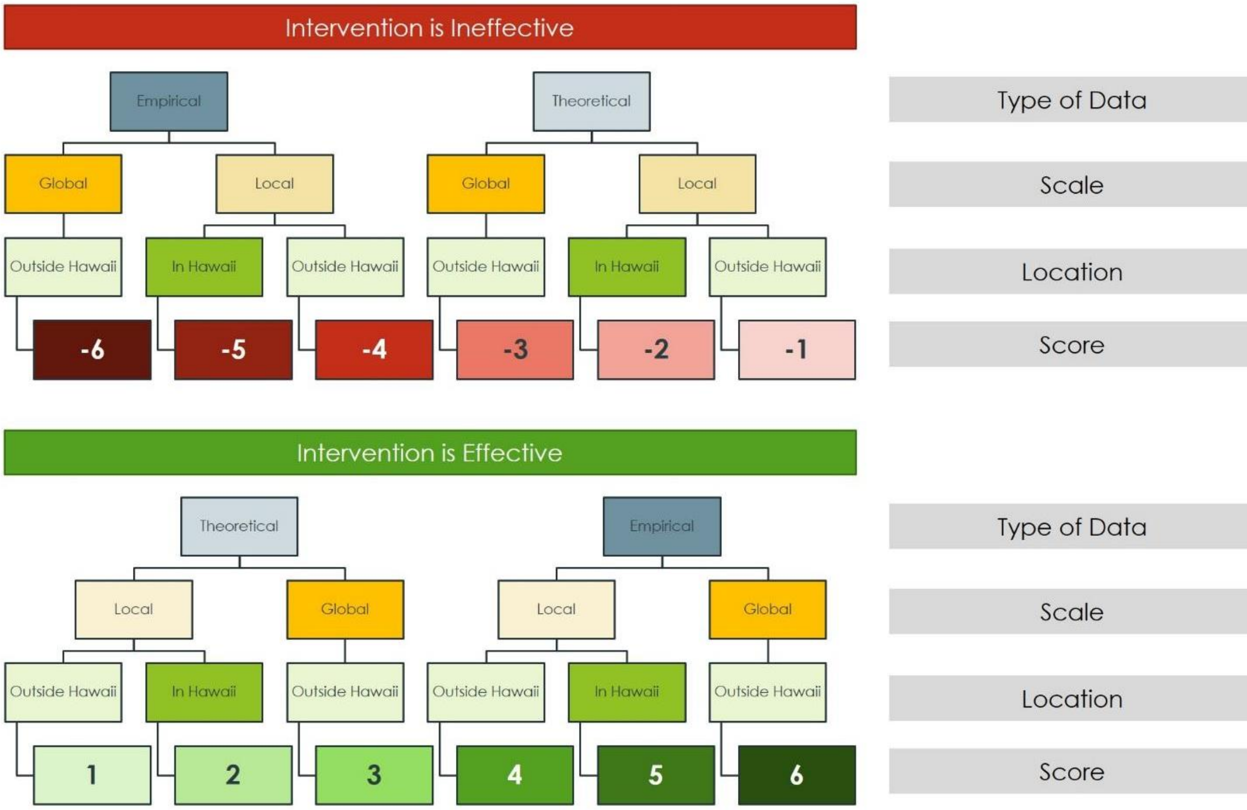


Figure 2.2. Evidence hierarchy used to assign score values to each paper included in the systematic review based on the type of data, scale, and location of the evidence.

Data analysis

Three measurements were used to describe the ability of each intervention to promote coral bleaching recovery: (i) a mean score for each intervention based on its management effectiveness, which was calculated by averaging the weighted scores across all papers for that intervention, (ii) a mean score for each intervention's ability to promote coral recovery using the same calculation, and (iii) the total number of papers collected for each intervention. Next, the ranking scores for management (ability to achieve management objective) and recovery (ability to promote coral recovery) for each action were calculated by normalizing the number of studies and the mean effectiveness and recovery score, then multiplying these metrics. Lastly, the management and recovery scores were summed to calculate the final, combined ranking score for each management action.

Results

Qualitative Description of Synthesized Evidence

A total of 100 studies were collected that fit the components and search strategy of the systematic review (see *Supplemental Information* for full bibliography and categorization). Several studies fell into multiple intervention categories and so were used multiple times when comparing the interventions to each other. Studies used multiple times were counted only once when describing the entire body of evidence. Studies were found for each intervention that described both effectiveness and ineffectiveness, except for one (prohibition of SCUBA spearfishing) which only had evidence of being effective. Studies were identified with both empirical and theoretical evidence as well as at each scale category

Distribution of Evidence across Evidence Hierarchy Categories

The number of papers varied by each of location, scale, and type of data collected (Figure 2.3). For the location of the research, the majority of the 100 papers collected (n=76) conducted research outside of Hawai‘i while 24 were conducted inside of Hawai‘i. Related to the type of research in the collected studies, 72 were based on empirical evidence, while 28 were based on theoretical evidence. Finally, related to the scale of the research 67 were local scale, meaning they focused on a single site or case study, while 33 papers were global studies based on multiple sites.

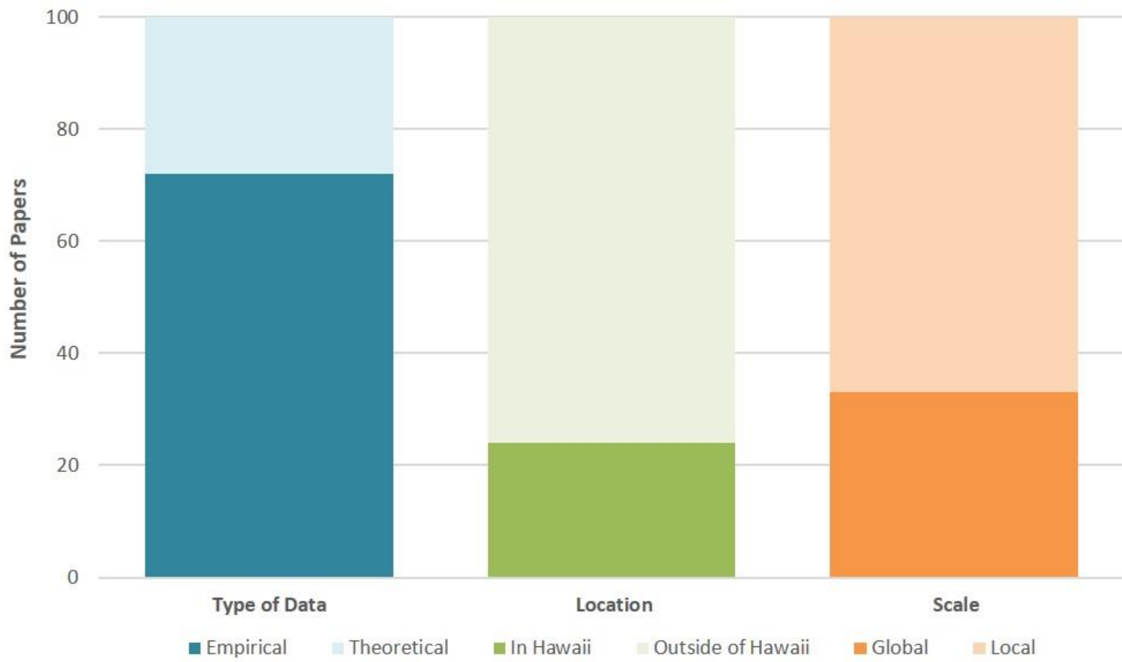
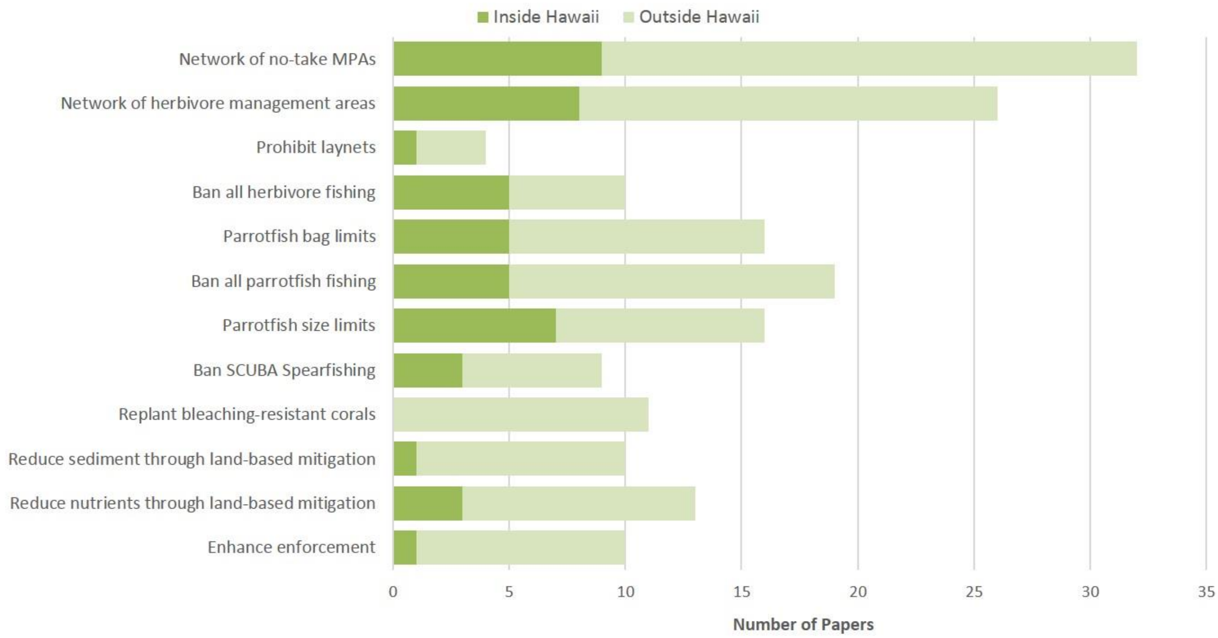


Figure 2.3. The number of papers collected based on a) the location of the research, b) the type of data collected, and c) the scale of the research.

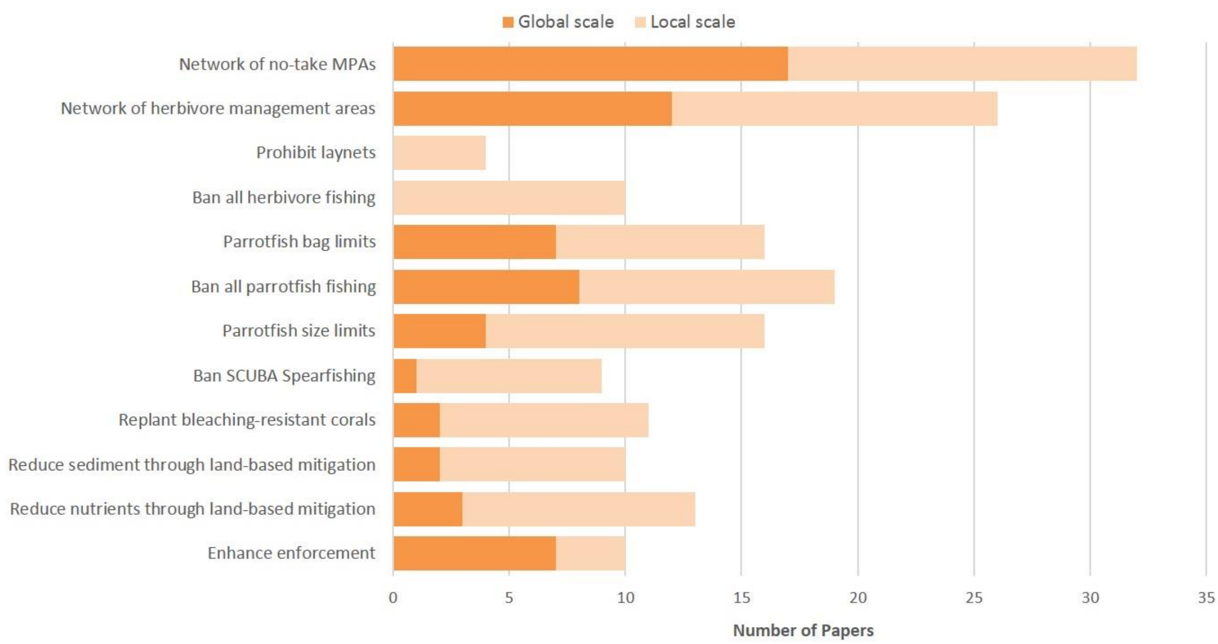
Distribution of Evidence across Interventions

Evidence was collected for each of the interventions and evidence quality categories, resulting in a total of twelve bodies of relevant evidence scored from -6 to 6. The distribution of this evidence varied across the categories of location, scale, and type of data (Figure 2.4a-c). Related to the location of the research, the interventions with the highest numbers of papers from Hawai‘i were "Establish a network of no-take Marine Protected Areas (MPAs)", "Establish parrotfish size limits", and "Establish a network of herbivore management areas" (Figure 2.4a). Tools with little or no papers from Hawai‘i were "Replant bleaching resistant corals", "Reduce sediment through land-based mitigation", "Reduce nutrients through land-based mitigation", and "Enhance enforcement." Related to the scale of research, the interventions with the highest global scale research were "Establish a network of no-take MPAs", "Enhance enforcement", and "Ban all parrotfish fishing" (Figure 2.4b). Related to the type of data collected, the management tools with the highest number of papers based on empirical data were "Establish a network of no-take MPAs", "Establish parrotfish size limits", and "Ban all parrotfish fishing" (Figure 2.4c). The tool to "Enhance enforcement" had a relatively high proportion of papers based on theoretical evidence.

a)


Inside Hawaii
Outside Hawaii
Network of no-take MPAs
Network of herbivore management areas
Prohibit laynets
Ban all herbivore fishing
Parrotfish bag limits
Ban all parrotfish fishing
Parrotfish size limits
Ban SCUBA Spearfishing
Replant bleaching-resistant corals
Reduce sediment through land-based mitigation
Reduce nutrients through land-based mitigation
Enhance enforcement
0
5
10
15
20
25
30
35
Number of Papers

b)


Global scale
Local scale
Network of no-take MPAs
Network of herbivore management areas
Prohibit laynets
Ban all herbivore fishing
Parrotfish bag limits
Ban all parrotfish fishing
Parrotfish size limits
Ban SCUBA Spearfishing
Replant bleaching-resistant corals
Reduce sediment through land-based mitigation
Reduce nutrients through land-based mitigation
Enhance enforcement
0
5
10
15
20
25
30
35
Number of Papers

c)

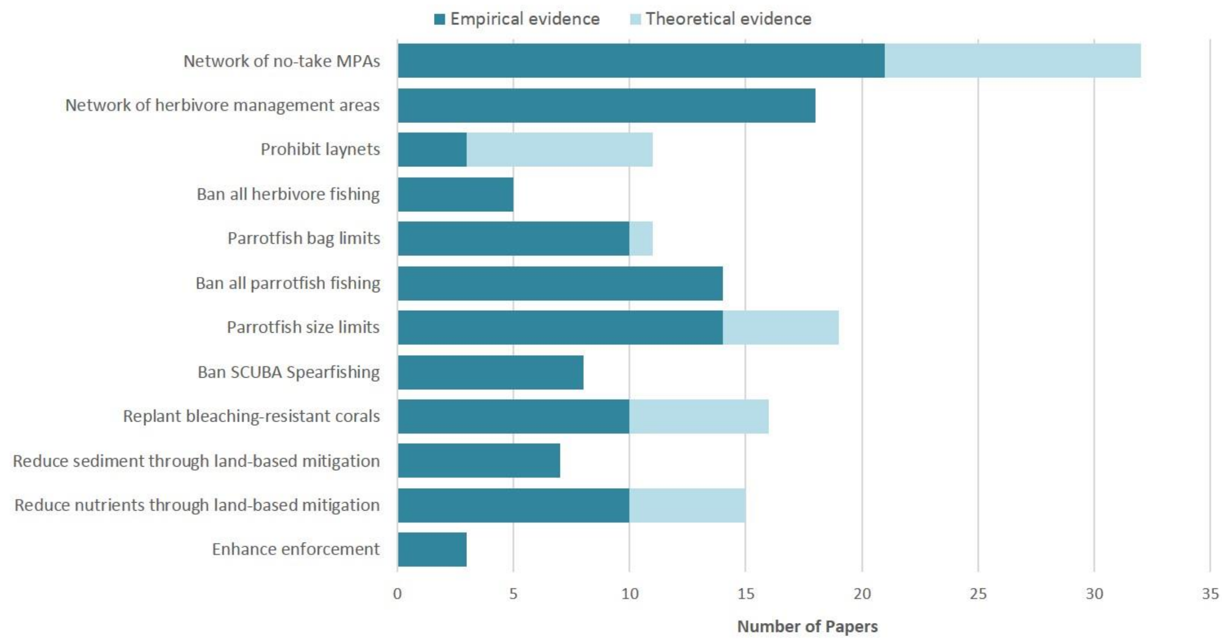


Figure 2.4. The distribution of papers collected across each intervention indicating the number of papers by a) the location of the research, b) the scale of the research, and c) the type of data collected.

The total number of papers collected also varied by intervention. Overall, the most evidence was found for spatial planning, fisheries rules, and enforcement strategies, while gear restrictions, aquaculture techniques, and land-based mitigation strategies had considerably less evidence. "Establish a network of permanent, fully protected no-take MPAs" had the highest number of papers (32 papers) describing its effectiveness while "Prohibit all use of laynets" had the fewest number of papers (4 papers). The average number of papers found for an intervention was 14.6 papers.

All interventions included in the review had evidence showing both effectiveness and ineffectiveness. Furthermore, both the number of papers and distribution of the evidence quality varied by intervention (Figure 2.5). Overall, there was more supporting (describing effectiveness) evidence versus limiting (describing ineffectiveness) evidence. A 'network of no-take MPAs' had the highest number of papers (n=5) with empirical data at a global scale (category 6). A 'Network of herbivore management areas' had five papers in the 6 category. A 'network of no-take MPAs' also had the highest number of papers describing its ineffectiveness.

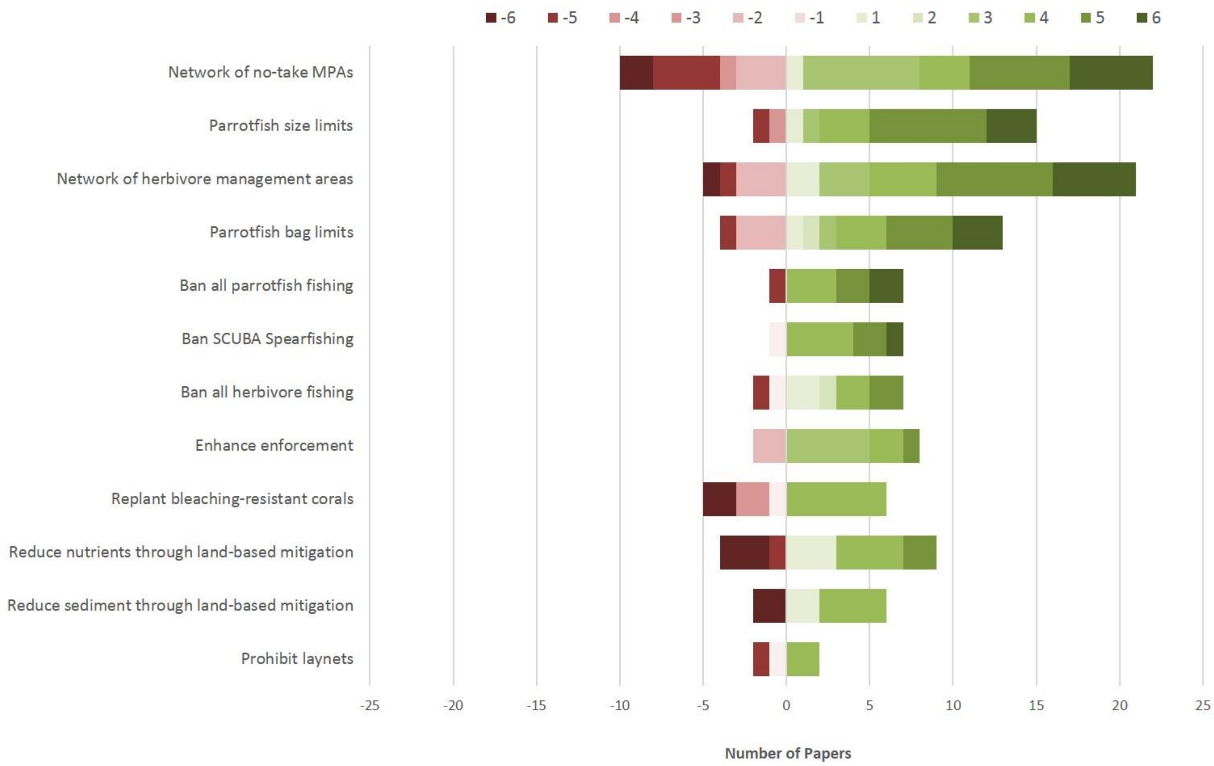


Figure 2.5. The total number of papers for each management tool that described either limiting or supporting evidence. Colors indicate the score categories that papers for each tool were categorized into ranging from -6 to 6.

In the final ranking of the management interventions, which accounted for the management and recovery metric as well as the number of papers describing the effectiveness of that intervention, 'Network of herbivore management areas' had the highest combined score (0.63) while fisheries rules focused on parrotfish (size limit, bag limit, and fishing ban) also received high scores (Table 2.2). 'Prohibit laynets' had the lowest combined score (0.02).

Table 2.2. Final combined ranking scores of potential management interventions to promote coral recovery in Hawai‘i.

Management Action	Management Ranking Score	Recovery Ranking Score	Final Combined Ranking Score
Network of herbivore management areas	0.28	0.35	0.63
Parrotfish size limits	0.20	0.28	0.48
Network of no-take MPAs	0.39	0.04	0.43
Ban all parrotfish fishing	0.25	0.11	0.36
Parrotfish bag limits	0.20	0.12	0.32
Ban SCUBA Spearfishing	0.25	0.06	0.31
Enhance enforcement	0.13	0.06	0.19
Ban all herbivore fishing	0.12	0.04	0.16
Reduce sediment through land-based mitigation	0.03	0.08	0.11
Reduce nutrients through land-based mitigation	0.04	0.02	0.06
Replant bleaching-resistant corals	-0.02	0.04	0.02
Prohibit laynets	-0.05	0.07	0.02

Recovery and management ranking scores differed between all management interventions (Figure 2.6). In most cases, the management ranking score was higher than the recovery ranking score (e.g. Ban SCUBA spearfishing). For other interventions, the recovery ranking score was higher (e.g. Reduce sediment through land-based mitigation). In two instances the management ranking score was negative (replant bleaching-resistant corals and prohibit laynets).

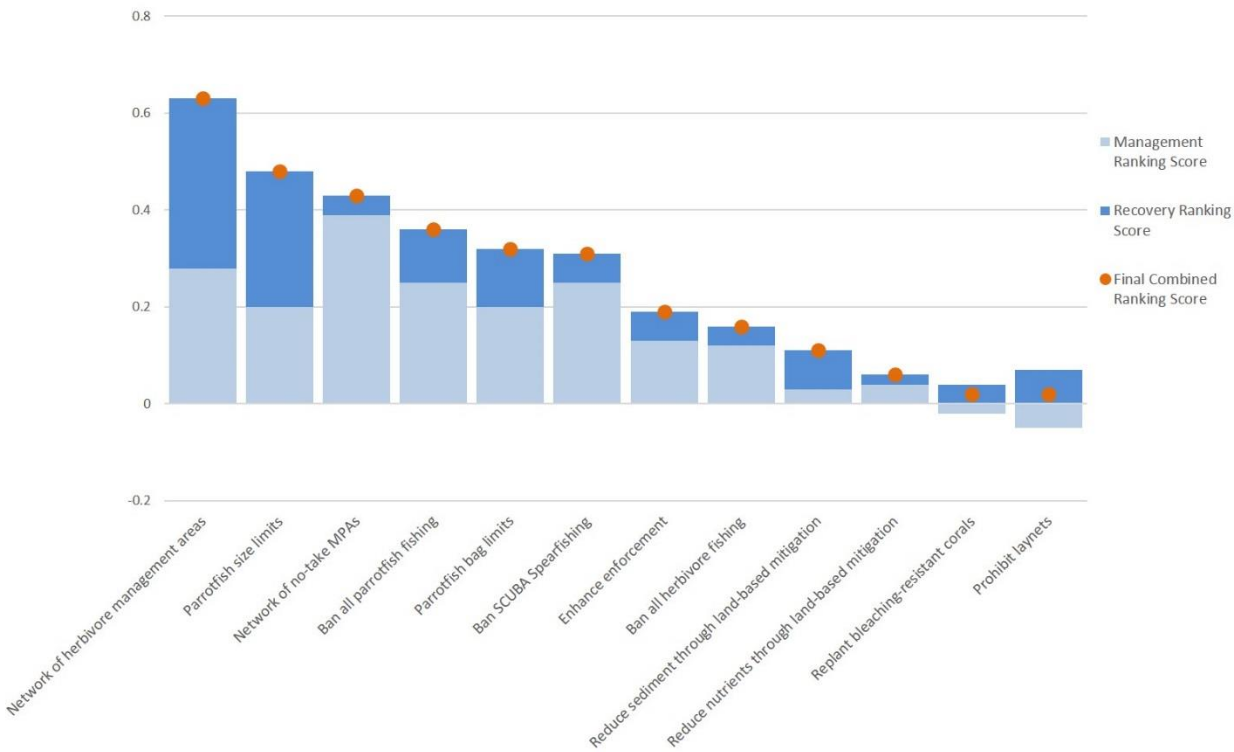


Figure 2.6. The management and recovery ranking score as well as the final combined ranking score for each management intervention.

Discussion

This study compared and evaluated the effectiveness of a wide array of coral reef management intervention options to promote coral bleaching recovery in Hawai‘i. Previous efforts have either a) focused on one particular intervention category such as MPAs (Sciberras et al. 2015) or gear types (Cinner et al. 2009) or b) have synthesized broad recommendations without prioritization or detailing specific interventions (Heller and Zavaleta 2009). There was considerable variability in the strength of evidence (average paper score) and the amount of evidence (number of papers) for the different potential interventions. Combining that information allowed for a ranking of interventions in a way that can be clearly communicated to managers. With this relative comparison of interventions, managers can hone in on actions that have been shown to be effective and which are suited to the region. This systematic review can thus be a decision-support tool that provides a way for managers to synthesize large amounts of information and apply it to prioritize locally relevant interventions.

Relative Effectiveness of Top-Ranked Interventions

Establishing a network of herbivore management areas ranked as the top intervention because of success in other regions, what is known about Hawai'i's herbivorous fish species, and previous success of herbivore management areas in Hawai'i. In the first six years of the Kahekili Herbivore Fisheries Management Areas on Maui, Hawai'i mean parrotfish and surgeonfish biomass increased by 139% and 28% respectively (Williams et al. 2016). Coral has also benefited at Kahekili where levels have stabilized and showed a slight increase from 2012 through early 2015 prior to the bleaching event (Williams et al. 2016). Additionally, the redlip parrotfish (*Scarus rubroviolaceus*), a critical species to nearshore fisheries in Hawai'i and a key reef herbivore, is a good candidate for spatial management because of its high site fidelity (Howard et al. 2013). In previous applications, spatial management has been found to have a strong connection to the ecological mechanism of herbivory and its role in shaping benthic communities, though this role has not been completely shown to lead to coral recovery (Graham et al. 2011). However, herbivores that form large roving schools and utilize large portions of reef may require additional management measures in addition to spatial management (Welsh and Bellwood 2012). Lastly, like all types of MPAs, there will be variability in its success based on the capacity of individual reefs to support herbivores (Heenan et al. 2015).

Parrotfish fisheries rules (a fishing ban and size and bag limits) also ranked high as interventions to promote recovery following a bleaching event. Parrotfish play multiple ecological functions in coral recovery, including controlling algal overgrowth and creating new space for coral settlement, and these relationships have been confirmed in Hawai'i (Jayewardene 2009). Specifically, scrapers (*Chlorurus spilurus*, *Chlorurus perspicillatus,* and *Scarus rubroviolaceus*) were most strongly associated with Hawai'i's reefs maintaining a coral-dominated state (Jouffray et al. 2014). There is evidence from a parrotfish ban in Belize that populations can recover quickly from overfishing (O'Farrell et al. 2015). Bag limits essentially equate to a partial ban on parrotfish harvest and therefore would have many of the same benefits, but likely with less impact. In Hawai'i, it has been suggested that prohibiting the take of male parrotfishes would protect against overfishing of sex-changed male fish (Ong and Holland 2010). Because the bioerosion abilities of parrotfish increase with size, protecting larger parrotfish will compound their ability to aid in coral recovery processes (Jayewardene 2009; Ong and Holland 2010; Bozec et al. 2016). However, because there are natural differences in the capacity of reefs to support herbivores, these restrictions may not have a consistent effect across all sites (McCook et al. 2001; Knowlton 2004; Bellwood and Fulton 2008; Heenan et al. 2016).

The interventions ranking the lowest in this review were restricted either in the amount of evidence available in the literature or in a lack of successful attempts to implement. Regarding reducing land-based pollution, there is sufficient information on the negative effects of both sediment and nutrients on coral (Gil et al. 2016). However there are extremely few examples of the successful reduction of sediments or nutrients on a large scale and subsequent coral revival (Kroon et al. 2014). Similarly, there have been successful pilot projects to replant bleaching-resistant corals (Van Oppen et al. 2011) and limited examples of consistent success on a larger scale (McClanahan et al. 2005; Aswani et al. 2015). There were only two studies, including one from Hawai‘i, that explored the connection between laynets and their effect on herbivore populations and found that lay nets were not in the top gear types for herbivore catch (Cinner et al. 2009; Puleloa 2012). Drawing conclusions from this limited evidence could generalize local-scale patterns that may or may not represent a larger area.

Focus on No-Take Marine Protected Areas

Establishing a network of no-take MPAs was the intervention with the most papers by a substantial margin. Globally and in Hawai‘i, no-take MPAs have been found to have both fisheries and ecosystem benefits (Selig and Bruno 2010; Graham et al. 2011) MPAs have maintained coral cover over time (but not necessarily increased it) and in some cases prevented algal overgrowth (Mumby et al. 2007; Stockwell et al. 2009) though they have failed to specifically accelerate coral recovery (Graham et al. 2011). No-take MPAs in Hawai‘i have been largely unsuccessful because they are too small given the current system of Marine Life Conservation Districts (Friedlander et al. 2007). Regional environmental and habitat variability also strongly affect MPA success and therefore strategic placement of no-take areas is crucial to their success (Heenan et al. 2015, Williams et al. 2015a,b,c).

This review also emphasizes the extent to which research and management has focused on a narrow handful of potential interventions, in particular no-take MPAs. These results indicate that other fisheries rules and gear restrictions have potential to be effective management tools but there is not sufficient evidence to properly assess them. Likewise, since managers must balance competing interests, this study suggests that focusing on each intervention's biological impacts as measured by specific metrics may be a successful method to evaluate relative effectiveness. Developing and implementing a diverse management toolbox has been found to be effective, particularly in rapidly changing and degraded environments like many coral reefs (Rogers et al. 2015). In addition, this method allows for connections to be made between what is understood biologically and what tools are available. For example, it is well understood that the process of herbivory, especially the protection of parrotfishes, can have a positive effect on coral recovery from disturbances (McCook, Jompa, and Diaz-Pulido 2001; Graham et al. 2013; Cheal et al. 2013). Several herbivore-specific management options including bag and size limits and a ban of SCUBA spearfishing had a higher average score than no-take MPAs; however, there are far fewer papers on those, and therefore less certainty on these outcomes. To clarify this question, future research should examine the effectiveness of interventions across a wider spectrum in order to provide managers with comprehensive recommendations.

Focus on Coral Recovery

This study identified management interventions following a bleaching event, focusing on the *recovery* aspect of coral reef resilience, which is the improvement of ecological function following the disturbance. The interventions that were selected as part of the review were chosen because they could be implemented after a bleaching event either to prevent further mortality or to accelerate coral regrowth. This has been the case in previous mass bleaching events where managers worked following the event and implemented recovery strategies (Beeden et al. 2014). Generally, this may be a common reality for managers due to policy restrictions or standard protocols that result in a lag in response time.

However, it also lessens focus on the second component of resilience as defined by Holling (1973), which is *resistance*, meaning the ability of the ecosystem to remain unchanged when subject to disturbance. Of the interventions included in this review, two have the potential to also aid in building bleaching resistance: networks of no-take MPAs and herbivore management areas (West and Salm 2003). Strategic design of spatial management networks to include areas with natural resistance due to a combination of physical factors (e.g. topography, wave energy, turbidity, slope, etc.) would ensure a holistic approach to resilience-based management.

Focusing on resistance could also raise the priority of actions to control nutrient and sediment run-off, which typically involve agency collaboration and planning and thus are typically mid- or long-term strategies.

Difference between Global and Hawai'i-Specific Management Interventions

The systematic review also identified gaps in the scale and location of the research. This study found the highest number of papers fell into the category of a single study site, outside of Hawai'i. The review identified one intervention ("Prohibit all use of laynets") that had only one study inside Hawai'i and another ("Replant bleaching resistant corals") that had zero studies inside Hawai'i. This ultimately affected the ability to measure the difference of place-based weighting on the results because there were insufficient papers from Hawai'i.

All of the interventions included in the review had limiting evidence lowering its average score. The content of the limiting evidence varied by intervention, yet common themes emerged that should be considered before implementation. A common theme in the literature was that regional environmental and habitat variability strongly affected the success of a managed area whether it was no-take or focused on herbivores in a given location (Heenan et al. 2015). Because of this, strategic placement of MPAs is crucial based on the specific goals of the protected area and local-level natural drivers that will increase the likelihood of successful spatial management. Natural variability has also been found to affect the success of protected areas to increase herbivore biomass (McCook, Jompa, and Diaz-Pulido 2001; Knowlton 2004; Bellwood and Fulton 2008). Success will vary based on the capacity of individual reef areas to support herbivores (Heenan et al. 2015). Fisheries rules may also be strategically zoned based on spatial drivers and managers should likewise consider which reef areas have the highest exposure to stress as well as where their management actions may have the greatest effect. Understanding the local-scale environmental drivers of key management species and habitats will increase the likelihood of successfully implemented policies on coral reefs.

Limitations and Biases

There are several limitations to the present study related to inherent biases in the scientific literature including the focus on case studies, the popularity in investigating certain interventions, and the fact that most papers report supporting evidence (when findings point towards effectiveness versus ineffectiveness). As described, the majority of evidence consisted of case studies based on one specific study area. Case studies can be useful, particularly if built on empirical data, to build broad theory (Eisenhardt 1989). However, frequent use of case studies has given rise to some challenges including building theory from cases that are not representative, dealing with various types of evidence across the case studies, and identifying the emergent theory from a set of examples (Eisenhardt and Graebner 2007). Secondly, published research tends to focus on certain topics of high popularity, which produces considerable discussion on both the pros and cons of these topics. From a management perspective, this dilutes intervention recommendations by creating a large and mixed pool of evidence through which to navigate, as well as potentially ignoring the breadth of interventions to be considered.

Lastly, scientific literature disproportionately reports complete studies with significant outcomes, known as publication bias. Publication bias has been found to produce an additional 'outcome reporting bias,' in that reported results have been revised based on the results of the study (Chan et al. 2004). It is also more common to report effective studies with significant results than studies that were ineffective, referred to as 'positive publication bias' (Sackett 1979). Thus, it is the inherent weakness of any systematic review to contain biases based on the body of evidence that it is reviewing, but perhaps like in this study, the biases can highlight areas for future research to create more consistency across topics.

This study also had a bias in the interventions that were considered. Because the systematic review focused on a specific case study, interventions were chosen that were relevant to Hawai‘i stakeholders. The twelve interventions were not an exhaustive list and did not include all potential types of actions (e.g. preventing physical damage to coral through mooring buoys). Interventions were chosen based on the case study context of managers in Hawai‘i searching for effective ways to promote coral recovery following a mass bleaching event (i.e., recovery rather than resistance) and represented a filtered set of options based on expert opinion. Including the 22 interventions initially presented to the experts in this analysis could have further expanded the results yet were not assessed due to time restrictions.

Conclusions

This work expands the application of resilience-based management to promote coral bleaching recovery by developing a systematic review framework (Figure 2.1). That framework was then applied to the case study of Hawai‘i, where managers were seeking to identify effective management tools following a recent mass bleaching event. The review process was tailored to the Hawai‘i example by identifying 12 place-based interventions and weighting the evidence of effectiveness so that evidence from Hawai‘i had greater influence. Building a systematic method for coral reef management decision making in this way helps to increase transparency and accountability of conservation actions (Bennett et al. 2017). Systematic reviews increase transparency by providing a clear map of the rationale for decisions, including the costs and benefits of options being considered, and ensure that this information is accessible to all stakeholders in a succinct format.

This study also has applications to the management of coral reefs in Hawai‘i and beyond. Coral reef managers across the world require new ways to distill evidence into locally-relevant and practical strategies, especially for jurisdictions with limited capacity and thus a need to prioritize action in a relatively straightforward way. This method could be applied in other regions also navigating how to select effective strategies following severe bleaching events. By pursuing systematic reviews which examine the biological effectiveness of interventions, managers can develop evidence-based policies, providing better understanding of the relative biological effectiveness of management tools on a place-based level. Repeating this type of effort for a different coral reef region would likely garner different results based on the natural biological and ecological variability of those regions. This type of systematic, place-based review may also support managers in distilling local-scale interventions from global-scale recommendations presented in the literature. The use of place-based considerations in the framework would benefit from additional research investigating the effectiveness of resilience-based strategies on coral reef ecosystems or by repeating this method in a locale with more extensive site-based research. This type of evaluation will ultimately support managers adapting their decision-making process to a resilience-based approach.

This study provides a transparent, objective, repeatable, and place-based method for coral reef managers in Hawai‘i to understand the relative effectiveness of management tools in their portfolio. This type of evidence-based analysis is critical to justify and communicate the need for management action in the marine environment. The need for evidence synthesis to support decision-making is becoming increasingly critical as coral reefs around the world face new, frequent, and severe disturbances. With tools like systematic reviews, perhaps we can move from a piecemeal, subjective, and fragmented paradigm to one based more firmly in available evidence. Methods of evaluating the effectiveness of interventions, including systematic reviews, can support managers to achieve evidence-based decision-making and ensure that challenges in the marine environment are overcome in an objective, logical, and transparent way. This type of evidence-based decision-making can then lead to an efficient process, systematically translating resilience-based management theory into practice.

References

Anthony, K., P. Marshall, A. Abdulla, R. Beeden, C. Bergh, R. Black, C.M. Eakin, et al. 2015. "Operationalizing Resilience for Adaptive Coral Reef Management under Global Environmental Change." Global Change Biology 21 (1):48–61. https://doi.org/10.1111/gcb.12700.

Aswani, S., P. Mumby, A. Baker, P. Christie, L. McCook, R. Steneck, and R. Richmond. 2015. "Scientific Frontiers in the Management of Coral Reefs." *Frontiers in Marine Science* 2 (July). https://doi.org/10.3389/fmars.2015.00050.

Beeden, R., J. Maynard, J. Johnson, J. Dryden, S. Kininmonth, and P. Marshall. 2014. "No-Anchoring Areas Reduce Coral Damage in an Effort to Build Resilience in Keppel Bay, Southern Great Barrier Reef." *Australasian Journal of Environmental Management* 21 (3): 311–19. https://doi.org/10.1080/14486563.2014.881307.

Bellwood, D., and C. Fulton. 2008. "Sediment-Mediated Suppression of Herbivory on Coral Reefs: Decreasing Resilience to Rising Sea-Levels and Climate Change?" Limnology and Oceanography 53 (6):2695–2701.

Bennett, N., L. Teh, Y. Ota, P. Christie, A. Ayers, J. Day, P. Franks, et al. 2017. "An Appeal for a Code of Conduct for Marine Conservation." Marine Policy 81:411–418.

Bozec, Y., S. O'Farrell, J. H. Bruggemann, B. Luckhurst, and P. Mumby. 2016. "Tradeoffs between Fisheries Harvest and the Resilience of Coral Reefs." *Proceedings of the National Academy of Sciences*, 201601529.

Cheal, A., M. Emslie, M. A. MacNeil, I. Miller, and H. Sweatman. 2013. "Spatial Variation in the Functional Characteristics of Herbivorous Fish Communities and the Resilience of Coral Reefs." *Ecological Applications* 23 (1): 174–188.

Cinner, J., C. Huchery, M. A. MacNeil, N. Graham, T. McClanahan, J. Maina, E. Maire, et al. 2016. "Bright Spots among the World's Coral Reefs." *Nature* 535 (7612): 416–19. https://doi.org/10.1038/nature18607.

Cinner, J., T. McClanahan, N. Graham, M. Pratchett, S. Wilson, and J. Raina. 2009. "Gear-Based Fisheries Management as a Potential Adaptive Response to Climate Change and Coral Mortality." *Journal of Applied Ecology* 46 (3): 724–32. https://doi.org/10.1111/j.1365-2664.2009.01648.x.

Eisenhardt, K. 1989. "Building Theories from Case Study Research." *Academy of Management Review* 14 (4): 532–550.

Eisenhardt, K., and M. Graebner. 2007. "Theory Building from Cases: Opportunities and Challenges." *Academy of Management Journal* 50 (1): 25–32.

Friedlander, A., M. Donovan, K. A. Stamoulis, and E. Schemmel. 2013. "A Perspective on the Management of Coral Reef Fisheries in Hawai'i."

Friedlander, A. M., E. K. Brown, P. L. Jokiel, W. R. Smith, and K. S. Rodgers. 2003. “Effects of Habitat, Wave Exposure, and Marine Protected Area Status on Coral Reef Fish Assemblages in the Hawaiian Archipelago.” *Coral Reefs* 22 (3): 291–305. https://doi.org/10.1007/s00338-003-0317-2.

Friedlander, A., E. Brown, and M. Monaco. 2007. “Defining Reef Fish Habitat Utilization Patterns in Hawai‘i: Comparisons between Marine Protected Areas and Areas Open to Fishing.” *Marine Ecology Progress Series* 351 (December): 221–33. https://doi.org/10.3354/meps07112.

Gil, M., S. Goldenberg, A. Ly Thai Bach, S. Mills, and J. Claudet. 2016. “Interactive Effects of Three Pervasive Marine Stressors in a Post-Disturbance Coral Reef.” *Coral Reefs* 35 (4): 1281–93. https://doi.org/10.1007/s00338-016-1489-x.

Graham, N., T. Ainsworth, A. Baird, N. Ban, L. Bay, J. Cinner, D. De Freitas, et al. 2011. “From Microbes to People: Tractable Benefits of No-Take Areas for Coral Reefs.” *Oceanography and Marine Biology-an Annual Review* 49: 105.

Graham, N., D. Bellwood, J. Cinner, T. Hughes, A. Norström, and M. Nyström. 2013. “Managing Resilience to Reverse Phase Shifts in Coral Reefs.” *Frontiers in Ecology and the Environment* 11 (10): 541–48. https://doi.org/10.1890/120305.

Heenan, A., A. Hoey, G. Williams, and I. Williams. 2016. “Natural Bounds on Herbivorous Coral Reef Fishes.” *Proceedings of the Royal Society B: Biological Sciences* 283 (1843): 20161716. https://doi.org/10.1098/rspb.2016.1716.

Heenan, A., R. Pomeroy, J. Bell, P. Munday, W. Cheung, C. Logan, R. Brainard, et al. 2015. “A Climate-Informed, Ecosystem Approach to Fisheries Management.” *Marine Policy* 57 (July): 182–92. https://doi.org/10.1016/j.marpol.2015.03.018.

Heller, N., and E. Zavaleta. 2009. “Biodiversity Management in the Face of Climate Change: A Review of 22 Years of Recommendations.” *Biological Conservation* 142 (1): 14–32. https://doi.org/10.1016/j.biocon.2008.10.006.

Holling, C.S. 1973. “Resilience and the Stability of Ecological Systems.”

Howard, K., J. Claisse, T. Clark, K. Boyle, and J. Parrish. 2013. “Home Range and Movement Patterns of the Redlip Parrotfish (Scarus Rubroviolaceus) in Hawai‘i.” *Marine Biology* 160 (7): 1583–95. https://doi.org/10.1007/s00227-013-2211-y.

Hughes, T., M. Barnes, D. Bellwood, J. Cinner, G. Cumming, J. Jackson, J. Kleypas, et al. 2017. “Coral Reefs in the Anthropocene.” *Nature* 546 (7656): 82–90. https://doi.org/10.1038/nature22901.

Jayewardene, D. 2009. “A Factorial Experiment Quantifying the Influence of Parrotfish Density and Size on Algal Reduction on Hawaiian Coral Reefs.” *Journal of Experimental Marine Biology and Ecology* 375 (1–2): 64–69. https://doi.org/10.1016/j.jembe.2009.05.006.

Jouffray, J., M. Nystrom, A. Norstrom, I. Williams, L. Wedding, J. Kittinger, and G. Williams. 2014. "Identifying Multiple Coral Reef Regimes and Their Drivers across the Hawaiian Archipelago." *Philosophical Transactions of the Royal Society B: Biological Sciences* 370 (1659): 20130268–20130268. https://doi.org/10.1098/rstb.2013.0268.

Kittinger, J. 2013. "Participatory Fishing Community Assessments to Support Coral Reef Fisheries Comanagement [1]." *Pacific Science* 67 (3): 361–81. https://doi.org/10.2984/67.3.5.

Knowlton, N. 2004. "Multiple 'Stable' States and the Conservation of Marine Ecosystems." *Progress in Oceanography* 60 (2–4): 387–96. https://doi.org/10.1016/j.pocean.2004.02.011.

Kramer, K., S. Cotton, M. Lamson, and W. Walsh. 2016. "Coral Bleaching: Monitoring, Management Responses and Resilience." http://coralreefs.org/wp-content/uploads/2016/12/Session-30-Kramer_etal_ICRS_Final-1-2.pdf.

Kroon, F.., B. Schaffelke, and R. Bartley. 2014. "Informing Policy to Protect Coastal Coral Reefs: Insight from a Global Review of Reducing Agricultural Pollution to Coastal Ecosystems." *Marine Pollution Bulletin* 85 (1): 33–41. https://doi.org/10.1016/j.marpolbul.2014.06.003.

McClanahan, T., J. Maina, C. Starger, P. Herron-Perez, and E. Dusek. 2005. "Detriments to Post-Bleaching Recovery of Corals." *Coral Reefs* 24 (2): 230–46. https://doi.org/10.1007/s00338-004-0471-1.

McClanahan, T., S. Donner, J. Maynard, M. A. MacNeil, N. Graham, J. Maina, A.Baker, et al. 2012. "Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate." Edited by Richard K. F. Unsworth. *PLoS ONE* 7 (8): e42884. https://doi.org/10.1371/journal.pone.0042884.

McCook, L., J. Jompa, and G. Diaz-Pulido. 2001. "Competition between Corals and Algae on Coral Reefs: A Review of Evidence and Mechanisms." *Coral Reefs* 19 (4): 400–417. https://doi.org/10.1007/s003380000129.

Mumby, P., A. Harborne, J. Williams, C. Kappel, D. Brumbaugh, F. Micheli, K. Holmes, Craig P. Dahlgren, C. Paris, and P. Blackwell. 2007. "Trophic Cascade Facilitates Coral Recruitment in a Marine Reserve." *Proceedings of the National Academy of Sciences* 104 (20): 8362–8367.

Nyström, M., N. Graham, J. Lokrantz, and A. Norström. 2008. "Capturing the Cornerstones of Coral Reef Resilience: Linking Theory to Practice." *Coral Reefs* 27 (4): 795–809. https://doi.org/10.1007/s00338-008-0426-z.

O'Farrell, S., A. Harborne, Y. Bozec, B. Luckhurst, and P. Mumby. 2015. "Protection of Functionally Important Parrotfishes Increases Their Biomass but Fails to Deliver Enhanced Recruitment." *Marine Ecology Progress Series* 522 (March): 245–54. https://doi.org/10.3354/meps11134.

Ong, L., and K. Holland. 2010. "Bioerosion of Coral Reefs by Two Hawaiian Parrotfishes: Species, Size Differences and Fishery Implications." *Marine Biology* 157 (6): 1313–23. https://doi.org/10.1007/s00227-010-1411-y.

Puleloa, W. 2012. "Moloka'i Island Gill-net Project." Division of Aquatic Resources Technical Report.

Pullin, A., and T. Knight. 2003. "Support for Decision Making in Conservation Practice: An Evidence-Based Approach."

Rodgers, K., M. Kido, P. Jokiel, T. Edmonds, and E. Brown. 2012. "Use of Integrated Landscape Indicators to Evaluate the Health of Linked Watersheds and Coral Reef Environments in the Hawaiian Islands." *Environmental Management* 50 (1): 21–30. https://doi.org/10.1007/s00267-012-9867-9.

Rogers, A., A. Harborne, C. Brown, Y. Bozec, C. Castro, I. Chollett, K. Hock, et al. 2015. "Anticipative Management for Coral Reef Ecosystem Services in the 21st Century." *Global Change Biology* 21 (2): 504–14. https://doi.org/10.1111/gcb.12725.

Sackett, D. 1979. "Bias in Analytic Research". *Journal of Chronic Diseases* 32 (1-2): 51-63. https://doi.org/10.1016/0021-9681(79)90012-2.

Sciberras, M., S. Jenkins, R. Mant, M. Kaiser, S. Hawkins, and A. Pullin. 2015. "Evaluating the Relative Conservation Value of Fully and Partially Protected Marine Areas." *Fish and Fisheries* 16 (1): 58–77. https://doi.org/10.1111/faf.12044.

Selig, E., and J. Bruno. 2010. "A Global Analysis of the Effectiveness of Marine Protected Areas in Preventing Coral Loss." *PLoS One* 5 (2): e9278.

Stockwell, B., C. Jadloc, R. Abesamis, A. Alcala, and G. Russ. 2009. "Trophic and Benthic Responses to No-Take Marine Reserve Protection in the Philippines." *Marine Ecology Progress Series* 389 (September): 1–15. https://doi.org/10.3354/meps08150.

Van Oppen, M., P. Bongaerts, J. Underwood, L. Peplow, and T. Cooper. 2011. "The Role of Deep Reefs in Shallow Reef Recovery: An Assessment of Vertical Connectivity in a Brooding Coral from West and East Australia: Vertical Connectivity in a Brooding Coral." *Molecular Ecology* 20 (8): 1647–60. https://doi.org/10.1111/j.1365-294X.2011.05050.x.

Welsh, J., and D. Bellwood. 2012. "Spatial Ecology of the Steephead Parrotfish (*Chlorurus microrhinos*): An Evaluation Using Acoustic Telemetry." *Coral Reefs* 31 (1): 55–65. https://doi.org/10.1007/s00338-011-0813-8.

West, J., and R. Salm. 2003. "Resistance and Resilience to Coral Bleaching: Implications for Coral Reef Conservation and Management." *Conservation Biology* 17 (4): 956–967.

Williams, I., D. White, R. Sparks, K. Lino, J. Zamzow, E. Kelly, and H. Ramey. 2016. "Responses of Herbivorous Fishes and Benthos to 6 Years of Protection at the Kahekili

Herbivore Fisheries Management Area, Maui." Edited by Sebastian C. Ferse. *Plos One*. 11 (7): e0159100. https://doi.org/10.1371/journal.pone.0159100.

Young, O., G. Osherenko, J. Ekstrom, L. Crowder, J. Ogden, J. Wilson, J. Day, et al. 2007. "Solving the Crisis in Ocean Governance: Place-Based Management of Marine Ecosystems." *Environment: Science and Policy for Sustainable Development* 49 (4): 20–32. https://doi.org/10.3200/ENVT.49.4.20-33.

Appendix 1. Literature compiled for each management intervention organized by metric it describes (ability to achieve management objective or ability to promote coral recovery). A total of 100 individual studies were used in the systematic review.

Management Intervention	Metric	Literature
Network of no-take MPAs	Ability to achieve management objective	Heenan et al. 2016, Williams et al. 2015a, Williams et al. 2015b, Williams et al. 2015c, Magris et al. 2015, Beverton and Holt 1957, Polacheck 1990, DeMartini 1993, Saldek et al. 1999, Bellwood et al. 2004, McClanahan 2009, Friedlander et al. 2007, Christie et al. 2010, Wedding and Friedlander 2008, Friedlander and DeMartini 2002, McClanahan and Kaunda-Arara 1996, Roberts et al. 2001, Russ et al. 2004, Abesamis and Russ 2005
	Ability to promote coral recovery	Graham et al. 2011, Mumby and Steneck 2008, Stockweel et al. 2009, McCook et al. 2001, Knowlton 2004, Bellwood and Fulton 2008, Graham et al. 2013, Bohnsack 1998, Mumby et al .2007, Ledlie et al. 2007, Stockwell et al. 2009, Friedlander et al. 2007, Selig and Bruno 2010
Network of herbivore management areas	Ability to achieve management objective	Heenan et al. 2016, McLoed et al. 2009, Graham et al. 2011, McClanahan et al. 2011, Howard et al. 2013, Williams et al. 2016, Friedlander and DeMartini 2002, Bellwood et al. 2012, Edwards et al. 2014
	Ability to promote coral recovery	Graham et al. 2011, McCook et al. 2001, Knowlton 2004, Bellwood and Fulton 2008, Edwards et al. 2011, Rogers et al. 2015, Graham et al. 2013, Nash et al. 2016, Holbrook et al. 2016, Cramer et al. 2017, Jaywardene 2009, Williams et al. 2016, Hixon et al. 1996, Smith et al. 2010, Bellwood et al. 2004, Hughes et al. 2004, Marshall and Schuttenberg 2004
Prohibit laynets	Ability to achieve management objective	Puleloa 2012, Cinner et al. 2009
	Ability to promote coral recovery	Mangi and Roberts 2006, McClanahan and Cinner 2008
Ban all herbivore fishing	Ability to achieve management objective	Heenan et al. 2016, Mumby et al. 2014, O'Farrell et al. 2016, Cox et al. 2013, Heenan et al. 2016, Friedlander et al. 2007
	Ability to promote coral recovery	Carassou et al. 2013, Mumby et al. 2014, Smith et al. 2002, Friedlander et al. 2007
Enhance enforcement	Ability to achieve management objective	Kaplan et al. 2015, Selig and Bruno 2010, Edgar et al. 2014, McClanahan et al. 2006, Crawford et al. 2004, Kaplan et al. 2015, Pollnac et al. 2010, DLNR 2015
	Ability to promote coral recovery	Selig and Bruno 2010, Haisfield et al. 2010,
Ban SCUBA Spearfishing	Ability to achieve management objective	Cinner et al. 2009, Lindfield et al. 2014, Meyer 2006, Howard et al. 2013, Stoffle and Allen 2012, Gillet and Moy 2006,
	Ability to promote coral recovery	Cinner et al. 2009, Nash et al. 2016,
	Ability to achieve management objective	Mangi and Roberts 2006, Heenan et al. 2016, O'Farrell et al. 2015, Cox et al. 2012, O'Farrell et al. 2016, Friedlander et al. 2007, Heenan et al. 2016, Bellwood et al. 2012, Edwards et al. 2014

Ban all parrotfish fishing	Ability to promote coral recovery	Graham et al. 2011, McCook et al. 2001, Knowlton 2004, Bellwood and Fulton 2008, Bozec et al. 2016, Graham et al. 2013, Bellwood et al. 2006, Ledlie et al. 2007, Jaywardene 2009, Jouffray et al. 2014, Mumby et al. 2006
Parrotfish size limits	Ability to achieve management objective	Heenan et al. 2016, Kuempel and Altieri 2017, Friedlander et al. 2007, Heenan et al. 2016, DeMartini et al. 2016, Ong and Holland 2010, Bellwood et al. 2012, Edwards et al. 2014
	Ability to promote coral recovery	Bozec et al. 2016, Graham et al. 2013, Bellwood et al. 2006, Ledlie et al. 2007, Lokrantz et al. 2008, Jaywardene 2009, Ong and Holland 2010, Mumby et al. 2006
Parrotfish bag limits	Ability to achieve management objective	Heenan et al. 2016, DeMartini 2016, O'Farrell et al. 2015, Friedlander et al. 2007, Heenan et al. 2016, Bellwood et al. 2012, Edwards et al. 2014
	Ability to promote coral recovery	McCook et al. 2001, Knowlton 2004, Bellwood and Fulton 2008, Bozec et al. 2016, Graham et al. 2013, Bellwood et al. 2006, Ledlie et al. 2007, Jaywardene 2009, Mumby et al. 2006
Reduce sediment stress through land-based mitigation	Ability to achieve management objective	Kroon et al. 2014, Richmond et al. 2005, Richmond et al. 2007, Chu et al. 2009
	Ability to promote coral recovery	Kroon et al. 2014, Richmond et al. 2005, Zimmer et al. 2006, Jokiel et al. 2006, Gil et al. 2016, Rodgers et al. 2012
Reduce nutrient stress through land-based mitigation	Ability to achieve management objective	Hunter and Evans 1995, Richmond et al. 2005, Richmond et al. 2007, Kroon et al. 2014
	Ability to promote coral recovery	Mumby and Steneck 2011, Kroon et al. 2014, Risk et al. 2014, Richmond et al. 2005, Zimmer et al. 2006, Jokiel et al. 2006, Gil et al. 2016, Smith et al. 1981, Rodgers et al. 2012
Replant bleaching-resistant corals	Ability to achieve management objective	Aswani et al. 2015, McClanahan et al. 2005, D'Angelo et al. 2015, Mbije et al. 2013, Gomez et al. 2014, van Oppen et al. 2011
	Ability to promote coral recovery	Aswani et al. 2015, Cremieux et al. 2010, Rinkevich 2005, Rinkevich 2006, Rinkevich 2008

CHAPTER 3. BUILDING CORAL REEF RESILIENCE THROUGH SPATIAL HERBIVORE MANAGEMENT IN HAWAIʻI

Submitted As:

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Abstract

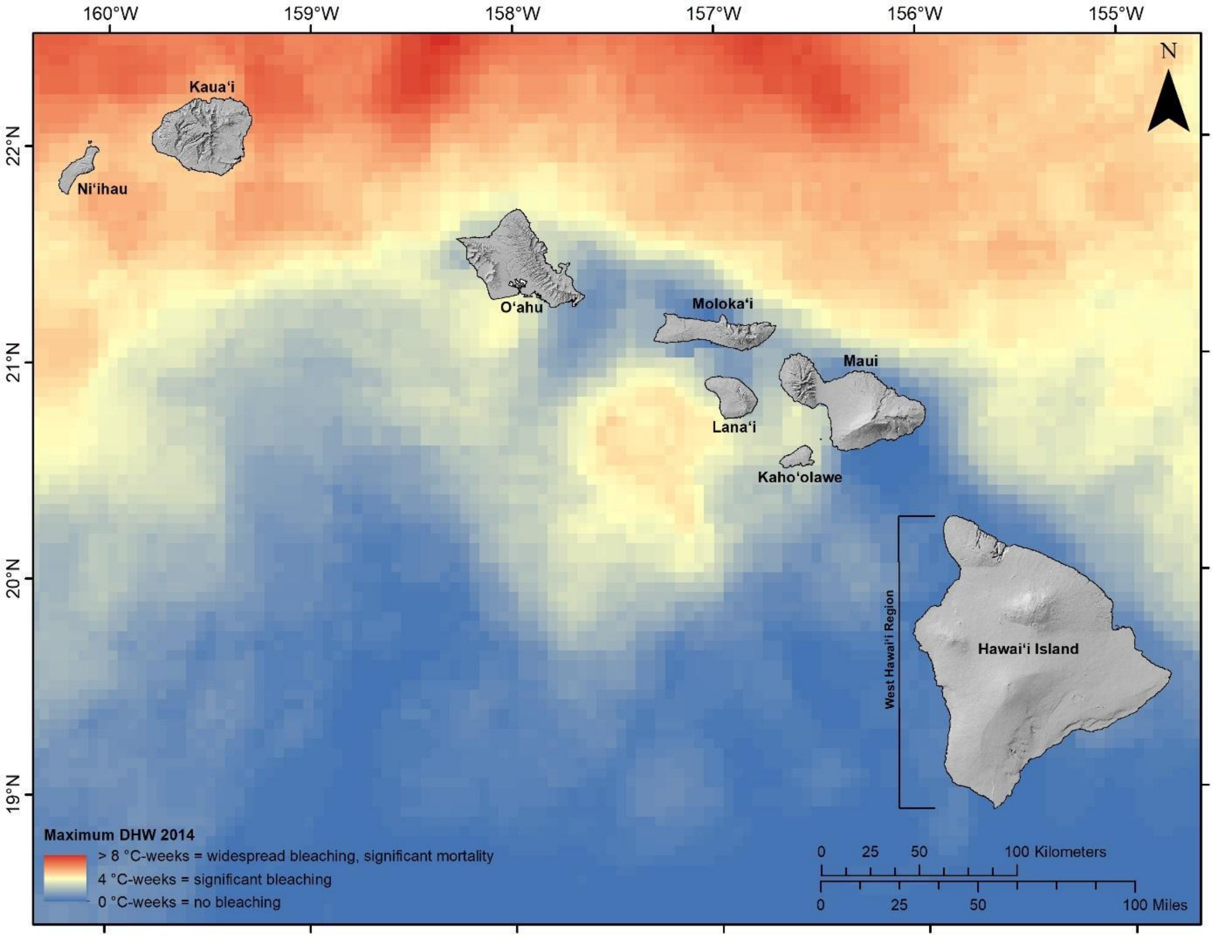
Coral reef managers currently face the challenge of mitigating global stressors by enhancing local ecological resilience in the face of a changing climate. Effective herbivore management is one tool that managers can use in order to prevent regime shifts from coral to macroalgae dominated reefs. One recommended approach is to establish networks of Herbivore Management Areas (HMAs), which prohibit the take of herbivorous reef fishes; however there is a need to develop design principles to guide planning and implementation. We refine available guidance from no-take Marine Protected Area (MPA) networks and develop a set of 12 ecological design principles specifically for HMAs. We then provide a case study of how to apply these principles using the main Hawaiian Islands. We address site-specific considerations in terms of protecting habitats, including ecologically critical areas, incorporating connectivity, and addressing climate and local threats. This synthesis integrates core marine spatial planning concepts with resilience-based management and provides actionable guidance on the design of HMAs. When combined with social considerations, these principles will support spatial planning in Hawaiʻi and could guide the future design of HMA networks globally.

Introduction

Coral reefs are among the most diverse and complex ecosystems in the world and provide biological, economic, and cultural resources as well as ecosystem services to millions of coastal residents in nearly 100 nations (Moberg and Folke 1999). When climate-induced coral bleaching events act in concert with local stressors (e.g., overfishing, land-based pollution, and coastal development), the result is often an increased potential for regime shifts (e.g., coral-dominated to macroalgae-dominated systems) leading to a loss of biodiversity as well as ecosystem goods and services (Graham et al. 2013; Ateweberhan et al. 2013; Hoegh-Guldberg et al. 2017). Enhancing the ecological resilience of coral reefs has become a central focus for managers worldwide as the frequency of coral bleaching increases (Hoegh-Guldberg 1999; Baker et al. 2008). Improving coral reef resilience relies on fostering its two central components: the ability of coral reefs to both resist and recover from ecological disturbances, (Holling 1973). To achieve increased resilience through conservation planning, that is, resilience-based management, managers must reduce local stressors while fostering key resilience processes throughout their jurisdiction (Graham et al. 2013; Anthony et al. 2015).

Herbivory is a critical ecological process that underpins the ability of corals to recover from disturbances and resist regime shifts to algal-dominated reef states. Herbivores prevent algal overgrowth (e.g., thick turfs and macroalgae) that can inhibit coral settlement and survival, thereby reducing reef structural complexity (Hixon 2015). Integrating herbivore management into local conservation planning has been identified as a key mechanism to bolster coral resilience to global stressors (Heller and Zavaleta 2009; Graham et al. 2013a; Hughes et al. 2017). Thus, herbivore management areas (HMAs), where the take of herbivorous fishes and invertebrates (such as some urchins) is prohibited while other extractive and non-extractive uses are allowed, may be an effective tool to prevent ecosystem shifts and increase the resilience of coral reef ecosystems (McClanahan et al. 2012; Graham et al. 2013a; Mumby et al. 2014; Bozec et al. 2016).

Consecutive and unprecedented mass coral bleaching events in 2014 and 2015 in the main Hawaiian Islands ignited a new conversation about the role of herbivore management areas in promoting coral reef resilience in Hawaiʻi. Exposure and severity of temperature stress during these two consecutive events was variable across the state, with some coastlines far exceeding levels previously observed (Figure 3.1). In 2015, areas along the west coast of Hawaiʻi island (known as west Hawaiʻi) reached 16 degree heating weeks (DHW), which is double the level of accumulated temperature stress expected to trigger widespread bleaching and significant coral mortality (NOAA Coral Reef Watch). Following these bleaching events, the average coral loss along west Hawaiʻi was 50% (Kramer et al. 2016) and substantial mortality was also reported around the islands of Maui and Oʻahu (Figure 3.2).


160°W
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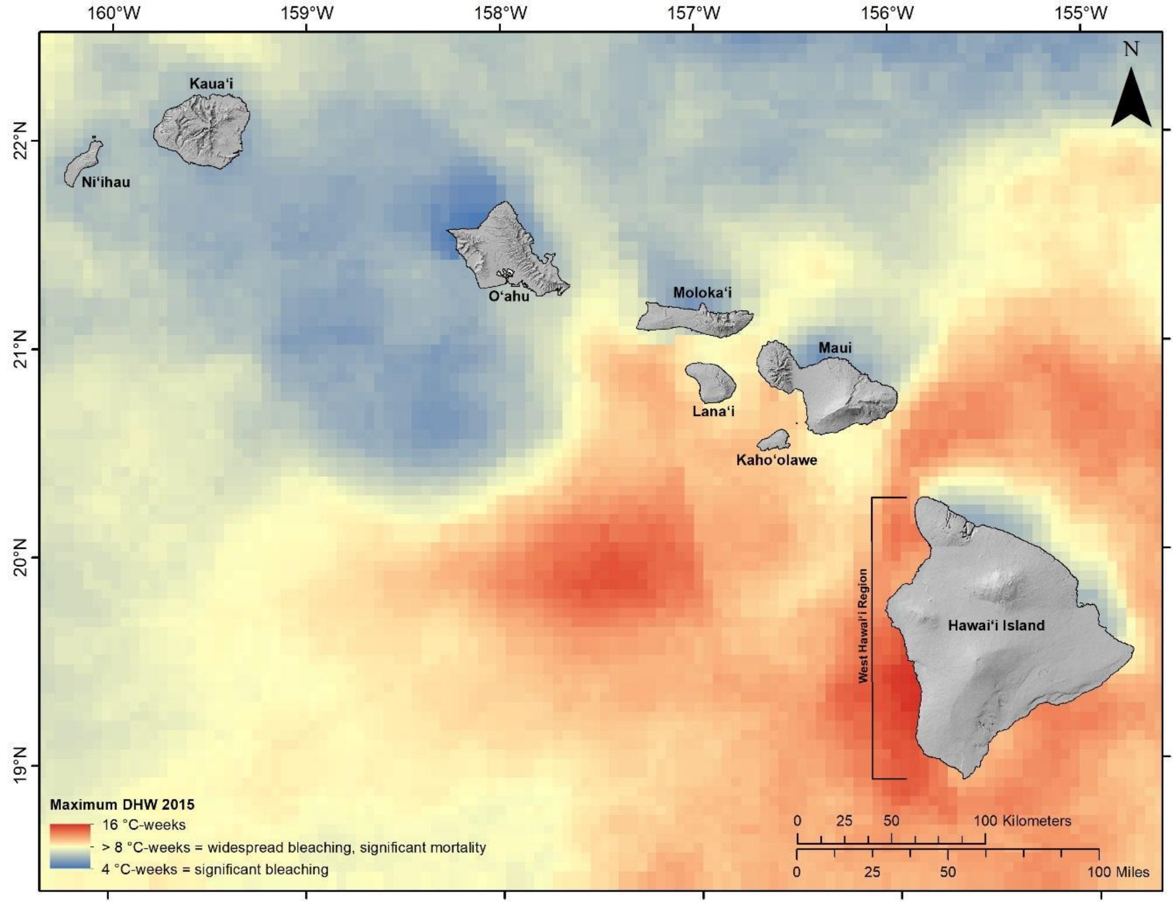
Kaua'i
Ni'ihau
O'ahu
Moloka'i
Maui
Lana'i
Kaho'olawe
West Hawai'i Region
Hawai'i Island
Maximum DHW 2014
> 8 °C-weeks = widespread bleaching, significant mortality
4 °C-weeks = significant bleaching
0 °C-weeks = no bleaching
0 25 50 100 Kilometers
0 25 50 100 Miles

a)



b)

Figure 3.1. The maximum Degree Heating Week (DHW) observed in 2014 (a) and 2015 (b) across the main Hawaiian Islands (climate data source: NOAA Coral Reef Watch).

Figure 3.2. Coral bleaching across the main Hawaiian Islands in 2014 and 2015, where reefs experienced up to 16 degree heating weeks. Clockwise from left: west Hawaiʻi, Hawaiʻi Island, credit: DAR; Kāneʻohe Bay, Oʻahu, credit: Catlin Seaview Survey; Molokini crater, Maui, credit: DAR.

Concerns about the long-term resilience of coral reefs in Hawaiʻi spurred local resource managers to consider intervention measures. In Hawaiʻi, the Department of Land and Natural Resources (DLNR) Division of Aquatic Resources (DAR) is responsible for "managing, conserving, and restoring the state's aquatic resources and ecosystems for present and future generations" (DLNR 2018). In 2016, DAR initiated the development of The Hawaiʻi Coral Bleaching Recovery Plan, which evaluated 12 management options following major bleaching events. Establishing a network of HMAs was ranked as one of the top recommendations from multiple expert opinion surveys and a literature review (Rosinski et al. 2017). DAR is currently considering options for spatial management as well as revised statewide bag and size limits that would further protect herbivorous fishes (especially parrotfishes). These efforts create a realistic opportunity for the design principles to be developed and applied to create a scientifically rigorous network of herbivore management areas using systematic conservation planning.

Currently, there are 84 existing Marine Protected Areas (MPAs) across the main Hawaiian Islands, which includes several types of spatial designations, including Marine Life Conservation Districts, Fisheries Management Areas, and Community-based Subsistence Fishing Areas (DAR 2018). Despite numerous MPAs, only a few of these areas (e.g. Kaho‘olawe) provide full protection for herbivorous fishes, while most provide only partial or no herbivore protection (Figure 3.3). Furthermore, the Kahekili HMA on Maui is the only area specifically aimed at the recovery of herbivore populations and their habitats.

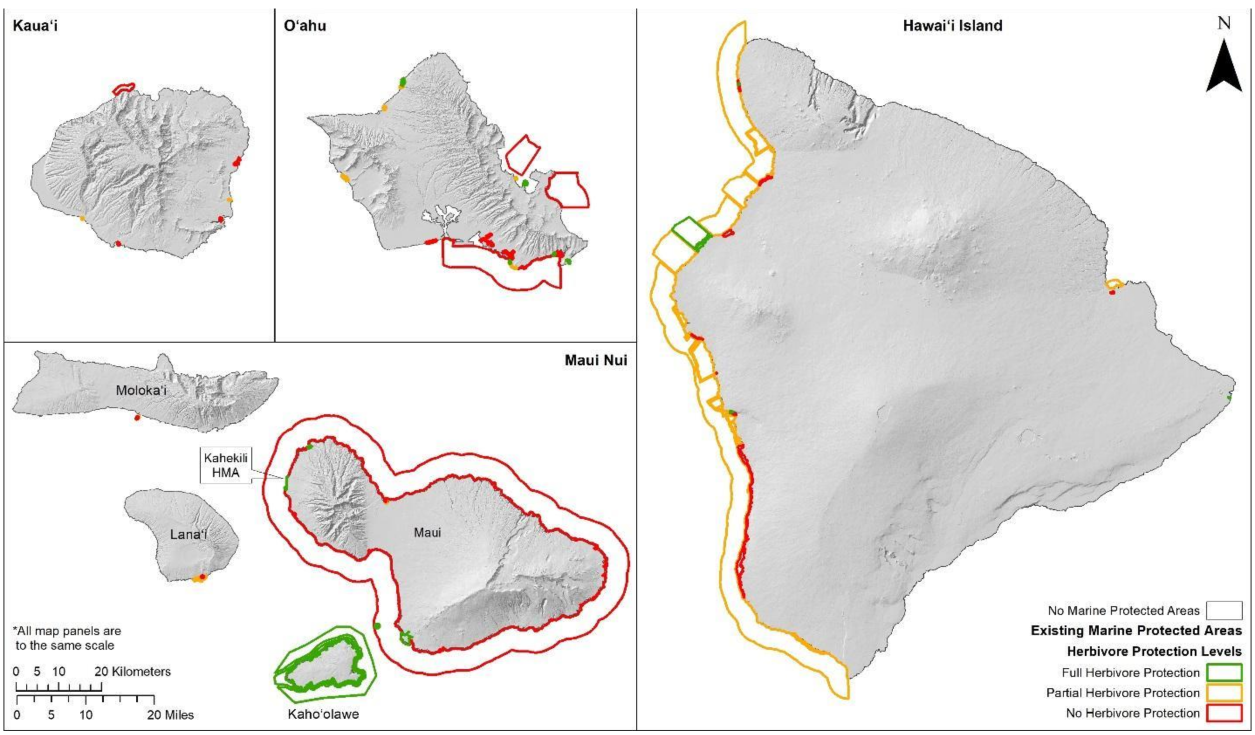


Figure 3.3. The current extent of spatial herbivore management around the main Hawaiian Islands.

Although the existing MPAs were not designed as an ecologically connected network, previous success with spatial management suggests that a network of herbivore management areas could be successful in a Hawai‘i-specific context. For example, the existing Marine Life Conservation Districts, where fishing and consumptive uses are limited (and in many completely prohibited), generally have higher herbivore biomass, larger overall fish size, and higher biodiversity than adjacent areas of similar habitat quality (Friedlander et al. 2007a; Friedlander et al. 2007b). In the first six years of herbivore management at the Kahekili HMA on Maui, mean parrotfish and surgeonfish biomass increased by 139% and 28%, respectively, macroalgal cover remained low, crustose coralline algae (a settlement habitat for coral larvae) increased from 2% to 15%, and coral cover stabilized from a declining trend (Williams et al. 2016). Thus, HMAs appear to be a useful tool to assist with coral reef recovery in Hawai‘i.

Despite global recommendations to improve the management of herbivorous fishes to increase reef resilience, there is currently a lack of practical guidelines on how this theoretical goal could be achieved. In this study, we identify design principles specifically to develop a network of herbivore management areas as a climate adaptation tool. To demonstrate how to apply this concept, we use Hawai‘i as a case study to explore unique place-based factors that could guide site-specific implementation. This process could guide the configuration and placement of networks of herbivore management areas to build climate resilience in other areas globally.

Methods

Networks of no-take MPAs have been shown to enhance fish stocks within their boundaries and provide fisheries benefits outside these protected areas (Gaines et al. 2010; Lubchenco and Grorud-Colvert 2015; Baskett and Barnett 2015). Thus, the use of no-take MPA networks has been strongly recommended for fisheries management, preservation of biodiversity, and intervention to foster adaptation to climate change (Salm and Coles 2001; Keller et al. 2009; Baskett et al. 2010; Ban et al. 2011; Roberts et al. 2017). Ecological principles for designing networks of no-take MPAs provide criteria required to rebuild fish stocks, conserve biodiversity, and mitigate climate impacts in tropical marine environments worldwide (McLeod et al. 2009; Weeks et al. 2014). Thus, the general framework for designing networks of no-take MPAs provides a useful foundation for developing specific criteria for designing networks of herbivore management areas.

Results

Starting with design principles for no-take MPAs, we developed 12 principles that were adapted and refined specifically to design a network of herbivore management areas (Table 3.1), where the aim is to build reef resilience and prevent ecological phase shifts. We also provide specific considerations for applying these principles to design a network of herbivore management areas in Hawai‘i based on local ecological conditions.

Table 3.1. Ecological design principles for the development of a network of herbivore management areas.

Category	Herbivore Management Area Design Principle	Considerations in Hawai'i	References/Data sources
Habitats	1. Protect 20-40% of each habitat type that supports herbivores. 1. Protect habitat types relevant to each herbivore functional group.	Include areas with multiple habitat types that support multiple herbivore functional groups (aggregate reef, patch reefs, spur and groove, rock/boulder, rubble, sand, pavement).	Costa and Kendall 2016
Critical Areas	3. Protect areas with naturally high herbivore biomass and/or functional diversity.	Include areas predicted to have high current herbivore biomass and functional diversity	Hawai'i Monitoring and Research Collaborative data
	4. Protect areas likely to have the greatest herbivore fisheries recovery potential.	Include areas predicted to have high potential gain in resource fish biomass with reduction in fishing intensity	Stamoulis et al. 2018; Gorospe et al. 2018
	5. Ensure the network includes areas important for the ecological needs of all post-settlement life-history stages of herbivores (e.g. nursery, sheltering, feeding, and spawning grounds).	Include known spawning habitat (e.g. boulders, 7-10 m deep).	Schemmel and Friedlander 2017
		Include known nursery grounds as well as juvenile and adult habitat (e.g. shallow, coastal waters and deeper reef areas 1-30 m depth).	Randall 1961; Friedlander and Parrish 1998; Ortiz and Tissot 2012; Kane 2018
Connectivity	6. Ensure larval connectivity within the network.	Areas should be replicated within major shores (e.g. north, east, south, and west) on each major island.	Christie et al. 2012; Toonen et al. 2011; Stamoulis and Friedlander 2013
		Due to strong physical drivers (e.g. prevailing currents, wave forcing), space areas appropriately to the geography and biophysical attributes of the coastline.	Dollar 1982; Friedlander and Parrish 1998
	7. Ensure network is large enough to sustain herbivore populations.	Ensure areas cover no less than 1 km of the coastline to accommodate known home ranges of large-bodied herbivores, establish multiple areas per coastline.	*See Table 3.2*

	8. Scale size and spacing of HMAs based on movement patterns of herbivorous species.		
Climate Considerations	9. Include areas that have withstood ecological disturbance in the past.	Include areas with high water temperature variability that resisted and recovered from the 2014-2015 bleaching events.	Hawai‘i Coral Bleaching Collaborative data
	10. Include some areas likely to withstand future disturbances.	Spread future climate risk by including areas stratified evenly across and within islands (i.e. across major shores: north, south, east, west).	Salm et al. 2006, Green et al .2007, van Hooidonk et al. 2016
	11. Include some areas at high risk of regime shifts from coral to algae.	Prioritize Maui, Moloka‘i, Lana‘i, and west Hawai‘i, and within these islands, areas that reached > 8 degree heating weeks during the 2014-2015 coral bleaching events.	NOAA Coral Reef Watch 2018
Local Threats	12. Avoid areas with unnaturally high levels of sediment and nutrients (that are beyond the direct jurisdiction of fisheries managers).	Avoid areas near: 1) high sediment outfalls, 2) urban effluent, 3) agriculture, 4) golf courses, and 5) major impervious surfaces (paved roads, etc.).	Lecky 2016; Wedding et al. 2018
		Pair marine areas adjacent to priority watershed management areas as identified by the Division of Forestry and Wildlife.	Sustainable Hawai‘i Initiative 2018

Habitats

The first principle is to represent habitat heterogeneity that occurs at multiple scales from individual reefs to the entire MHI within the network. Spatial pattern metrics can be applied to describe seascape structure and habitat complexity (Wedding et al. 2011). These metrics have already been put into practice in Hawai‘i to describe relationships between habitat structure and reef fish assemblages (Wedding et al. 2008ab), with more complex seascape structure associated with greater abundance, species richness, and biomass of reef fish.

Areas with a high diversity of habitats relevant to herbivorous fishes should be included in the network. Throughout Hawai‘i, parrotfish distributions are significantly correlated with areas of high rugosity, coral cover, non-turf macroalgae, and crustose coralline algae (Howard et al. 2009) and in particular shallow (5-10m) spur and groove habitat (Ong and Holland 2010). *Zebrasoma flavescens*, a common surgeonfish, is known to forage in shallow complex reef flat and boulder habitats (Claisse et al. 2011). Herbivore density is also highest in shallow, backreef habitat (Friedlander and Parrish 1998), whereas biomass shows a negative relationship with macroalgal cover (Friedlander et al. 2007).

Critical Areas

In Hawai‘i, herbivore biomass and functional diversity are variable and therefore hotspots of both characteristics should be incorporated into the network. Herbivores have been classified in groups based on their functional role as grazers, scrapers, or browsers, so a combination of their unique ecological roles will be critical to build resilience (Choat, Robbins, and Clements 2004; Hixon 2015). In Hawai‘i, the distribution of herbivorous fishes varies by habitat regime, which is driven by ecological and biophysical characteristics (Donovan et al. *in review*). In addition, current herbivore biomass naturally varies considerably across the archipelago driven by differences in benthic habitat cover, physical characteristics, and oceanography (Gorospe et al. 2018). HMAs should be prioritized for the network that have a diversity of functional groups and presently high biomass to maximize benefit to corals. In Hawai‘i, herbivorous fish data has been synthesized from multiple agencies and organizations and then mapped using a predictive model based on approximately 10,000 in-water observations, known as the Hawai‘i Monitoring and Research Collaborative.

While many species of herbivores are considered overfished in Hawai‘i, there are areas that are predicted to have high potential gain if fishing were reduced and thus should be included in the network. There is strong evidence of overfishing in the MHI when compared with the neighboring, unpopulated northwestern Hawaiian Islands (Friedlander and DeMartini 2002) as well as historical levels on the main Hawaiian Islands (Friedlander and DeMartini 2002; Williams et al. 2011; Howard et al. 2013; Heenan et al. 2016). In a recent stock assessment, surgeonfishes and parrotfishes had the highest number (83% and 50% respectively) of species with low Spawning Potential Ratio (SPR) values, which defines overexploitation (Nadon 2016). However, there is also substantial spatial variation in the predicted ability of nearshore areas to recover from fishing pressure (Gorospe et al. 2018; Stamoulis et al. 2018). These hotspots for fisheries recovery should be prioritized for inclusion in the network of HMAs.

It is also important to ensure that herbivores will be protected at all life-history phases within the HMA network. In particular, herbivores are concentrated in areas that are important for their various ecological needs (e.g. nursery, sheltering, feeding, and spawning areas), and protecting these critical habitats can yield significant benefits for conserving herbivore functional groups (Green et al. 2014a,b, 2017). Thus critical areas for herbivores during spawning and nursery stages, as well as feeding and sheltering, should also be prioritized for protection within a network of HMAs. For example, spawning aggregations of *Acanthurus nigrorus* have been observed in large boulder habitat 7-10 m deep near a steep (25-30 m) dropoff (Schemmel and Friedlander 2017), and larval surgeonfishes (e.g. *Acanthurus triostegus*) are known to leave the pelagic stage and enter very shallow water in Hawai’i, often in tide pools where they grow to juvenile size in these shallow-water refugia (Randall 1961).

In addition, ontogenetic patterns of habitat use by herbivores should be considered in network design. Depth has a strong correlation to fish assemblages in the main Hawaiian Islands (Friedlander et al. 2007) and herbivore biomass has been observed to be highest at the relatively shallow depth range of 4.3 – 7.2 m (Friedlander and Parrish 1998). Furthermore, Kane (2018) reports that herbivorous fishes in west Hawai‘i are not abundant below 30 m, suggesting priority should be given to nearshore waters 1 - 30 m deep. However, in various life stages, herbivorous fish have been observed to move between shallow and deep reef habitats (Ortiz and Tissot 2008; Ortiz and Tissot 2012), highlighting the need for areas of both deep aggregate coral habitat and shallow nearshore habitat (such as rubble and turf-rich boulders) to be included within HMAs.

Connectivity

To accommodate larval connectivity in the sizing and spacing of herbivore management areas, barriers to gene flow across the MHI must be considered. Coral reefs in Hawai‘i, as is common in the Indo-Pacific reefs, are relatively isolated and commonly self-seeding (Halford and Caley 2009). Multispecies dispersal barriers have been documented within the MHI between island groups corresponding to major ocean channels (Toonen et al. 2011). Within islands, studies of existing MPAs in Hawai‘i indicate the potential for management areas to support not only protected reef areas but successfully seed neighboring unprotected reefs as well (Christie et al. 2010; Stamoulis and Friedlander 2013). Christie et al. (2010) found that the distance of *Zebrasoma flavescens* larval dispersal ranged between 15 and 184 km along the coast of West Hawai‘i. Lastly, coral reef community structure in Hawai‘i is primarily driven by wave exposure (Dollar 1982) with sheltered areas maintaining larger fish populations (Friedlander and Parrish 1998). These characteristics emphasize the need for stratification between and within islands to achieve evenness in larval dispersal across the network. Therefore, we suggest that herbivore management areas should be replicated within major shores (e.g. north, east, south, and west) on each major island, and spaced appropriately to the geography and biophysical attributes of the nearshore region (e.g. prevailing currents, wave forcing) to ensure connectivity among HMAs and fished areas.

In addition to larval connectivity, adult movements should be considered throughout the network. However spatial use patterns are variable as some herbivores in Hawai‘i are site-associated most of the time, while others take periodic forays for specific activities. For example, *Zebrasoma flavescens* use shallow (3-6 m deep) during the day (Williams et al. 2009) then make considerable crepuscular migrations to deeper waters up to 600 m away from foraging to spawning and sheltering sites (Claisse et al. 2011). Similarly, parrotfishes, especially large individuals, also take forays at crepuscular hours and rely heavily on the availability of nocturnal holes for shelter (Meyer et al. 2010; Howard et al. 2013). These intermittent movements should be captured in the size of HMAs, extending to the full depth range (1 – 30 m) and ensuring multiple areas per coastline.

Movements of adult and juvenile herbivorous fishes, which range from resident to long-ranging species, should also bear on the size of individual herbivore management areas (Table 3.2). Multiple species of small-bodied surgeonfishes and parrotfishes are resident in a small (0.14 km^2) marine reserve in Kāne'ohe Bay, Oʻahu (Meyer and Holland 2005; Bierwagen et al. 2017; Stamoulis et al. 2017). The bluespine unicornfish (*Naso unicornis*), a medium-sized herbivorous fish, demonstrated daily movement patterns in Hawaiʻi less than 1 km (Meyer and Holland 2005). Large-bodied adult herbivorous fishes often have larger home ranges (Holland et al. 1993) and seek refuge commensurate with their body size (Friedlander and Parrish 1998). For instance, (Howard et al. 2013) found persistent mean adult fish home range sizes for large-bodied parrotfish to range between 834 and 2,279 m^2 depending on depth. Chubs (*Kyphosus* spp.) are unique in that they have much larger home ranges than many other reef fishes (Eristhee 2001; Pillans et al. 2017), with some even observed to make trans-island movements over 300 km in Hawaiian waters (Sakihara et al. 2015).

Table 3.2. Recommended minimum MPA size for herbivorous fishes in Hawaiʻi, based on Green et al. (2015), (Weeks et al. 2017). ** median distance based on 11 fish species, 5 herbivore species) ** linear distance based on Green et al. 2015.*

Family	**Common name (Hawaiian name)**	**Observed home range size in Hawaiʻi**	**Recommended minimum MPA size****	**References for Hawaiʻi home ranges**
Acanthuridae (surgonfishes)				
Acanthurus blochii	Ringtail surgeonfish (pualu)	0.5 km*	1 km	Meyer et al. 2010
Naso literatus	Orangespine unicornfish (umaumalei)	0.5 km*	1 km	Meyer et al. 2010
Naso unicornis	Bluespine unicornfish (kala)	300 m, 600 m	1 km	Meyer and Holland 2005, Bierwagen et al. 2017
Zebrasoma flavescens	Yellow tang (lau'īpala)	0.6 km	2 km	Claisse et al. 2011
Kyphosidae (chubs)				
Kyphosus vaigiensis	Lowfin chub (nenue)	311 km	600 km	Sakihara 2015

Labridae (parrotfishes)				
Chlorurus perspicillatus	Spectacled parrotfish (uhu 'ahu'ula)	0.5 km*	1 km	Meyer et al. 2010
Chlorurus sordidus	Bullethead parrotfish (uhu)	0.5 km*	1 km	Meyer et al. 2010
Scarus psittacus	Palenose parrotfish (uhu)	0.5 km*, 80 m	1 km	Meyer et al. 2010, Annandale 2014
Scarus rubroviolaceus	Redlip parrotfish (uhu pālukaluka)	0.5 km*, 100 m, occasional forays up to 400 m, 160 m	1 km	Meyer et al. 2010, Howard 2013, Annandale 2014

Green et al. (2015) recommend that no take MPAs should cover at least twice the length of coastline that focal species adults and juveniles require. To accommodate the full range of movements of herbivorous fishes in Hawai‘i, each HMA should be sized to accommodate large-bodied parrotfish movements, covering no less than 2 km of the coastline. Large distances traveled by chub species can be accommodated through placement of multiple HMAs per coastline.

Climate Considerations

Given changing climatic conditions, it will be important to protect ecological communities relative to their past or future response to climate change. The network should encompass protecting reefs that have either withstood bleaching in the past or are more likely to withstand bleaching in the future (i.e. climate refugia), areas currently at high risk of regime change or shift, and a distribution of areas that spreads the risk to address uncertainty regarding how conditions may change.

In Hawai‘i, there is a lack of long-term information on the effect of bleaching events as the 2014 and 2015 events were unprecedented in their extreme and widespread effects. Because of this, refugia should be based on biophysical drivers that were observed to correlate with areas either resisting or quickly recovering from the bleaching events. Based on mortality and recovery data synthesized through the Hawai‘i Coral Bleaching Collaborative, areas with high weekly temperature variability were found to better resist and immediately recover from high temperature stress. The network should include the upper quantile of values (top 25%) of these areas to capture potential climate refugia.

In addition to refugia, areas with the greatest need for bleaching recovery following the consecutive bleaching events must be addressed. To maximize recovery potential of coral communities in Hawai‘i, the network should prioritized to Maui, Moloka‘i, Lana‘i, and west Hawai‘i, areas of the state that saw the highest bleaching stress (NOAA Coral Reef Watch 2018). The network should include a portion of nearshore areas within these islands that reached > 8 DHW during the event, which is the level at which widespread bleaching and substantial mortality is expected to occur.

Future climate risk should also be mitigated by evenly spreading herbivore management areas both across and within island units (Salm et al. 2006, Green et al. 2007). Given the recent and unique mass bleaching events in the MHI, the network should be structured to accommodate evolutionary processes and natural variation that may aid in long-term preservation of habitat and species. Differences in exposure between the 2014 and 2015 bleaching events suggest future exposure will also be variable across the entire archipelago. Modeling suggests annual severe bleaching starting between 2030 and 2040 in the MHI, with variable effects across islands (van Hooidonk et al. 2016). To spread the climate risk, the design should include multiple herbivore management areas around each island. Stratifying and replicating herbivore management areas within the network will support the natural process of adaptation to climate change and lessen the possibility of major ecological impacts to the entire network from individual disturbances.

Local Threats

Nutrient input has been shown to increase algal biomass, trigger invasive blooms, and result in reef decline in Hawaiian waters (Smith et al. 1981), particularly when combined with decreased herbivory (Smith et al. 2001). Areas with high sedimentation can suppress herbivory on coral reefs (Bellwood and Fulton 2008) and increased sediment loads may result in more persistent algal coverage (Goatley and Bellwood 2013; Goatley et al. 2016). In Hawai‘i, sources of land-based pollution of particular concern include sedimentation from erosion (both natural and human-induced), nutrient flux from on-site sewage disposal systems, agriculture and golf-course runoff, and urban runoff from impervious surfaces (Lecky 2016; Wedding et al. 2018). Effects of land-based pollution on coral health vary spatially with leeward, sheltered reefs having a stronger relationship to watershed health compared to windward, exposed coastlines with enhanced mixing (Rodgers et al. 2012). Therefore, where possible, it will be important to avoid placing HMAs in areas strongly affected by land-based pollution. In addition, the network should be implemented to complement land-based management strategies to support reef resilience. In Hawai‘i, the Division of Forestry and Wildlife has identified priority watershed areas covering forests on each island (Sustainable Hawai‘i Initiative 2018). HMAs should be paired with these watershed restoration areas to align priorities between management bodies.

Discussion

We offer these ecological principles to guide the designation of a network of new herbivore management areas, especially across the main Hawaiian Islands. However local social, economic, and governance contexts must also be considered. In Hawai‘i, herbivorous fishes are a valued nearshore food resource, critical to both commercial and noncommercial fisheries. Nearshore fisheries in Hawai‘i consist of diverse groups of people using a wide array of gears and targeting a diverse group of species (Smith 1993; Friedlander and Parrish 1997). The estimated nearshore, noncommercial, reef-associated fisheries in the MHI is >1,000 tons per year, while the commercial reef fish catch is estimated to be ~185,000 kg per year (McCoy et al. 2018). Herbivores comprise a large component of the non-commercial catch, approximately 500,000 kg per year (Williams and Ma 2013). Mapping this effort across the state revealed variability in gear type and activity level, emphasizing that the closure or restriction of certain areas may have a disproportionate social and economic effect depending on placement (McCoy et al. 2018; Wedding et al. 2018). While maintaining the network’s ability to achieve its ecological objectives, it will be essential to place new areas strategically to reduce their impact to areas valued by herbivore fishers.

Community co-management is relevant in the Hawai‘i context and could contribute to the success of newly-implemented herbivore management areas. In 2016, the first Community-Based Subsistence Fisheries Area (CBSFA) was established at Hāʻena, Kaua‘i. Since then, several communities currently pursuing CBSFA designation and many others are participating in grassroots, community-based stewardship. This community interest could be leveraged to appropriately place HMAs along coastlines where they would be welcomed and supported, rather than those where they may be misaligned with the community's interests (Friedlander et al. 2013; Ayers and Kittinger 2014; Friedlander et al. 2014). However such community co-management areas, like most managed areas in Hawai'i, are likely to be small (current average size of a Marine Life Conservation District is 0.40 km^2, Fisheries Management Area is 1.08 km^2), and previous studies have found that current small MPAs are ecologically ineffective in Hawai'i (Friedlander et al. 2007). Therefore, it will be important that smaller MPAs are integrated into a larger network to mitigate social costs (Russ and Alcala 2003; Aburto-Oropeza et al. 2011). Thus we recommend pursuing both an ecologically and socially connected network of herbivore management areas appropriately sized in areas of high community involvement and support.

Based on general guidance for designing networks of no-take MPAs, we have developed 12 ecological principles for designing networks of herbivore management areas as a reef resilience-building tool. Design principles fall into five major categories regarding protecting habitats and ecologically critical areas, incorporating connectivity, and addressing climate change and local threats.

We then describe how these design principles could be applied in Hawai'i by addressing several site-specific ecological qualities that should be considered when implementing herbivore management areas. These include providing guidance on specific areas to be included in the network, as well as guidance on the location, size and spacing of HMAs throughout the MHIs. These design principles can be used to analyze relevant spatial data to design a network of herbivore management areas for the MHI.

The next step in planning for a network of herbivore management areas across the MHI is to use the design principles and Hawai'i-specific considerations to conduct a systematic spatial planning analysis. This is currently underway as part of the state's Marine 30·30 – an effort to achieve "30% effective management in Hawai'i's nearshore marine waters by 2030" (Sustainable Hawai'i Initiative 2018). One objectives of this initiative is to increase reef resilience through improved spatial management. These design principles could be applied to prioritize specific nearshore areas to protect herbivorous fishes, promote recovery from coral bleaching, and build ecological resilience. Once potential locations have been identified for establishing new HMAs using this analytical approach, additional planning will be required to ensure adequate size and spacing of proposed areas. Final placement and design of HMAs in Hawai‘i will be determined through collaborative planning with stakeholders and the public rulemaking process.

References

Aburto-Oropeza, O., B. Erisman, G. Galland, I. Mascareñas-Osorio, E. Sala, and E. Ezcurra. 2011. "Large Recovery of Fish Biomass in a No-Take Marine Reserve." Edited by Howard Browman. *PLoS ONE* 6 (8): e23601. https://doi.org/10.1371/journal.pone.0023601.

Friedlander, A., and J. Parrish. 1998. "Temporal Dynamics of Fish Communities on an Exposed Shoreline in Hawai'i." *Environmental Biology of Fishes* 1.18: 19.

Anthony, K., P. Marshall, A. Abdulla, R. Beeden, C. Bergh, R. Black, M. Eakin, et al. 2015. "Operationalizing Resilience for Adaptive Coral Reef Management under Global Environmental Change." *Global Change Biology* 21 (1): 48–61. https://doi.org/10.1111/gcb.12700.

Ateweberhan, M., D. Feary, S. Keshavmurthy, A. Chen, M. Schleyer, and C. Sheppard. 2013. "Climate Change Impacts on Coral Reefs: Synergies with Local Effects, Possibilities for Acclimation, and Management Implications." *Marine Pollution Bulletin* 74 (2): 526–39. https://doi.org/10.1016/j.marpolbul.2013.06.011.

Ayers, A., and J. Kittinger. 2014. "Emergence of Co-Management Governance for Hawai'i Coral Reef Fisheries." *Global Environmental Change* 28: 251–262.

Baker, A., P. Glynn, and B. Riegl. 2008. "Climate Change and Coral Reef Bleaching: An Ecological Assessment of Long-Term Impacts, Recovery Trends and Future Outlook." *Estuarine, Coastal and Shelf Science* 80 (4): 435–71. https://doi.org/10.1016/j.ecss.2008.09.003.

Ban, N., V. Adams, G. Almany, S. Ban, J. Cinner, L. McCook, M. Mills, R. Pressey, and A. White. 2011. "Designing, Implementing and Managing Marine Protected Areas: Emerging Trends and Opportunities for Coral Reef Nations." *Journal of Experimental Marine Biology and Ecology* 408 (1–2): 21–31. https://doi.org/10.1016/j.jembe.2011.07.023.

Baskett, M., and L. Barnett. 2015. "The Ecological and Evolutionary Consequences of Marine Reserves." *Annual Review of Ecology, Evolution, and Systematics* 46 (1): 49–73. https://doi.org/10.1146/annurev-ecolsys-112414-054424.

Baskett, M., R. Nisbet, C. Kappel, P. Mumby, and S. Gaines. 2010. "Conservation Management Approaches to Protecting the Capacity for Corals to Respond to Climate Change: A Theoretical Comparison." *Global Change Biology* 16 (4): 1229–46. https://doi.org/10.1111/j.1365-2486.2009.02062.x.

Bellwood, D., and C. Fulton. 2008. "Sediment-Mediated Suppression of Herbivory on Coral Reefs: Decreasing Resilience to Rising Sea-Levels and Climate Change?" *Limnology and Oceanography* 53 (6): 2695–2701.

Bierwagen, S., D. Price, A. Pack, and C. Meyer. 2017. "Bluespine Unicornfish (*Naso unicornis*) Are Both Natural Control Agents and Mobile Vectors for Invasive Algae in a Hawaiian Marine Reserve." *Marine Biology* 164 (1). https://doi.org/10.1007/s00227-016-3049-x.

Bozec, Y., S. O'Farrell, J. Henrich Bruggemann, Brian E. Luckhurst, and Peter J. Mumby. 2016. "Tradeoffs between Fisheries Harvest and the Resilience of Coral Reefs." *Proceedings of the National Academy of Sciences*, 201601529.

Choat, J., W. Robbins, and K. Clements. 2004. "The Trophic Status of Herbivorous Fishes on Coral Reefs: II. Food Processing Modes and Trophodynamics." *Marine Biology* 145 (3). https://doi.org/10.1007/s00227-004-1341-7.

Christie, M., B. Tissot, M. Albins, J. Beets, Y. Ortiz, S. Thompson, and M. Hixon. 2010. "Larval Connectivity in an Effective Network of Marine Protected Areas." Edited by Sharyn Jane Goldstien. *PLoS ONE* 5 (12): e15715. https://doi.org/10.1371/journal.pone.0015715.

Claisse, J., T. Clark, B. Schumacher, S. McTee, M. Bushnell, C. Callan, C. Laidley, and J. Parrish. 2011. "Conventional Tagging and Acoustic Telemetry of a Small Surgeonfish, *Zebrasoma flavescens*, in a Structurally Complex Coral Reef Environment." *Environmental Biology of Fishes* 91 (2): 185–201. https://doi.org/10.1007/s10641-011-9771-9.

Department of Land and Natural Resources (DLNR). 2018. Division of Aquatic Resources. http://dlnr.hawaii.gov/dar/.

Division of Aquatic Resources (DAR). 2018 – Marine Managed Areas. http://dlnr.hawaii.gov/dar/marine-managed-areas/about-marine-managed-areas/

Dollar, S. 1982. "Wave Stress and Coral Community Structure in Hawai'i." *Coral Reefs* 1 (2): 71–81.

Donovan, M., A. Friedlander, J. Lecky, J. Jouffray, G. Williams, L. Wedding, et al. (in press). Integrating Fish and Benthic Assemblages Provides a More Nuanced Understanding of Coral Reef Regimes. *Science Advances.*

Eristhee, N. 2001. "Home Range Size and Use of Space by Bermuda Chub *Kyphosus sectatrix* (L.) in Two Marine Reserves in the Soufriere Marine Management Area, St Lucia, West Indies." *Journal of Fish Biology* 59 (December): 129–51. https://doi.org/10.1006/jfbi.2001.1754.

Friedlander, A., E. Brown, and M. Monaco. 2007. "Coupling Ecology and GIS to Evaluate Efficacy of Marine Protected Areas in Hawai'i." *Ecological Applications* 17 (3): 715–730.

Friedlander, A., and E. DeMartini. 2002. "Contrasts in Density, Size, and Biomass of Reef Fishes between the Northwestern and the Main Hawaiian Islands: The Effects of Fishing down Apex Predators." *Marine Ecology Progress Series* 230: 253–264.

Friedlander, A., and J. Parrish. 1997. “Fisheries Harvest and Standing Stock in a Hawaiian Bay.” *Fisheries Research* 32 (1): 33–50.

———. 1998. “Habitat Characteristics Affecting Fish Assemblages on a Hawaiian Coral Reef.” *Journal of Experimental Marine Biology and Ecology* 224 (1): 1–30. https://doi.org/10.1016/S0022-0981(97)00164-0.

Friedlander, A., J. Shackeroff, and J. Kittinger. 2013. “Customary Marine Resource Knowledge and Use in Contemporary Hawai’i 1.” *Pacific Science* 67 (3): 441–460.

Friedlander, A., K. Stamoulis, J. Kittinger, J. Drazen, and B. Tissot. 2014. “Understanding the Scale of Marine Protection in Hawai‘I.” In *Advances in Marine Biology*, 69:153–203. Elsevier. https://doi.org/10.1016/B978-0-12-800214-8.00005-0.

Friedlander, A., E. Brown, and M. Monaco. 2007. “Defining Reef Fish Habitat Utilization Patterns in Hawai‘i: Comparisons between Marine Protected Areas and Areas Open to Fishing.” *Marine Ecology Progress Series* 351 (December): 221–33. https://doi.org/10.3354/meps07112.

Gaines, S., C. White, M. Carr, and S. Palumbi. 2010. “Designing Marine Reserve Networks for Both Conservation and Fisheries Management.” *Proceedings of the National Academy of Sciences* 107 (43): 18286–93. https://doi.org/10.1073/pnas.0906473107.

Goatley, C., R. Bonaldo, R. Fox, and D. Bellwood. 2016. “Sediments and Herbivory as Sensitive Indicators of Coral Reef Degradation.” *Ecology and Society* 21 (1).

Goatley, C., and D. Bellwood. 2013. “Ecological Consequences of Sediment on High-Energy Coral Reefs.” *PloS One* 8 (10): e77737.

Gorospe, K., M. Donahue, A. Heenan, J. Gove, I. Williams, and R. Brainard. 2018. “Local Biomass Baselines and the Recovery Potential for Hawaiian Coral Reef Fish Communities.” *Frontiers in Marine Science* 5 (May). https://doi.org/10.3389/fmars.2018.00162.

Graham, N., D. Bellwood, J. Cinner, T. Hughes, A. Norström, and M. Nyström. 2013. “Managing Resilience to Reverse Phase Shifts in Coral Reefs.” *Frontiers in Ecology and the Environment* 11 (10): 541–48. https://doi.org/10.1890/120305.

Green, A., A. Maypa, G. Almany, K. Rhodes, R. Weeks, R. Abesamis, M. Gleason, P. Mumby, and A.White. 2015. “Larval Dispersal and Movement Patterns of Coral Reef Fishes, and Implications for Marine Reserve Network Design.” *Biological Reviews*, 1215–47. https://doi.org/10.1111/brv.12155.

Green, A., Nature Conservancy (Australia), Indo Pacific Resource Centre, United States, Agency for International Development, and David & Lucile Packard Foundation. 2007. *Scientific Design of a Resilient Network of Marine Protected Areas: Kimbe Bay, West New Britain, Papua New Guinea*. South Brisbane, QLD, Australia: Nature Conservancy, Indo-Pacific Resource Center.

Halford, A., and M. Caley. 2009. “Towards an Understanding of Resilience in Isolated Coral Reefs.” *Global Change Biology* 15 (12): 3031–45. https://doi.org/10.1111/j.1365-2486.2009.01972.x.

Heenan, A., A. Hoey, G. Williams, and I. Williams. 2016. “Natural Bounds on Herbivorous Coral Reef Fishes.” *Proceedings of the Royal Society B: Biological Sciences* 283 (1843): 20161716. https://doi.org/10.1098/rspb.2016.1716.

Heller, N. and E. Zavaleta. 2009. “Biodiversity Management in the Face of Climate Change: A Review of 22 Years of Recommendations.” *Biological Conservation* 142 (1): 14–32. https://doi.org/10.1016/j.biocon.2008.10.006.

Hixon, M. 2015. “Reef Fishes, Seaweeds, and Corals.” In *Coral Reefs in the Anthropocene*, edited by Charles Birkeland, 195–215. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-017-7249-5_10.

Hoegh-Guldberg, O. 1999. “Climate Change, Coral Bleaching and the Future of the World’s Coral Reefs.” *Marine and Freshwater Research* 50 (8): 839. https://doi.org/10.1071/MF99078.

Hoegh-Guldberg, O., E. Poloczanska, W. Skirving, and S. Dove. 2017. “Coral Reef Ecosystems under Climate Change and Ocean Acidification.” *Frontiers in Marine Science* 4 (May). https://doi.org/10.3389/fmars.2017.00158.

Holland, K., J. Peterson, C. Lowe, and B. Wetherbee. 1993. “Movements, Distribution and Growth Rates of the White Goatfish *Mulloides flavolineatus* in a Fisheries Conservation Zone.” *Bulletin of Marine Science* 52 (May): 982–92.

Holling, C. 1973. “Resilience and the Stability of Ecological Systems.”

Hooidonk, R., J. Maynard, J. Tamelander, J. Gove, G. Ahmadia, L. Raymundo, G. Williams, S. Heron, and S. Planes. 2016. “Local-Scale Projections of Coral Reef Futures and Implications of the Paris Agreement.” *Scientific Reports* 6 (December): 39666. https://doi.org/10.1038/srep39666.

Howard, K., J. Claisse, T. Clark, K. Boyle, and J. Parrish. 2013. “Home Range and Movement Patterns of the Redlip Parrotfish (*Scarus rubroviolaceus*) in Hawai‘i.” *Marine Biology* 160 (7): 1583–95. https://doi.org/10.1007/s00227-013-2211-y.

Howard, K., B. Schumacher, and J. Parrish. 2009. “Community Structure and Habitat Associations of Parrotfishes on O‘ahu, Hawai‘i.” *Environmental Biology of Fishes* 85 (2): 175–86. https://doi.org/10.1007/s10641-009-9478-3.

Hughes, T., M. Barnes, D. Bellwood, J. Cinner, G. Cumming, J. Jackson, J. Kleypas, et al. 2017. “Coral Reefs in the Anthropocene.” *Nature* 546 (7656): 82–90. https://doi.org/10.1038/nature22901.

Keller, B., D. Gleason, E. McLeod, C. Woodley, S. Airamé, B. Causey, A. Friedlander, et al. 2009. “Climate Change, Coral Reef Ecosystems, and Management Options for Marine

Protected Areas." *Environmental Management* 44 (6): 1069–88. https://doi.org/10.1007/s00267-009-9346-0.

Kramer, K., S. Cotton, M. Lamson, and W. Walsh. 2016. "Coral Bleaching: Monitoring, Management Responses and Resilience." http://coralreefs.org/wp-content/uploads/2016/12/Session-30-Kramer_etal_ICRS_Final-1-2.pdf.

Lecky, J.. 2016. "Ecosystem Vulnerability and Mapping Cumulative Impacts on Hawaiian Reefs." University of Hawai'i at Manoa.

Lubchenco, J., and K. Grorud-Colvert. 2015. "Making Waves: The Science and Politics of Ocean Protection." *Science* 350 (6259): 382–383.

McClanahan, T., S. Donner, J. Maynard, M. MacNeil, N. Graham, J. Maina, A. Baker, et al. 2012. "Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate." Edited by Richard K. F. Unsworth. *PLoS ONE* 7 (8): e42884. https://doi.org/10.1371/journal.pone.0042884.

McCoy, K., I. Williams, A. Friedlander, H. Ma, L. Teneva, and J. Kittinger. 2018. "Estimating Nearshore Coral Reef-Associated Fisheries Production from the Main Hawaiian Islands." Edited by Sebastian C. A. Ferse. *PLOS ONE* 13 (4): e0195840. https://doi.org/10.1371/journal.pone.0195840.

McLeod, E., R. Salm, A. Green, and J. Almany. 2009. "Designing Marine Protected Area Networks to Address the Impacts of Climate Change." *Frontiers in Ecology and the Environment* 7 (7): 362–70. https://doi.org/10.1890/070211.

Meyer, C., and K. Holland. 2005. "Movement Patterns, Home Range Size and Habitat Utilization of the Bluespine Unicornfish, *Naso unicornis* (Acanthuridae) in a Hawaiian Marine Reserve." *Environmental Biology of Fishes* 73 (2): 201–10. https://doi.org/10.1007/s10641-005-0559-7.

Meyer, C. Y. Papastamatiou, and T. Clark. 2010. "Differential Movement Patterns and Site Fidelity among Trophic Groups of Reef Fishes in a Hawaiian Marine Protected Area." *Marine Biology* 157 (7): 1499–1511. https://doi.org/10.1007/s00227-010-1424-6.

Moberg, F., and C. Folke. 1999. "Ecological Goods and Services of Coral Reef Ecosystems." *Ecological Economics* 29 (2): 215–33. https://doi.org/10.1016/S0921-8009(99)00009-9.

Mumby, P., N. Wolff, Y. Bozec, I. Chollett, and P. Halloran. 2014. "Operationalizing the Resilience of Coral Reefs in an Era of Climate Change: Mapping Resilience." *Conservation Letters* 7 (3): 176–87. https://doi.org/10.1111/conl.12047.

Nadon, M. 2016. "Stock Assessment of the Coral Reef Fishes of Hawai'i, 2016," 217.

NOAA Coral Reef Watch. 2018. 5 km Virtual Stations (Version 3), Latest Stress Level, Data, and Graphs. https://coralreefwatch.noaa.gov/satellite/index.php.

Ong, L., and K. Holland. 2010. "Bioerosion of Coral Reefs by Two Hawaiian Parrotfishes: Species, Size Differences and Fishery Implications." *Marine Biology* 157 (6): 1313–23. https://doi.org/10.1007/s00227-010-1411-y.

Ortiz, D., and B. Tissot. 2012. "Evaluating Ontogenetic Patterns of Habitat Use by Reef Fish in Relation to the Effectiveness of Marine Protected Areas in West Hawai'i." *Journal of Experimental Marine Biology and Ecology* 432–433 (November): 83–93. https://doi.org/10.1016/j.jembe.2012.06.005.

Ortiz, D., and B. Tissot. 2008. "Ontogenetic Patterns of Habitat Use by Reef-Fish in a Marine Protected Area Network: A Multi-Scaled Remote Sensing and in Situ Approach." *Marine Ecology Progress Series* 365 (August): 217–32. https://doi.org/10.3354/meps07492.

Pillans, R., R. Babcock, D. Thomson, M. Haywood, R. Downie, M. Vanderklift, and W. Rochester. 2017. "Habitat Effects on Home Range and Schooling Behaviour in a Herbivorous Fish (*Kyphosus bigibbus*) Revealed by Acoustic Tracking." *Marine and Freshwater Research* 68 (8): 1454. https://doi.org/10.1071/MF16199.

Randall, J. 1961. "Vol15n2-215-272.Pdf." Pacific Science.

Roberts, C., B. O'Leary, D. McCauley, P. Cury, C. Duarte, J. Lubchenco, D. Pauly, et al. 2017. "Marine Reserves Can Mitigate and Promote Adaptation to Climate Change." *Proceedings of the National Academy of Sciences*, June, 201701262. https://doi.org/10.1073/pnas.1701262114.

Rodgers, K., M. Kido, P. Jokiel, T. Edmonds, and E. Brown. 2012. "Use of Integrated Landscape Indicators to Evaluate the Health of Linked Watersheds and Coral Reef Environments in the Hawaiian Islands." *Environmental Management* 50 (1): 21–30. https://doi.org/10.1007/s00267-012-9867-9.

Russ, G., and A. Alcala. 2003. "Marine Reserves: Rates and Patterns of Recovery and Decline of Predatory Fish, 1983–2000." *Ecological Applications* 13 (6): 1553–65. https://doi.org/10.1890/01-5341.

Sakihara, T., L. Nishiura, T. Shimoda, T. Shindo, and R. Nishimoto. 2015. "Brassy Chubs *Kyphosus vaigiensis* Display Unexpected Trans-Island Movement along Inshore Habitats." *Environmental Biology of Fishes* 98 (1): 155–63. https://doi.org/10.1007/s10641-014-0245-8.

Salm, R., and S. Coles. 2001. "Scientific Principles for Establishing MPAs to Alleviate Coral Bleaching and Promote Recovery." In *Coral Bleaching and Marine Protected Areas. Proceedings of the Workshop on Mitigating Coral Bleaching Impact through MPA Design. Bishop Museum, Honolulu, Hawai'i, 29-31 May 2001. Asia Pacific Coastal Program Report# 0102-Pages: 53-59.* http://epubs.aims.gov.au/handle/11068/6542.

Schemmel, E., and A. Friedlander. 2017. "Participatory Fishery Monitoring Is Successful for Understanding the Reproductive Biology Needed for Local Fisheries Management."

Environmental Biology of Fishes 100 (2): 171–85. https://doi.org/10.1007/s10641-016-0566-x.

Smith, M. Kimberly. 1993. "An Ecological Perspective on Inshore Fisheries in the Main Hawaiian Islands." *Marine Fisheries Review* 55 (2): 34–49.

Smith, S., W. Kimmerer, E. Laws, R. Brock, and T. Walsh. 1981. "Kāneʻohe Bay Sewage Diversion Experiment: Perspectives on Ecosystem Responses to Nutritional Perturbation." *Pacific Science*, 279–395.

Stamoulis, K., J. Delevaux, I. Williams, M. Poti, J. Lecky, B. Costa, M. Kendall, et al. 2018. "Seascape Models Reveal Places to Focus Coastal Fisheries Management." *Ecological Applications*, May. https://doi.org/10.1002/eap.1696.

Stamoulis, K., and A. Friedlander. 2013. "A Seascape Approach to Investigating Fish Spillover across a Marine Protected Area Boundary in Hawaiʻi." *Fisheries Research* 144 (July): 2–14. https://doi.org/10.1016/j.fishres.2012.09.016.

Stamoulis, K., A. Friedlander, C. Meyer, I. Fernandez-Silva, and R. Toonen. 2017. "Coral Reef Grazer-Benthos Dynamics Complicated by Invasive Algae in a Small Marine Reserve." *Scientific Reports* 7 (March): 43819. https://doi.org/10.1038/srep43819.

Sustainable Hawaiʻi Initiative. 2018. https://governor.hawaii.gov/sustainable-hawaii-initiative/.

Toonen, R., K. Andrews, I. Baums, C. Bird, G. Concepcion, T. Daly-Engel, J. Eble, et al. 2011. "Defining Boundaries for Ecosystem-Based Management: A Multispecies Case Study of Marine Connectivity across the Hawaiian Archipelago." *Journal of Marine Biology* 2011: 1–13. https://doi.org/10.1155/2011/460173.

Wedding, L., J. Lecky, J. Gove, H. Walecka, M. Donovan, G. Williams, J. Jouffray, et al. 2018. "Advancing the Integration of Spatial Data to Map Human and Natural Drivers on Coral Reefs." *PLOS One* 13 (3): e0189792.

Weeks, R., P. Aliño, S. Atkinson, P. Beldia, A. Binson, W. Campos, R. Djohani, et al. 2014. "Developing Marine Protected Area Networks in the Coral Triangle: Good Practices for Expanding the Coral Triangle Marine Protected Area System." *Coastal Management* 42 (2): 183–205. https://doi.org/10.1080/08920753.2014.877768.

Weeks, R., A. Green, E. Joseph, N. Peterson, and E. Terk. 2017. "Using Reef Fish Movement to Inform Marine Reserve Design." Edited by Michael Bode. *Journal of Applied Ecology* 54 (1): 145–52. https://doi.org/10.1111/1365-2664.12736.

Williams, I., W. Walsh, J. Claisse, B. Tissot, and K. Stamoulis. 2009. "Impacts of a Hawaiian Marine Protected Area Network on the Abundance and Fishery Sustainability of the Yellow Tang, *Zebrasoma flavescens*." *Biological Conservation* 142 (5): 1066–73. https://doi.org/10.1016/j.biocon.2008.12.029.

Williams, I., B. Richards, S. Sandin, J. Baum, R. Schroeder, M. Nadon, B. Zgliczynski, P. Craig, J. McIlwain, and R. Brainard. 2011. "Differences in Reef Fish Assemblages between Populated and Remote Reefs Spanning Multiple Archipelagos Across the Central and Western Pacific." *Journal of Marine Biology* 2011: 1–14. https://doi.org/10.1155/2011/826234.

Williams, I., D. White, R. Sparks, K. Lino, J. Zamzow, E. Kelly, and H. Ramey. 2016. "Responses of Herbivorous Fishes and Benthos to 6 Years of Protection at the Kahekili Herbivore Fisheries Management Area, Maui." Edited by Sebastian C. A. Ferse. *PLOS ONE* 11 (7): e0159100. https://doi.org/10.1371/journal.pone.0159100.

Williams, I., and H. Ma. 2013. "Estimating Catch Weight of Reef Fish Species Using Estimation and Intercept Data from the Hawai‘i Marine Recreational Fishing Survey." *Honolulu: NOAA Pacific Islands Fisheries Science Center Administrative Report H-13-04*, 61.

CHAPTER 4. PRIORITIZING REEF RESILIENCE THROUGH SPATIAL PLANNING FOLLOWING A MASS CORAL BLEACHING EVENT

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Abstract

Following the 2014-2017 global bleaching event, managers are seeking local interventions to promote resilience beyond monitoring coral decline. Here, we applied a spatial approach to map and prioritize areas to increase coral reef resilience for the recent and future climate events based on habitat, fisheries, and climate features. Specifically, Marxan was used to identify the most effective areas for herbivore management in Hawai‘i following consecutive mass bleaching events in 2014 and 2015. We found distinct resilience hotspots along the west coast of Hawai‘i Island and around the islands of Moloka‘i, Lana‘i, Maui, and Kahao‘olawe. We further analyzed the top 25% of planning units contained in these hotspots and found that a subset of habitat types, current biomass of herbivore functional groups, and temperature variability were significantly different from surrounding areas and thus contain potential resilience drivers. Additionally, the top quartile of reef resilience areas had a 14% overlap with existing Marine Managed Areas (MMAs); however, they had only a 1% overlap with areas that currently provide full protection of herbivores, indicating that these results can be used to design additional Herbivore Management Areas (HMAs). This resilience-based approach can serve as an example for coral reef management in Hawai‘i, on other Pacific Islands, and beyond, in developing practical strategies that build on existing tools and prioritized areas.

Introduction

Coral reefs worldwide are experiencing more frequent and severe mass bleaching events (Berkelmans et al. 2004; Hughes, Kerry, et al. 2017), which are predicted to become annual occurrences in some locales within the next ten years (van Hooidonk et al. 2016a). Further, it is estimated that over 20% of the world’s coral reefs have died due to bleaching in the last 20 years (Hoegh-Guldberg and Bruno 2010) owing to the mass global bleaching events in 1998, 2010, and 2014-17 (Heron et al. 2016; Hughes et al. 2018). In Hawai‘i, coral reefs were exposed to extremely high temperatures in back-to-back bleaching events in 2014 and 2015. This event was the most severe coral bleaching event to date with a maximum of 16 Degree Heating Weeks (DHW) observed in west Hawaiʻi, double the level at which one would expect widespread coral bleaching and mortality (NOAA Coral Reef Watch 2015). Coral mortality following the event was extensive: on average 50% of corals died at monitoring sites in west Hawaiʻi (Kramer et al. 2016) (Figure 4.1). Managers in Hawaiʻi and around the world are now searching for local-scale interventions that may build long-term resilience to bleaching events as well as promote recovery from the latest global event (Great Barrier Reef Marine Park Authority 2017; Rosinski et al. 2017).

Figure 4.1. Coral mortality along the west coast of Hawaiʻi Island following consecutive bleaching events in 2014 and 2015. An average of 50% coral loss was observed in this region and now local managers are eager to go beyond monitoring decline to developing strategies to build long-term resilience. (Photo credit: DAR)

When an ecological disturbance, such as the recent global bleaching event, occurs on reefs, it can result in regime shifts (e.g., coral to macroalgae dominated systems). Regime shifts can be permanent or temporary, depending on the resilience of the system. Resilience refers to the ability of coral reefs to "absorb or withstand perturbations and other stressors such that the system remains within the same regime, maintaining its structure and functions," and includes recovery from past events and resistance to future events (Holling 1973; Walker et al. 2004). Without local management intervention to bolster reef resilience, recurrent coral bleaching events will increase the risk of tipping points – the point at which recovery will be considerably more difficult, if not impossible (Ateweberhan et al. 2013; Graham et al. 2013; Selkoe et al. 2015; Ove Hoegh-Guldberg et al. 2017).

Globally, there has been a shift towards resilience-based management for coral reefs, which presents a process to identify management levers that will reduce coral reef vulnerability to climate impacts, including bleaching events (Graham et al. 2013; Anthony et al. 2015). Underpinning the resilience-based management concept is promoting processes, including herbivory, that build both resistance to and recovery from bleaching events (Graham et al. 2013; Hixon 2015; Hughes, Barnes, et al. 2017). In addition to herbivore management, examples of other reef resilience strategies can include management of land-based stressors, generally reducing fishing pressure through no-take areas, and coral transplantation efforts (McClanahan 2012, Aswani et al. 2015). Strategically designing networks of Marine Managed Areas (MMAs) and increasing herbivorous fish abundance are two dominant strategies that have been recommended to prevent phase shifts and build resilience (McLeod et al. 2009; Graham et al. 2013; Green et al. 2014). Leveraging the ecological roles of multiple herbivore functional groups (e.g. browsers, grazers, and scrapers) by ensuring functional diversity within protected areas is recommended to maximize recovery processes (Nyström et al. 2000; Bellwood et al. 2004; Nyström 2006; Green and Bellwood 2009). Current strategies to promote recovery following bleaching events are limited and focus on a narrow segment of options. Thus, there is an urgent need to explore a wider breadth of management options for bleaching recovery and long-term resilience (Aswani et al. 2015; Comte and Pendleton 2018).

Here, we apply the concept of resilience-based management for the development of practical management actions in Hawai‘i after consecutive mass bleaching events. In this analysis, we designed a spatial planning approach to manage herbivory--the establishment of Herbivore Management Areas (HMAs), where the take of herbivorous fishes and invertebrates (e.g., sea urchins) is prohibited, while other extractive and non-extractive uses are allowed (McClanahan et al. 2012; Mumby et al. 2014; Bozec et al. 2016). Our overall goal was to identify specific areas around two regions in the main Hawaiian Islands that were severely impacted by the 2014-2017 global bleaching event where HMAs would have the greatest possibility of contributing to long-term resilience. Also, we investigated the habitat, fisheries, and climate features within the areas that were prioritized in our Marxan analysis and compared selected areas with existing MMAs. This resilience-based management approach can serve as an example for bleaching mitigation and resilience-based management for other regions affected by the global event.

Materials and Methods

Planning Area and Stratification

The main Hawaiian Islands comprise an isolated archipelago that stretches approximately 300 miles from the island of Hawai‘i to Niihau. Approximately one quarter of all Hawaiian marine species are endemic (Abbott 1999, Randall 2007, Briggs and Bowen 2012) and herbivorous fishes dominate the region’s reefs, comprising approximately 55% of the total fish biomass (Friedlander and DeMartini 2002). Ecological patterns across the main Hawaiian Islands are structured by both biological and physical forcing factors (Dollar 1982; Friedlander et al. 2003; Storlazzi et al. 2005; Franklin et al. 2013). Hard bottom benthic habitats in Hawai‘i are dominated by hard corals, turf algae, or macroalgae regimes (Jouffray et al. 2014).

The planning areas for this analysis were Maui Nui and west Hawai‘i, which both experienced high levels of exposure to bleaching conditions and coral mortality during the 2014/15 bleaching events (NOAA Coral Reef Watch 2015, Kramer et al. 2016) (Figure 4.2). This project explores the use of herbivore management which has been proven effective within the planning areas. For example, in the first six years of the Kahekili Herbivore Fisheries Management Area in west Maui, mean herbivorous fish biomass has increased (surgeonfish by 28% and parrotfish by 139%) and coral cover has stabilized, demonstrating promise for additional HMAs in this region

(Williams et al. 2016). Maui Nui and west Hawai‘i were selected because they represent two regions in the main Hawaiian Islands where herbivore protection could be prioritized and piloted to promote recovery from the past bleaching events as well as long-term climate resilience.

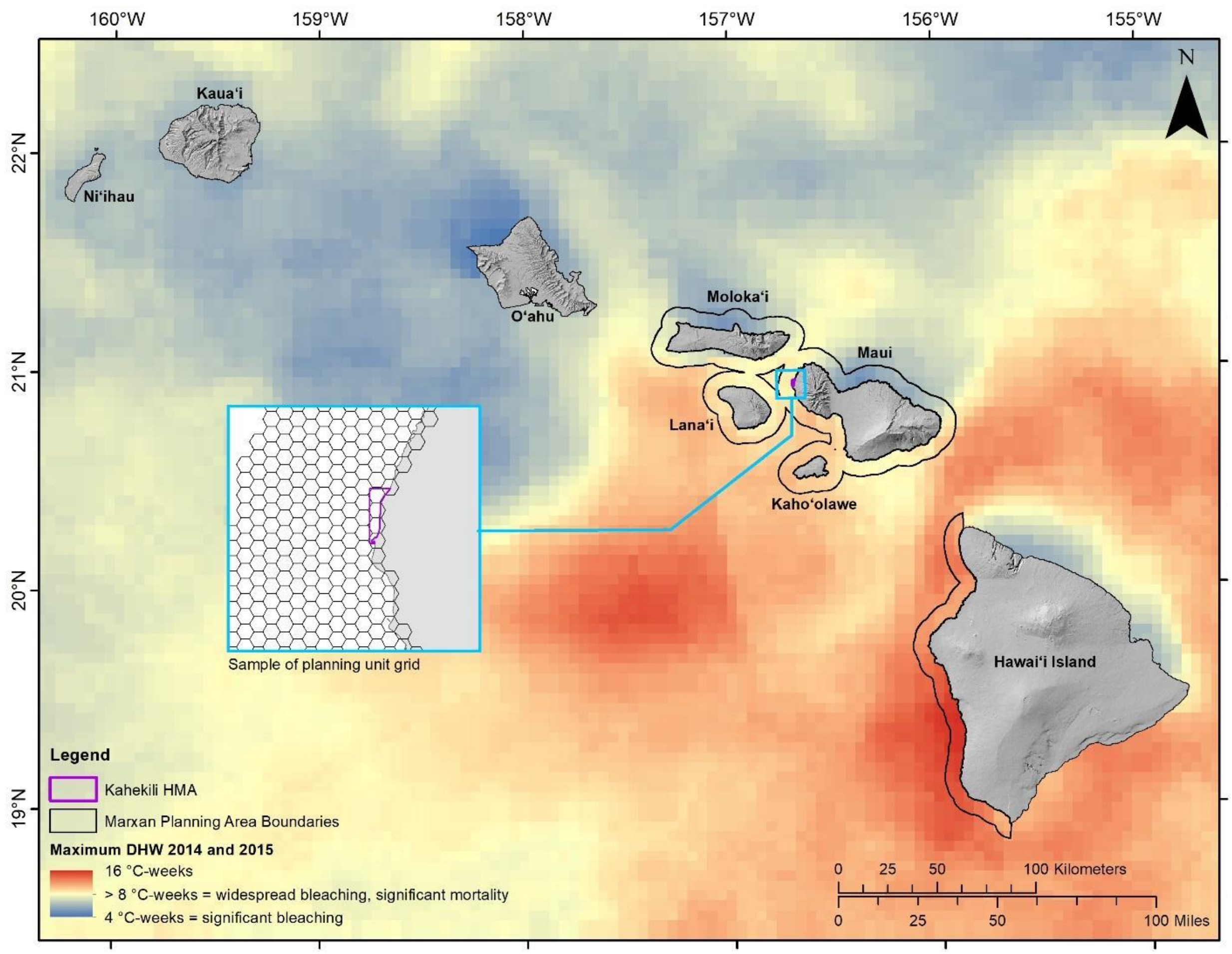

Figure 4.2. The planning area included the western shore of Hawai‘i Island and Maui Nui (islands of Moloka‘i, Lana‘i, Maui, and Kahao‘olawe). These areas were selected because of their high exposure to temperature stress during the 2014/15 mass bleaching events across the main Hawaiian Islands. The planning unit grid consisted of 0.65 km^2 hexagons with 500 m sides (see map inset).

The offshore extent of the planning area was 7.5 km from the coastline, in order to incorporate the furthest extent of existing MMA boundaries. The planning area was divided into hexagonally shaped planning units with 500-meter sides, producing an area of 0.65 km^2 per planning unit. There were a total of 10,100 planning units included in the analysis, covering an area of 6,565 km^2. The planning area was also stratified by region, ensuring that results would be relatively spread across the two regions and accounted for documented genetic breaks between island groups (Toonen et al. 2011). Maui Nui was left as a single stratification unit as the islands share a certain amount of genetic connectivity (Toonen et al. 2011).

Data synthesis and preparation

We conducted a Marxan analysis to identify priority hotspots for herbivore management. Marxan has guided numerous MPA network design projects, including the re-zoning of the Great Barrier Reef (Fernandes et al. 2005; Game et al. 2008) and re-design of protected areas along California's coast (Klein et al. 2008; Gleason et al. 2013). The Marxan algorithm identifies units within a planning area that meet user-defined conservation targets for features in the environment, while minimizing the total cost (also a user-defined layer) and achieving a certain level of compactness across the results (Ball, Possingham, and Watts 2009) . For this analysis, we used "Marxan with Probabilities," known as MarProb, to incorporate impacts from local threats such as land-based sources of pollution and sedimentation into the network design (Tulloch et al. 2013).

We first synthesized existing statewide data relevant to the ecological design principles for HMAs and Hawai'i-specific considerations established by Chung et al. (2018), which investigated how habitat, life history, and other ecological considerations could be addressed in HMA design (Table 4.1). Each conservation feature was then assigned a target, which was the percentage of that layer that should be represented in the resulting Marxan solutions. Targets ranged from 5-100% based on the relative importance of the feature and its rarity within the planning area.

Table 4.1. Data layers used in this analysis as they relate to HMA ecological design principles (Chung et al. 2018). An "x" indicates the data layer fulfills the corresponding design principle. An asterisk (*) indicates data layers created for this analysis.

		Herbivore Management Area Ecological Design Principles													
Category	**Data layer**	Protect 20-40% of each herbivore habitat type	Protect habitat relevant to each functional group	Protect areas with naturally high herbivore biomass	Protect areas likely to have high herbivore fisheries recovery	Include areas important for all life-history stages	Ensure larval connectivity	Ensure network is large enough to sustain herbivores	Scale size and spacing based on movement patterns	Include areas that have withstood ecological disturbance	Include areas likely to withstand future disturbance	Include areas at high risk of regime shifts	Avoid areas with high levels of sediment and nutrients	***Marxan treatment***	***Target***
Habitats	Aggregate Reef	x	x			x	Not addressed as individual data layers, could be addressed post-analysis through final placement and design of HMAs.					Not addressed as individual data layers, but was addressed through the selection of the planning area.		Conservation Feature	30%
	Aggregated Patch Reef	x	x			x									100%
	Individual Patch Reef	x	x			x									100%
	Spur and Groove	x	x			x									30%
	Rock/Boulder	x	x			x									15%
	Rubble	x	x												15%
	Sand	x	x												15%
	Scattered coral/rock	x	x												15%
	Pavement	x	x												5%
	Pavement with Sand Channels	x	x												5%
	Estuaries	x	x			x									30%
Critical Areas	Weekly Temperature Variability									x	x				30%
	Coral Percent Cover*	x	x			x									5%
	Herbivore biomass: scrapers*			x											30%

	Herbivore biomass: grazers*			x									30%
	Herbivore biomass: browsers*			x									30%
	Potential gain in fish biomass				x								30%
Local Threats	Sediment										x	Probability of Impact	Avoided in analysis
	Effluent										x		
	Agriculture and Golf Course runoff										x		
	Impervious Surfaces										x		
Local Use	Herbivorous fish catch by gear type											Cost Layer	

Layers for ten benthic habitat types that are relevant to herbivorous fish life history and daily movements were used as conservation features in the analysis (Costa and Kendall 2016). Estuaries were also included as they can serve as nursery habitat for multiple herbivorous fish species (Boehlert and Mundy 1988; Friedlander and Parrish 1997). High temperature variability has been found to be a local driver of both bleaching resistance and recovery in the main Hawaiian Islands and elsewhere and so was also included as a conservation feature (Safaie et al. 2018, T. Oliver, personal communication, 2018). The upper quartile of values in this continuous layer was selected to include only areas with high variability. We also included a layer that modeled which areas across the state would see the greatest increase in resource fish biomass, many of which were herbivorous fishes, if fishing effort was reduced (Stamoulis et al. 2018).

In addition to existing data layers, we created several layers to include as conservation features specific to coral reef resilience concepts. To do this we used a database of in-water benthic and fish monitoring data for the main Hawaiian Islands which contains observations from 1706 sites in West Hawaiʻi and 3329 sites from Maui Nui collected between 2000 and 2017, synthesized and calibrated by Donovan (2017). Spatial predictions for fish and benthic variables were created using Boosted Regression Trees following methods of Stamoulis et al. (2016), who also developed a database of gridded predictors on terrain, habitat, oceanographic, and human influences. First, we created a predictive layer of coral cover and used the upper quartile to target areas with high coral percent cover. We also created individual layers of biomass by herbivore functional group (e.g. grazers, browsers, and scrapers (as defined by Donovan (in review)) and again used the top quartile in the analysis. First, we created a predictive layer of coral cover and used the upper quartile to target areas with high coral percent cover before the bleaching event. We also created individual layers of biomass by herbivore functional group (e.g. grazers, browsers, and scrapers (as defined by Donovan (in review)) and again used the top quartile in the analysis.

Layers representing local threats were incorporated using the MarProb probabilities feature to avoid selecting areas with a high risk of impact from these threats. Sediment, effluent, agriculture and golf course runoff, and urban runoff from impervious surfaces were each integrated into the MarProb feature (Lecky 2016; Wedding et al. 2018). Layers representing non-commercial fishing catch by gear type were combined into a cost layer, allowing areas of high use, and thus high potential conflict, to be minimized in network solutions (McCoy et al. 2018; Wedding et al. 2018). We specifically used a subset of gear types that would be likely to target herbivorous fish catch (e.g. shore-based spear, boat-based spear, and shore-based net fishing).

We integrated spatial data into Marxan by calculating the total area of each feature in each planning unit using the Tabulate Area tool in ArcGIS. Data layers representing continuous data (e.g. herbivorous fish biomass and coral cover) were classified into quartiles before analysis, so that the top 25% of data values could be targeted in the Marxan solution. Data layers representing local threats (e.g. sediment, effluent, urban runoff, and agriculture/golf course runoff) were normalized and combined into a probability of impact value for each planning unit within the planning area. The cost layer was created by normalizing and summing the multiple layers representing non-commercial catch by the shore-based net and both shore and boat-based spear fishing. In order to further prioritize planning units within shallow, nearshore waters most representative of the coral reef ecosystem, the cost layer was adjusted so that a higher cost value was given to areas deeper than the 50-meter depth contour.

Data Analysis

We then ran two analysis scenarios, one where no specific areas were locked in (known as an unrestrained scenario), to allow for the software to primarily consider conservation features and cost. Alternatively, we ran a scenario where MMAs that offer full herbivore protection (no-take areas and current HMAs) were locked in, meaning the software automatically included them in the results and also used these planning units as a starting point to include additional areas. For both scenarios, the Boundary Length Modifier (BLM), which affects size and compactness of the results, was calibrated to 0.1 to ensure a certain level of compactness, and the Probability Weighting Factor (PWF), which scales the relative importance of meeting all targets while minimizing the probability of impacts, was calibrated to 10,000. We then ran Marxan 100 times for each scenario, with 10,000,000 iterations per run, producing 100 distinct results per scenario.

Selection frequency maps were created by displaying the percentage of time a particular area was selected for inclusion in the network out of 100 runs in Marxan. From this output, we selected the upper quartile, highlighting planning units that were chosen ≥75 out of the 100 runs.

Within this focused output, we calculated the average area (km^2) of each conservation feature within each planning unit by using the Tabulate Area tool in ArcGIS. We tested for significant differences between the average area of each feature both within the top 25% and in the remaining area using two-sample t-tests with unequal variances. We also identified the subset of planning units that overlap with existing MMAs that offer full herbivore protection. Lastly, we compared the unrestrained results with those locking in MMAs currently protecting herbivores by calculating the percent overlap of the two scenario planning units.

Results

Selection Frequency Outputs

We used Marxan to identify resilience hotspots, i.e., areas that fulfilled the conservation feature targets that were set while also minimizing the cost of areas selected within Maui Nui and west Hawai‘i. The results of the unrestrained Marxan scenario displayed several potential resilience hotspots within the planning area of Maui Nui and west Hawai‘i (Figure 4.3). In Maui Nui, a large number of planning units within the top quartile of selection were located around Moloka‘i (58% of planning units), especially along the southeastern and north shores. Approximately 21% of areas were selected around Maui, concentrated near the southern and eastern shores of the island. Lana‘i had considerably less area selected, 0.5%, likely because of limited data availability. Kahao‘olawe was not selected in the unrestrained scenario due to poor data availability for features in that area. In west Hawai‘i, hotspots were spread throughout the coastline with larger hotspots in the northern and southern ends of the coastline, totaling 20.5% of the top quartile selected area.

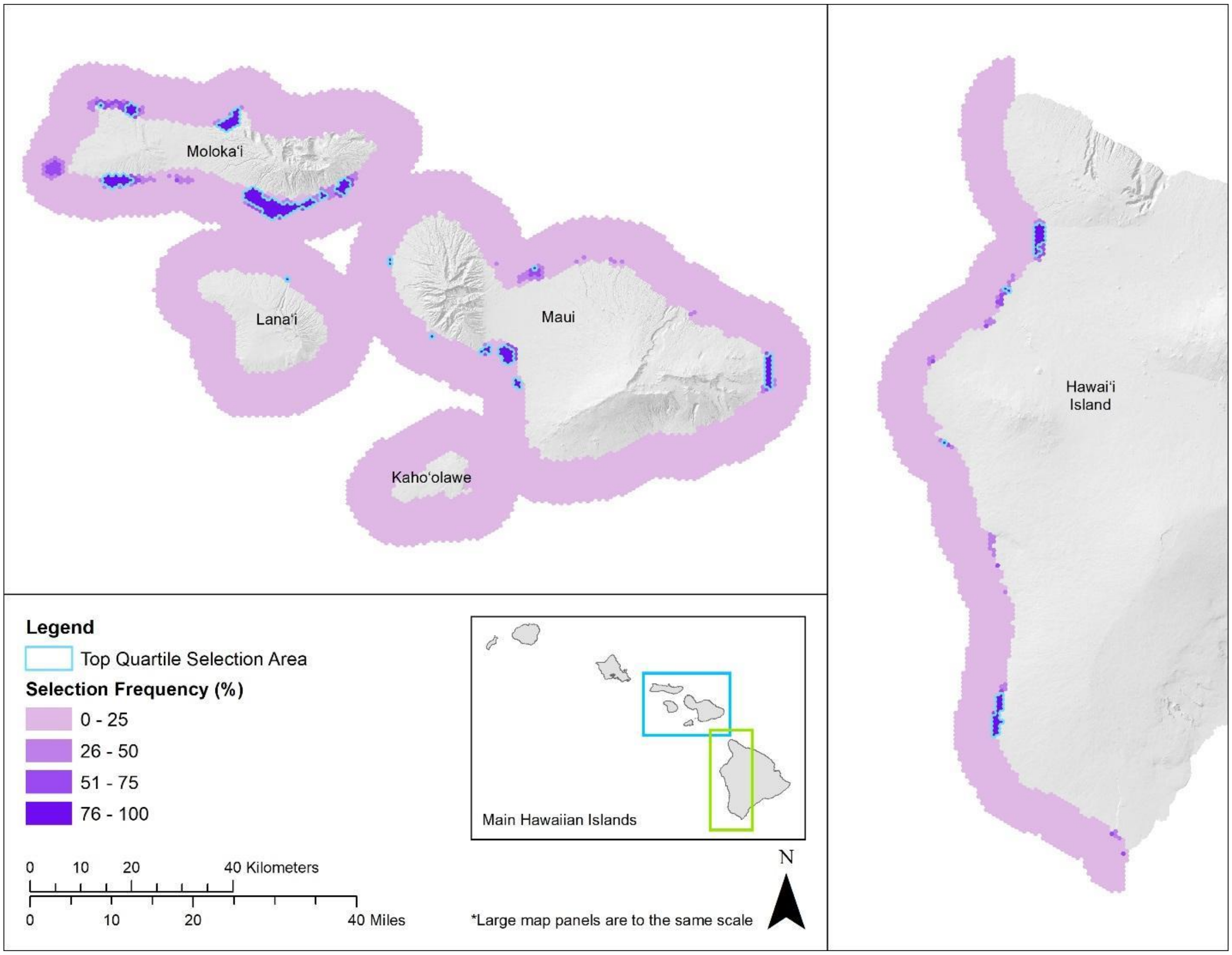

Figure 4.3. Selection frequency map for the unrestrained Marxan scenario with no areas locked in, which identify areas around West Hawai‘i and Maui Nui where HMAs could be prioritized.

Comparatively, locking in existing MMAs that offer full herbivore protection automatically included the Kahao‘olawe Island Reserve, some small areas around Maui including the Kahekili Herbivore Management Area, and a few areas in west Hawai‘i, notably the Ka‘ūpūlehu no-take area (Figure 4.4). These locked-in areas represent 5% of the total planning area.

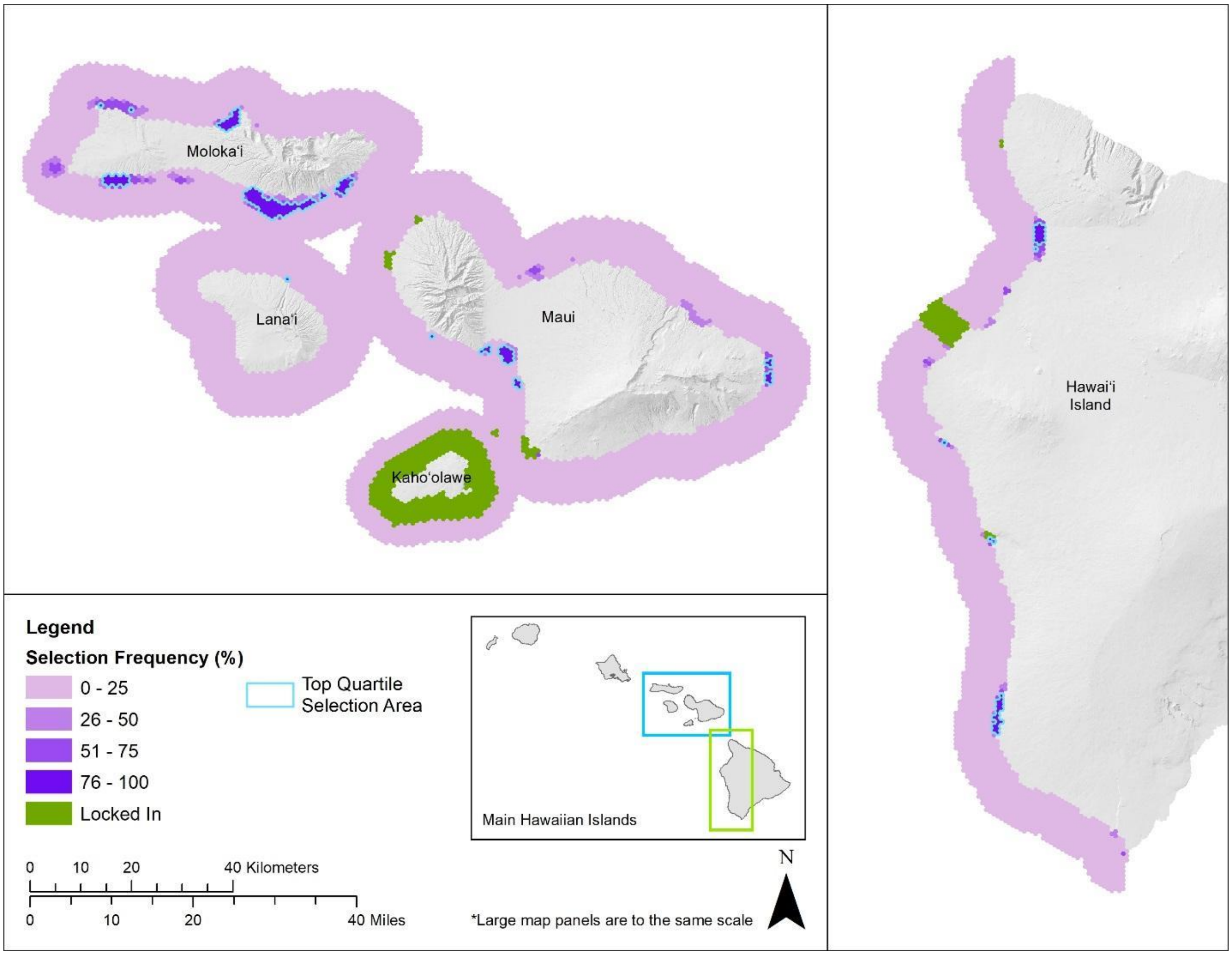

Figure 4.4. Selection frequency map for the Marxan scenario with MMAs that offer currently full herbivore protection (no-take and current HMAs) locked in.

Top Quartile Results

Selecting the top quartile of the unrestrained results, meaning planning units that were selected ≥ 75 out of 100 Marxan runs, resulted in 191 selected planning units comprising a total area of 124.15 km^2 (~2% of the total planning area). Out of those planning units, 39 of them (25.35 km^2) were located in west Hawai‘i while 152 of them (98.8 km^2) were in Maui Nui. We then compared the tabulated average area of each conservation feature within each planning unit for both the top quartile and the remaining planning area (Figure 4.5). The average area for all conservation features (see Table 4.1) except for ‘rubble’ and ‘estuaries’ was significantly higher in the planning units within the top quartile ($p \leq 0.05$). All of the critical area conservation features had a significantly higher average area within the top quartile planning units when compared with the rest of the planning units ($p \leq 0.05$).

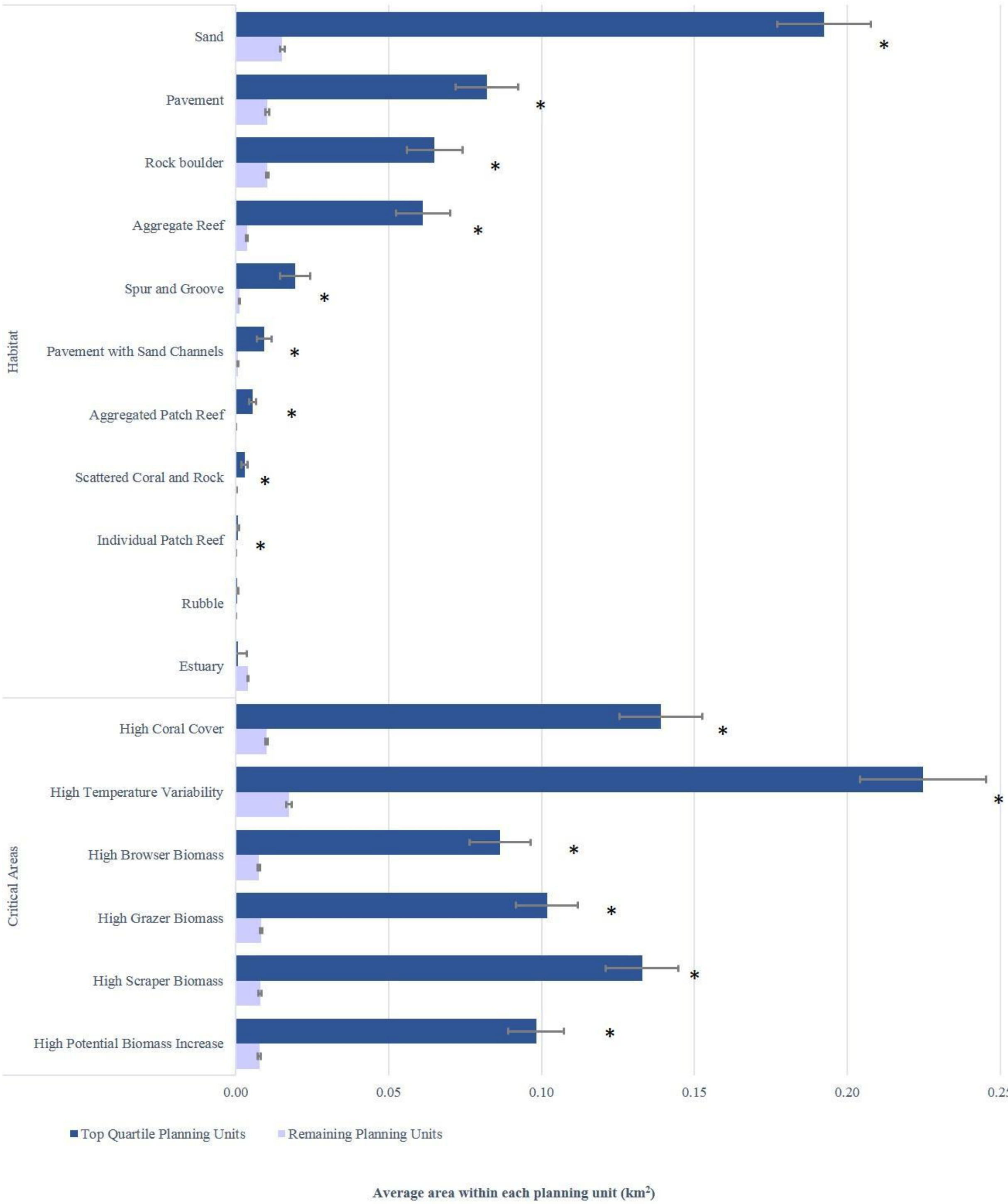

Figure 4.5. Comparison between the average area of each conservation feature within each planning unit in the top quartile (planning units that appeared in ≥75% of Marxan results) (n = 191) and planning units in the remaining planning area (n = 9,909). Asterisk (*) indicates significantly different values ($p \leq 0.05$). Error bars represent standard error.

Overlap with existing MMAs

Comparing the top quartile of the unrestrained scenario results to existing MMAs, there were two planning units (1%) that overlapped with the subset of existing MMAs currently fully protecting herbivores, which both fall within the Kahekili Herbivore Fisheries Management Area on Maui. Additionally, there was a 14% overlap between the top quartile and the overall footprint of existing MMAs across the planning area. Further, when we compared the unrestrained scenario to the locked in scenario, 97% of units selected in the unrestrained scenario were also selected when existing MMAs were locked in. Conversely, 99% of planning units selected in the locked in scenario were also selected when the analysis was unrestrained.

Discussion

Mass coral bleaching events have spurred management action to build coral reef resilience on a local scale. For example, creation of a Great Barrier Reef Blueprint for Resilience and the Coral Bleaching Recovery Plan in Hawai‘i have brought together researchers, managers, and those dependent on reefs to explore innovative interventions. However, a current challenge is how to apply concepts of resilience-based management at a local scale in a practical and effective way. In this study, we targeted one recommended resilience-building action, establishing a network of HMAs, and explored how to spatially prioritize areas following the mass bleaching events in 2014 and 2015 across Maui Nui and West Hawai‘i in the main Hawaiian Islands. We found that the spatial prioritization tool, Marxan, helped to map multiple hotspots where HMAs would have the greatest effect based on local ecological conditions, while also balancing human use. This approach can enable managers in Hawai‘i to effectively target and implement HMAs to promote coral resilience. Additionally, this method could be expanded to managers in other islands and regions looking to integrate climate resilience considerations into their spatial planning following a mass coral bleaching event.

Spatial Prioritization Approach

We used Marxan to identify and spatially prioritize coral reef resilience hotspots within our planning area. There have been several studies using a similar approach, integrating resilience concepts into a spatial prioritization by using a combination of habitat and climate features (Green et al. 2009; Magris et al. 2015; Parker et al. 2015; Davies et al. 2016). However, this study uniquely used current herbivore biomass by functional group to hone in on specific geographic areas and habitats critical to these resilience-building species. These predictive layers, which were developed for this study based on in-water observations, demonstrated the wide variability of these groups across Maui Nui and West Hawai‘i. Although previous studies have emphasized the importance of monitoring and managing multiple herbivore functional groups (Bellwood et al. 2004; Green and Bellwood 2009), our research represents a strategy to prioritize specific geographic areas where functional diversity is high.

Additionally, there have been several approaches for integrating resilience concepts into conservation planning, which our study blended into a strategy that accounted for lack of certainty about future climate impacts. First, a strategy has been to prioritize specific resilient habitat features (e.g. depth, habitat complexity) in the analysis (Parker et al. 2015; Davies et al. 2016). Alternatively, the potential for future exposure to climate impacts can be accounted for by stratifying the planning area, ensuring the final design accounts for risk spreading, replication, and representation post-analysis (Green et al. 2009; Green et al. 2014). Lastly, Magris et al. (2015) developed multiple regimes based on past and future thermal refugia to configure potential MPAs in a resilient network. In the current study, we learned that this approach is not practical for regions like the main Hawaiian Islands that have not experienced past bleaching at the scale of the 2014/15 event. Also, we considered including data on future climate impacts. However, work by van Hooidonk et al. (2016), which projects severe coral bleaching to occur annually starting between 2035 – 2045 in the main Hawaiian Islands under a business as usual scenario (i.e. RCP8.5), showed that small differences exist (5 years) in the projected onset of annual severe bleaching across Maui Nui and West Hawai‘i. As such, we assumed spatial uniformity in future climate impacts across our planning area.

Ultimately, we used a coral reef regime-type approach, using modeled layer of temperature variability, which was shown to be a strong driver of resistance and recovery during the 2014/15 bleaching event in Hawai‘i as well as other coral reef regions (Safaie et al. 2018, T. Oliver, personal communication, 2018). This allowed us to examine variability along individual coastlines within the planning area; however, it is limited by the fact that it is based on performance in one environmental disturbance. Additional resilience concepts could be integrated in post-analysis including spreading HMAs evenly across the islands and ensuring multiple replicates across each coastline. This strategy may guide managers in other regions that may not have data related to patterns of climate impacts upon which to base spatial planning decisions.

Analytical Limitations

A Marxan-based approach has been used in numerous MPA design studies, yet there are several limitations to consider when interpreting these results. For instance, certain areas (e.g. the island of Kahaoʻolawe) were not selected due to lack of habitat data in this area and this affected the resulting outputs. However, since the Kahaoʻolawe is a Marine Reserve, it was locked into the second scenario and was therefore included in the network. Also, more refined data of drivers of coral resistance or recovery from bleaching events at a coastline scale (e.g. maps of presence of vulnerable taxa, high taxa or species diversity) would have added to the climate conservation features.

Regarding the existing MMAs, we explored the footprint of the current network; however, this does not consider the performance or effectiveness of these areas. Further, when we locked in areas into the Marxan analysis, the software builds on these areas first when suggesting other planning units. Information related to compliance or management priority may have narrowed down off of which MMAs it is appropriate to build. However, given that the portion of managed areas currently protecting herbivores is limited, most of the planning area was still open in the analysis.

Another limitation was that several design principles related to ensuring adequate size and spacing for larval and adult fish connectivity could not be incorporated into the Marxan analysis but should rather be a component of post-analysis HMA design. Marxan is a decision-support tool and thus ultimately the placement and arrangement of HMAs will call for collaborative design between reef managers, scientists, and ocean stakeholders. This approach could facilitate this next step because it incorporated data on fisheries catch to minimize impact to herbivore fishing grounds from the beginning of the design process.

Overlap with Existing Marine Managed Areas in West Hawaiʻi

When we compared the top quartile of areas from the Marxan results to the footprint of existing MMAs, we found that existing marine managed areas with full herbivore protection do not overlap well with the benthic and fisheries features targeted in the analysis. These priority reef resilience areas demonstrated some overlap with existing MMAs; however, they had only a minor overlap with MMAs that protect herbivores, indicating improvements could be made to better incorporate this critical ecological function. The fact that the top quartile had a fair amount of overlap with all types of existing MMAs in the planning area suggests that herbivore protections could be added to areas with current place-based rules or boundaries modified to include a great portion of the priority resilience areas.

Additionally, we found that the areas within the top quartile of Marxan results had almost complete overlap even when we locked in existing spatial protections. This result emphasizes that these areas are critically important to consider for additional protection and suggests that, regardless of existing MMAs, these areas are an efficient arrangement of HMAs based on desired habitat types, functional groups, and other considerations. We can also infer that inclusion of less common habitat types (e.g. spur and groove and patch reefs) reduces the flexibility of choosing between multiple areas along the same coastline and is driving the results towards the same locations where these habitats can be included. This also emphasizes the efficiency of the Marxan results given less common but important habitats in this region.

Specific to a particular type of MMA, there were two resiliency hotspots along the West Hawaiʻi coastline that overlap with the network of Fisheries Replenishment Areas (FRAs) at Puako-Anaehoʻomalu and Miloliʻi FRAs. FRAs were established with the specific purpose to manage a commercial aquarium trade in the region and is a significant feature of the West Hawaiʻi management landscape. These managed areas partially manage herbivores, as they restrict take to a small subset of fishes of interest to commercial aquarium collectors; however, the take of most herbivores and fishing is less restrictive in these areas. They have been proven effective for the primary target species, yellow tang (*Zebrasoma flavescens*), where within the first eight years closed areas had five times higher density of juveniles and 48% higher density of adult fish than open areas (Williams et al. 2009). The existing footprint of FRAs, which equates to roughly

30% of the coastline, represents a promising opportunity for effective future HMAs since their boundaries have been already legally established.

Ecosystem-based Management Implications in West Hawai'i

The results of the Marxan analysis provide science to support management in West Hawai'i and overlap with several regional management priorities including the NOAA Habitat Blueprint, the NOAA Sentinel Site Program, and the NOAA West Hawai'i Integrated Ecosystem Assessment (IEA). These findings can be combined with additional place-based science to support reef resilience and management. For example, the West Hawai'i IEA provides a useful framework to inform science-based management decisions across multiple sectors and multiple scales in the West Hawai'i region. The West Hawai'i IEA uses a suite of indicators to track the status and trends of West Hawai'i's coral reef fish and benthic communities (Gove et al. 2016). Several of these biological indicators would be directly linked to tracking the status of the HMAs, if implemented. These indicators convey information specific to detecting fishing effects, ecosystem structure and function and coral reef ecosystem resilience. This complimentary IEA effort could apply indicators such as herbivore biomass (total weight of herbivorous fishes per unit area), target fish biomass (e.g., large parrotfishes, like uhu, or redlip parrotfish, *Scarus rubroviolaceus)*, macroalgal cover, and coral cover. In the future, such IEA indicators can be applied to evaluate the performance of new HMAs in the region.

A number of recent studies in the region also provide complementary information to our findings. For example, stake-holder engagement efforts lead by the West Hawai'i IEA demonstrated that local community members perceived fishing as the strongest driver of coral reef decline in the region (Ingram et al. 2018). Additionally, an ecosystem modeling approach was applied to evaluate the efficacy of alternative fishery management strategies at Puakō, a community in West Hawai'i. This work demonstrated that the implementation of herbivore management areas produced analogous results to the implementation of line fishing only areas, and both showed similar ecological benefits when compared with complete no take areas (Weijerman et al. 2018). These two studies complement our findings in that they demonstrate that fishing pressure is an important concern to those living in this region and that there are several management approaches that may be taken to protect herbivores, including restricting gear (no net and spear), protecting herbivores completely through an HMA, or restricting all fishing and creating a no-take area. Finally, managing for reef resilience must also move beyond just herbivore protection and include a wider array of integrated management strategies. Maynard et al. (2015) assessed the relative resilience of coral reefs within a northern portion of the West Hawai‘i coastline and found some of the areas that Marxan selected to have high relative resilience, namely the Kīholo and Puakō areas. This further emphasizes the importance of these places to focus management efforts that build long-term resilience.

Managing Coral Reefs Following a Mass Bleaching Event

Coral reef managers are looking beyond simply monitoring and reporting on coral bleaching and mortality when a mass bleaching event occurs in their region. Using a spatial planning approach, such as conducting a Marxan analysis, can guide managers on how to prioritize management within the affected areas while balancing the needs of local fishers. The results present an option to apply a tool that managers are already using but with a new, climate-driven objective. This provides a practical resilience-based strategy within the realm of fisheries management and suggests ways to maximize its chance for success through strategic placement and design.

This case study offers specific examples of how local data can be used to identify distinct areas where resilience could be prioritized. Our unique integration of herbivorous fish biomass data at the functional group level is an advancement in implementing resilience-based management. It is predicted that mass bleaching will become an annual phenomenon in Hawai‘i as early as 2035 (van Hooidonk et al. 2016). This study can guide managers in Hawai‘i to implement interventions to build resilience before this fast approaching benchmark. This approach can also serve as an example for other coral reef managers and coastal planners in the Pacific Islands and beyond affected by the 2014-2017 bleaching event and those yet to come.

References

Abbott, I. 1999. "Marine red algae of the Hawaiian Islands." Bishop Museum Press.

Anthony, K., P. Marshall, A. Abdulla, R. Beeden, C. Bergh, R. Black, M. Eakin, et al. 2015. "Operationalizing Resilience for Adaptive Coral Reef Management under Global Environmental Change." *Global Change Biology* 21 (1): 48–61. https://doi.org/10.1111/gcb.12700.

Aswani, S., P. Mumby, A. Baker, P. Christie, L. McCook, R. Steneck, and R. Richmond. 2015. "Scientific Frontiers in the Management of Coral Reefs." *Frontiers in Marine Science* 2 (July). https://doi.org/10.3389/fmars.2015.00050.

Ateweberhan, M., D. Feary, S. Keshavmurthy, A. Chen, M. Schleyer, and C. Sheppard. 2013. "Climate Change Impacts on Coral Reefs: Synergies with Local Effects, Possibilities for Acclimation, and Management Implications." *Marine Pollution Bulletin* 74 (2): 526–39. https://doi.org/10.1016/j.marpolbul.2013.06.011.

Ball, I., H. Possingham, and M. Watts. 2009. "Marxan and Relatives: Software for Spatial Conservation Prioritisation." *Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, Oxford*, 185–195.

Bellwood, D., T. Hughes, C. Folke, and M. Nyström. 2004. "Confronting the Coral Reef Crisis." *Nature* 429 (6994): 827–833.

Berkelmans, R., G. De'ath, S. Kininmonth, and W. Skirving. 2004. "A Comparison of the 1998 and 2002 Coral Bleaching Events on the Great Barrier Reef: Spatial Correlation, Patterns, and Predictions." *Coral Reefs* 23 (1): 74–83. https://doi.org/10.1007/s00338-003-0353-y.

Boehlert, G., and B. Mundy. 1988. "Roles of Behavioral and Physical Factors in Larval and Juvenile Fish Recruitment to Estuarine Nursery Areas." *American Fisheries Society Symposium* 3 (5): 17.

Bozec, Y., S. O'Farrell, J. Bruggemann, B. Luckhurst, and P. Mumby. 2016. "Tradeoffs between Fisheries Harvest and the Resilience of Coral Reefs." *Proceedings of the National Academy of Sciences*, 201601529.

Briggs, J., and B. Bowen. 2012. "A Realignment of Marine Biogeographic Provinces with Particular Reference to Fish Distributions: Marine Biogeographic Provinces." *Journal of Biogeography* 39 (1): 12–30. https://doi.org/10.1111/j.1365-2699.2011.02613.x.

Comte, A., and L. Pendleton. 2018. "Management Strategies for Coral Reefs and People under Global Environmental Change: 25 Years of Scientific Research." *Journal of Environmental Management* 209 (March): 462–74. https://doi.org/10.1016/j.jenvman.2017.12.051.

Costa, B., and M. Kendall. 2016. "Marine Biogeographic Assessment of the Main Hawaiian Islands," 383.

Davies, H., L. Beckley, H. Kobryn, A. Lombard, B. Radford, and A. Heyward. 2016. "Integrating Climate Change Resilience Features into the Incremental Refinement of an Existing Marine Park." Edited by Kay C. Vopel. *PLOS ONE* 11 (8): e0161094. https://doi.org/10.1371/journal.pone.0161094.

Dollar, S. 1982. "Wave Stress and Coral Community Structure in Hawai'i." *Coral Reefs* 1 (2): 71–81.

Donovan, M. 2017. "A Synthesis of Coral Reef Community Structure in Hawai'i and the Caribbean." University of Hawai'i at Manoa, ProQuest Dissertations Publishing.

Donovan M., Friedlander A., Lecky J., Jouffray J., Williams G., Wedding L., Crowder L., Erickson A, Graham N., Gove J., Kappel C., Karr K., Kittinger J., Norström A., Nyström M., Oleson K., Stamoulis K., White C., Williams I., Selkoe K. Integrating fish and benthic communities for a new understanding of coral reef regimes. *Scientific Reports*. In review

Fernandes, L., J. Day, A. Lewis, S. Slegers, B. Kerrigan, D. Breen, D. Cameron, et al. 2005. "Establishing Representative No-Take Areas in the Great Barrier Reef: Large-Scale Implementation of Theory on Marine Protected Areas." *Conservation Biology* 19 (6): 1733–44. https://doi.org/10.1111/j.1523-1739.2005.00302.x.

Franklin, E., P. Jokiel, and M. Donahue. 2013. "Predictive Modeling of Coral Distribution and Abundance in the Hawaiian Islands." *Marine Ecology Progress Series* 481 (May): 121–32. https://doi.org/10.3354/meps10252.

Friedlander, A., E. Brown, P. Jokiel, W. Smith, and K. Rodgers. 2003. "Effects of Habitat, Wave Exposure, and Marine Protected Area Status on Coral Reef Fish Assemblages in the Hawaiian Archipelago." *Coral Reefs* 22 (3): 291–305. https://doi.org/10.1007/s00338-003-0317-2.

Friedlander, A., and E. DeMartini. 2002. "Contrasts in Density, Size, and Biomass of Reef Fishes between the Northwestern and the Main Hawaiian Islands: The Effects of Fishing down Apex Predators." *Marine Ecology Progress Series* 230: 253–264.

Friedlander, A., and J. Parrish. 1997. "Fisheries Harvest and Standing Stock in a Hawaiian Bay." *Fisheries Research* 32 (1): 33–50. https://doi.org/10.1016/S0165-7836(97)00038-6.

Game, E., M. Watts, S. Wooldridge, and H. Possingham. 2008. "Planning for Persistence in Marine Reserves: A Question of Catastrophic Importance." *Ecological Applications* 18 (3): 670–680.

Gleason, M., E. Fox, S. Ashcraft, J. Vasques, E. Whiteman, P. Serpa, E. Saarman, et al. 2013. "Designing a Network of Marine Protected Areas in California: Achievements, Costs, Lessons Learned, and Challenges Ahead." *Ocean & Coastal Management* 74 (March): 90–101. https://doi.org/10.1016/j.ocecoaman.2012.08.013.

Gove, J. J. Polovina, W. Walsh, A. Heenan, I. Williams, L. Wedding, R. Ingram, et al. 2016. "West Hawai'i Integrated Ecosystem Assessment: Ecosystem Trends and Status Report," 53.

Graham, N., D. Bellwood, J. Cinner, T. Hughes, A. Norström, and M. Nyström. 2013. "Managing Resilience to Reverse Phase Shifts in Coral Reefs." *Frontiers in Ecology and the Environment* 11 (10): 541–48. https://doi.org/10.1890/120305.

Great Barrier Reef Marine Park Authority. 2017. *Reef Blueprint: Great Barrier Reef Blueprint for Resilience : Improving the Capacity of Corals and Coral Reefs to Resist and Recover from Disturbance.*

Green, A., D. Bellwood, and International Union for Conservation of Nature. 2009. *Monitoring Functional Groups of Herbivorous Reef Fishes as Indicators of Coral Reef Resilience: A Practical Guide for Coral Reef Managers in the Asia Pacific Region*. http://docs.lib.noaa.gov/noaa_documents/CoRIS/IUCN_herbivorous_reef-fishes_2009.pdf.

Green, A., L. Fernandes, G. Almany, R. Abesamis, E. McLeod, P. Alino, A. White, R. Salm, J. Tanzer, and R. Pressey. 2014. "Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation." *Coastal Management* 42 (2): 143–59. https://doi.org/10.1080/08920753.2014.877763.

Green, A., S. Smith, G. Lipsett-Moore, C. Groves, N. Peterson, S. Sheppard, P. Lokani, et al. 2009. "Designing a Resilient Network of Marine Protected Areas for Kimbe Bay, Papua New Guinea." *Oryx* 43 (04): 488. https://doi.org/10.1017/S0030605309990342.

Heron, S., J. Maynard, R. van Hooidonk, and M. Eakin. 2016. "Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012." *Scientific Reports* 6 (1). https://doi.org/10.1038/srep38402.

Hixon, M. 2015. "Reef Fishes, Seaweeds, and Corals." In *Coral Reefs in the Anthropocene*, edited by Charles Birkeland, 195–215. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-017-7249-5_10.

Hoegh-Guldberg, O., and J. Bruno. 2010. "The Impact of Climate Change on the World's Marine Ecosystems." *Science* 328 (5985): 1523–28. https://doi.org/10.1126/science.1189930.

Hoegh-Guldberg, O., E. Poloczanska, W. Skirving, and S. Dove. 2017. "Coral Reef Ecosystems under Climate Change and Ocean Acidification." *Frontiers in Marine Science* 4 (May). https://doi.org/10.3389/fmars.2017.00158.

Holling, C. 1973. "Resilience and the Stability of Ecological Systems."

Hooidonk, R. van, J. Maynard, J. Tamelander, J. Gove, G. Ahmadia, L. Raymundo, G.Williams, S. Heron, and S. Planes. 2016a. "Local-Scale Projections of Coral Reef Futures and

Implications of the Paris Agreement." *Scientific Reports* 6 (December): 39666. https://doi.org/10.1038/srep39666.

Hughes, T. et al. 2018. "Spatial and Temporal Patterns of Mass Bleaching of Corals in the Anthropocene." *Science* 359 (6371): 80–83. https://doi.org/10.1126/science.aan8048.

Hughes, T., M. Barnes, D. Bellwood, J. Cinner, G. Cumming, J. Jackson, J. Kleypas, et al. 2017. "Coral Reefs in the Anthropocene." *Nature* 546 (7656): 82–90. https://doi.org/10.1038/nature22901.

Hughes, T., J. Kerry, M. Álvarez-Noriega, J. Álvarez-Romero, K. Anderson, A. Baird, R. Babcock, et al. 2017. "Global Warming and Recurrent Mass Bleaching of Corals." *Nature* 543 (7645): 373–77. https://doi.org/10.1038/nature21707.

Ingram, R., K. Oleson, and J. Gove. 2018. "Revealing Complex Social-Ecological Interactions through Participatory Modeling to Support Ecosystem-Based Management in Hawai'i." *Marine Policy* 94 (August): 180–88. https://doi.org/10.1016/j.marpol.2018.05.002.

Jouffray, J.., M. Nystrom, A. Norstrom, I. Williams, L. Wedding, J. Kittinger, and G. Williams. 2014. "Identifying Multiple Coral Reef Regimes and Their Drivers across the Hawaiian Archipelago." *Philosophical Transactions of the Royal Society B: Biological Sciences* 370 (1659): 20130268–20130268. https://doi.org/10.1098/rstb.2013.0268.

Klein, C., C. Steinback, A. Scholz, and H. Possingham. 2008. "Effectiveness of Marine Reserve Networks in Representing Biodiversity and Minimizing Impact to Fishermen: A Comparison of Two Approaches Used in California: Biodiversity, Fishing, and Marine Reserve Design." *Conservation Letters* 1 (1): 44–51. https://doi.org/10.1111/j.1755-263X.2008.00005.x.

Kramer, K., S. Cotton, M. Lamson, and W. Walsh. 2016. "Coral Bleaching: Monitoring, Management Responses and Resilience." http://coralreefs.org/wp-content/uploads/2016/12/Session-30-Kramer_etal_ICRS_Final-1-2.pdf.

Lecky, J. 2016. "Ecosystem Vulnerability and Mapping Cumulative Impacts on Hawaiian Reefs." University of Hawai'i at Manoa.

Magris, R., S. Heron, and R. Pressey. 2015. "Conservation Planning for Coral Reefs Accounting for Climate Warming Disturbances." Edited by Bayden D Russell. *PLOS ONE* 10 (11): e0140828. https://doi.org/10.1371/journal.pone.0140828.

Maynard, J., E. Conklin, D. Minton, R. Most, C. Couch, G. Williams, J. Gove, et al. 2015. "Relative Resilience Potential and Bleaching Severity in the West Hawai'i Habitat Focus Area in 2015." https://doi.org/10.7289/v5t43r4z.

McClanahan, T., S. Donner, J. Maynard, M. MacNeil, N. Graham, J. Maina, A. Baker, et al. 2012. "Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate." Edited by Richard K. F. Unsworth. *PLoS ONE* 7 (8): e42884. https://doi.org/10.1371/journal.pone.0042884.

McCoy, K., I. Williams, A. Friedlander, H. Ma, L. Teneva, and J. Kittinger. 2018. "Estimating Nearshore Coral Reef-Associated Fisheries Production from the Main Hawaiian Islands." Edited by Sebastian C. A. Ferse. *PLOS ONE* 13 (4): e0195840. https://doi.org/10.1371/journal.pone.0195840.

McLeod, E., R. Salm, A. Green, and J. Almany. 2009. "Designing Marine Protected Area Networks to Address the Impacts of Climate Change." *Frontiers in Ecology and the Environment* 7 (7): 362–70. https://doi.org/10.1890/070211.

Mumby, P., N. Wolff, Y. Bozec, I. Chollett, and P. Halloran. 2014. "Operationalizing the Resilience of Coral Reefs in an Era of Climate Change: Mapping Resilience." *Conservation Letters* 7 (3): 176–87. https://doi.org/10.1111/conl.12047.

NOAA Coral Reef Watch. 2015. 5-km Regional Virtual Stations (Version 3). https://coralreefwatch.noaa.gov/vs/data.php

Nyström, M. 2006. "Redundancy and Response Diversity of Functional Groups: Implications for the Resilience of Coral Reefs." *AMBIO: A Journal of the Human Environment* 35 (1): 30–35. https://doi.org/10.1579/0044-7447-35.1.30.

Nyström, M., C. Folke, and F. Moberg. 2000. "Coral Reef Disturbance and Resilience in a Human-Dominated Environment." *Trends in Ecology & Evolution* 15 (10): 413–17. https://doi.org/10.1016/S0169-5347(00)01948-0.

Parker, S., J. Truscott, C. Harpur, and S. Murphy. 2015. "Exploring a Resilience-Based Approach to Spatial Planning in Fathom Five National Marine Park, Lake Huron, Canada, Using Marxan with Zones." *Natural Areas Journal* 35 (3): 452–64. https://doi.org/10.3375/043.035.0308.

Rosinski, A., J. Gove, C. Birkeland, K. Gorospe, D. White, T. Oliver, E. Conklin, W. Walsh, and I. Williams. 2017. "Coral Bleaching Recovery Plan: Identifying Management Responses to Promote Coral Recovery in Hawai'i." Hawai'i Department of Land and Natural Resources, Division of Aquatic Resources.

Safaie, A., N. Silbiger, T. McClanahan, G. Pawlak, D. Barshis, J. Hench, J. Rogers, G. Williams, and K. Davis. 2018. "High Frequency Temperature Variability Reduces the Risk of Coral Bleaching." *Nature Communications* 9 (1). https://doi.org/10.1038/s41467-018-04074-2.

Selkoe, K., T. Blenckner, M. Caldwell, L. Crowder, A. Erickson, T. Essington, J. Estes, et al. 2015. "Principles for Managing Marine Ecosystems Prone to Tipping Points." *Ecosystem Health and Sustainability* 1 (5): 1–18. https://doi.org/10.1890/EHS14-0024.1.

Stamoulis, K., Poti, M., Delevaux, J., Donovan, M., Friedlander, A. & Kendall, M. (2016) Chapter 4: Fishes - Reef Fishes. *Marine Biogeographic Assessment of the Main Hawaiian Islands* (eds B.M. Costa & M.S. Kendall), pp. 156–196. Bureau of Ocean and Energy Management and National Oceanic and Atmospheric Administration.

Stamoulis, K., J. Delevaux, I. Williams, M. Poti, J. Lecky, B. Costa, M. Kendall, et al. 2018. "Seascape Models Reveal Places to Focus Coastal Fisheries Management." *Ecological Applications*, May. https://doi.org/10.1002/eap.1696.

Storlazzi, C., E. Brown, M. Field, K. Rodgers, and P. Jokiel. 2005. "A Model for Wave Control on Coral Breakage and Species Distribution in the Hawaiian Islands." *Coral Reefs* 24 (1): 43–55. https://doi.org/10.1007/s00338-004-0430-x.

Toonen, R., K. Andrews, I. Baums, C. Bird, G. Concepcion, T. Daly-Engel, J. Eble, et al. 2011. "Defining Boundaries for Ecosystem-Based Management: A Multispecies Case Study of Marine Connectivity across the Hawaiian Archipelago." *Journal of Marine Biology* 2011: 1–13. https://doi.org/10.1155/2011/460173.

Tulloch, V., H. Possingham, S. Jupiter, C. Roelfsema, A. Tulloch, and C. Klein. 2013. "Incorporating Uncertainty Associated with Habitat Data in Marine Reserve Design." *Biological Conservation* 162 (June): 41–51. https://doi.org/10.1016/j.biocon.2013.03.003.

Walker, B., C. Holling, S. Carpenter, and A. Kinzig. 2004. "Resilience, Adaptability and Transformability in Social–Ecological Systems." *Ecology and Society* 9 (2): 5.

Wedding, L., J. Lecky, J. Gove, H. Walecka, M. Donovan, G. Williams, J. Jouffray, et al. 2018. "Advancing the Integration of Spatial Data to Map Human and Natural Drivers on Coral Reefs." Edited by Christopher A. Lepczyk. *PLOS ONE* 13 (3): e0189792. https://doi.org/10.1371/journal.pone.0189792.

Weijerman, M., J. Gove, I. Williams, W. Walsh, D. Minton, and J. Polovina. 2018. "Evaluating Management Strategies to Optimise Coral Reef Ecosystem Services." Edited by Pia Lentini. *Journal of Applied Ecology* 55 (4): 1823–33. https://doi.org/10.1111/1365-2664.13105.

Williams, I., W. Walsh, J. Claisse, B. Tissot, and K. Stamoulis. 2009. "Impacts of a Hawaiian Marine Protected Area Network on the Abundance and Fishery Sustainability of the Yellow Tang, *Zebrasoma flavescens*." *Biological Conservation* 142 (5): 1066–73. https://doi.org/10.1016/j.biocon.2008.12.029.

Williams, I., D. White, R. Sparks, K. Lino, J. Zamzow, E. Kelly, and H. Ramey. 2016. "Responses of Herbivorous Fishes and Benthos to 6 Years of Protection at the Kahekili Herbivore Fisheries Management Area, Maui." Edited by Sebastian C. A. Ferse. *PLOS ONE* 11 (7): e0159100. https://doi.org/10.1371/journal.pone.0159100.

CHAPTER 5. CONCLUSION

Synthesis

The goals of this study were to 1) better understand the intervention options available to coral reef managers and develop a way to prioritize resilience-based interventions, 2) focusing on a top-ranked intervention, tailor the intervention to be applied in the main Hawaiian Islands, and 3) investigate where resilience-based strategies could be implemented to provide the best chance of success.

In Chapter 2, I conducted a systematic literature review to evaluate and rank twelve potential management interventions following a bleaching event. This approach provides a transparent way of honing in on interventions that are based on evidence and which have been shown to be effective either in Hawai‘i or elsewhere. Even though I found that ‘establishing a network of no-take Marine Protected Areas" by far had the most papers and did rank highly, this review widens the spectrum of available tools including other highly ranked approaches including other types of spatial management and fisheries rules. Although other studies present recommendations to build resilience (McLeod et al. 2009; Heller and Zavaleta 2009), this work takes the concept a step further by including site-specific weighting allowing for the options to be scored and ranked. This feature may allow managers to filter through potential management options to those that have a specific connection to resilience, have evidence of being effective, and are appropriate for their coral reef jurisdiction.

In Chapter 3, I developed design principles for the top-ranked intervention from Chapter 2, ‘establishing a network of Herbivore Management Areas.’ Although these principles build on previously-developed principles for no-take Marine Protected Areas (Green et al. 2014), this is the first guidance specifically for spatial herbivore management. This chapter drew together findings of the unique habitats, critical areas, connectivity, life history, and movements of Hawai‘i’s herbivorous fishes through the lens of resilience-based management. Additionally, previous spatial management in Hawai‘i has been piecemeal, with small, singular areas being established slowly over time. These results would provide managers with the information to create a comprehensive and cohesive network of Herbivore Management Areas in the main Hawaiian Islands.

In Chapter 4, I used a spatial analysis approach to map priority areas where ecological and social features may lead to successful Herbivore Management Areas, applying the principles outlined in Chapter 3. This work used the software program Marxan, which has been applied in the main Hawaiian Islands before to perform a gap analysis of existing Marine Managed Areas (Puniwai 2005) and currently as a means to explore areas to expand the coverage of existing areas through the Marine 30x30 Initiative. However, this application reflects the unique and focused question of how to increase or maintain herbivory as a resilience-building tool. The results found a few areas of overlap with Fisheries Management Areas along the Kona coast. Revising existing rules to add herbivore protections may be a realistic and politically viable way of integrating resilience-based management concepts into coral reef management in Hawaiʻi.

Limitations

This research was based on the exposure to two consecutive bleaching events that were the most severe and widespread observed in the main Hawaiian Islands to date. Hawaiʻi has had relatively fewer bleaching events compared to other regions of the Pacific as well as the Caribbean, and so this research was limited without knowing patterns of bleaching. Thus, this work and especially Chapter 4 incorporated general concepts of risk management including replication, representation, and stratification to increase the chance of success for future management interventions. The use of Marxan prevented certain aspects of Marine Protected Area design from being included in this research. Namely, currently, Marxan cannot incorporate concepts of genetic connectivity between areas within a network, which will become increasingly important to maintain diverse coral populations.

The general approach of designing herbivore management areas, as in Chapter 3 and 4, assumes that there are both conservation goals that if met, will lead to success, that there must be a tradeoff with socioeconomic costs (i.e. loss of fishing opportunities), and that land-based pollution threats must be avoided. First, the information available about how Hawaiian corals at a reef or coastline scale respond and recover from coral bleaching events is limited. The 2014 and 2015 bleaching events were unprecedented in the main Hawaiian Islands both in scale and severity. Therefore, the selection of ecosystem features to target for protection and which to avoid can only be chosen based on theory and preliminary recovery data from the bleaching event. Future research should closely track the mid and long-term patterns of change in coastal areas affected by the mass bleaching event to further refine spatial optimization exercises.

Future Directions

Evaluating Management Interventions for Bleaching Recovery

The systematic review approach used in Chapter 2 was specifically tailored to rank interventions in Hawai‘i. Site-specific weighting allowed for interventions that have been proven effective locally to influence the resulting rankings. Future research could further validate this approach by using the same method in a different location and comparing results. This approach would be effective in areas with comprehensive bodies of literature, for example, the Great Barrier Reef or areas within the Caribbean. Managers in other coral reef regions would similarly benefit from an evidence-based approach, which could add justification to their resilience-building strategies.

Prioritizing Areas for Resilience-based Management

A unique set of spatial data layers were synthesized to perform the Marxan analysis in Chapter 4. The analysis was prioritized to the Kona coast of Hawai‘i Island and Maui Nui due to their high mortality rates following the 2014 and 2015 bleaching events. Future efforts could extend this analysis to the remaining islands, expanding the potential network of Herbivore Management Areas across the entirety of the main Hawaiian Islands. Especially due to the little information that is known about regional differences in bleaching and mortality response, statewide maps would maximize future design options for Hawai‘i's coral reef managers.

Translating Resilience-based Management

There have been two mass global bleaching events, in 1998 and 2013-2017, that affected most of the world's coral reefs. A comparison of how managers responded after these events shows a change in attitude and urgency in promoting local action to a changing climate. Following the 1998 event, actions such as coral transplantation and prohibiting public access to affected areas were not aligned with more commonly accepted resilience indicators (McLeod et al. 2009; McClanahan et al. 2012). Seemingly, this event elevated awareness about coral bleaching as a threat to reefs but resilience-based management was not attainable as a practical strategy.

In contrast, following the most recent mass bleaching event, managers in Hawai‘i and Australia mobilized collaborative initiatives to find resilience-building solutions within their jurisdictions. In Hawai‘i, the Division of Aquatic Resources (DAR) surveyed over 100 scientists worldwide and locally to gather opinions on bleaching recovery strategies, which were included along with components of the research from Chapter 2 in the state's Coral Bleaching Recovery Plan (Rosinski et al. 2017). This plan brought researchers together, combining knowledge about corals, fish, and climate for an urgent cause. It also led to the first combined database of coral bleaching and recovery data from a multitude of partners, known as the Coral Bleaching Collaborative.

In 2017, I attended a multi-day workshop led by the Great Barrier Reef Marine Park Authority (GBRMPA), which resulted in the development of the Great Barrier Reef Blueprint for Resilience (Great Barrier Reef Marine Park Authority 2017). This report outlines distinct strategies that will be pursued to improve resiliency across the region. Similar to the Coral Bleaching Recovery Plan, the development of the blueprint brought together a spectrum of partners for a novel objective. The results included a commitment to design a 'resilience network' of managed areas, focusing efforts on sites on the reef that are disproportionately important to resilience and stronger regulations on species with a key role in assisting reef recovery following disturbance. Both the Hawai‘i and Australia examples demonstrate how coral reef managers are now acting in response to climate impacts and looking comprehensively across their tools and strategies to increase ecological resilience.

On October 8, 2018, the Intergovernmental Panel on Climate Change (IPCC) released a report assessing the projected impacts at a global average warming of 1.5°C (IPCC 2018). The report projects that coral reefs will decline by 70-90% at 1.5°C and by >99% at 2°C. Local-scale projections forecast that Hawai‘i will experience annual severe bleaching events by 2035, conditions at which recovery will be limited (van Hooidonk et al. 2016). Clearly, immense decreases in carbon emissions are ultimately needed in order to have more time in between major disturbances and a greater chance for reef recovery.

Regarding reef management on a local scale, the next decade will be a critical time to monitor if resilience-based strategies have had a positive impact against global stressors. This study translated resilience-based management on a local scale by answering questions relating to the implementation of one potential approach (i.e. spatial herbivore management) and a case study of the main Hawaiian Islands. It is my hope that this research will contribute to a change in the way we manage coral reefs. During the study, I was encouraged by the willingness of managers to think critically about their current approaches as well as the cooperative and creative feeling of the participants in the workshops that I attended. Many ideas were presented about how to operationalize resilience-based management using existing data and tools in new ways. Finally, I observed that one positive outcome of the bleaching event was that it brought together ocean stakeholders facing a common issue. I believe that if managers and their essential networks of partners can maintain the momentum stemming from this experience, it will accelerate innovation in coral reef science and policy that will rise up to the challenge of global climate change.

References

Great Barrier Reef Marine Park Authority. 2017. Reef Blueprint: Great Barrier Reef Blueprint for Resilience : Improving the Capacity of Corals and Coral Reefs to Resist and Recover from Disturbance.

Green, Alison L., Leanne Fernandes, Glenn Almany, Rene Abesamis, Elizabeth McLeod, Porfirio M. Ali?o, Alan T. White, Rod Salm, John Tanzer, and Robert L. Pressey. 2014. "Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation." Coastal Management 42 (2): 143–59. https://doi.org/10.1080/08920753.2014.877763.

Heller, Nicole E., and Erika S. Zavaleta. 2009. "Biodiversity Management in the Face of Climate Change: A Review of 22 Years of Recommendations." Biological Conservation 142 (1): 14–32. https://doi.org/10.1016/j.biocon.2008.10.006.

Hooidonk, Ruben van, Jeffrey Maynard, Jerker Tamelander, Jamison Gove, Gabby Ahmadia, Laurie Raymundo, Gareth Williams, Scott F. Heron, and Serge Planes. 2016. "Local-Scale Projections of Coral Reef Futures and Implications of the Paris Agreement." Scientific Reports 6 (December): 39666. https://doi.org/10.1038/srep39666.

McClanahan, Tim R., Simon D. Donner, Jeffrey A. Maynard, M. Aaron MacNeil, Nicholas A. J. Graham, Joseph Maina, Andrew C. Baker, et al. 2012. "Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate." Edited by Richard K. F. Unsworth. PLoS ONE 7 (8): e42884. https://doi.org/10.1371/journal.pone.0042884.

McLeod, Elizabeth, Rodney Salm, Alison Green, and Jeanine Almany. 2009. "Designing Marine Protected Area Networks to Address the Impacts of Climate Change." Frontiers in Ecology and the Environment 7 (7): 362–70. https://doi.org/10.1890/070211.

Puniwai, Noelani. 2005. "Marine Gap Analysis for the Main Hawaiian Islands." University of Hawai'i at Manoa.

Rosinski, Anne, Charles Birkeland, Eric Conklin, Jamison Gove, Kelvin D Gorospe, Thomas Oliver, William Walsh, Darla White, and Ivor Williams. 2017. Coral Bleaching Recovery Plan: Identifying Management Responses to Promote Coral Recovery in Hawai'i. Hawai'i Department of Land and Natural Resources.