Title: Translating Resilience-based Management Theory to Practice for Coral Bleaching Recovery in Hawaiʻi

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Acknowledgements

This research was funded by the NOAA Coral Reef Conservation Program and the Department of Land and Natural Resources, Division of Aquatic Resources (NA15NOS4820037). The funding sources did not have a role in the preparation of this manuscript. Special thanks to Charissa Minato and Pamela Fujii from the Hawaiʻi Coral Reef Initiative for their invaluable support and to the staff at the Division of Aquatic Resources for their feedback and contributions to this work.

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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 Hawaiʻi, back-to-back bleaching events in 2014 and 2015 caused significant damage motivating the state to seek guidance on next steps for recovery. Hawaiʻi 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 Hawaiʻi-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 Hawaiʻi), 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 Hawaiʻi. 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.

Keywords: resilience-based management; coral reefs; fisheries

Highlights:

- Systematic review operationalizes resilience theory, identifying specific interventions to promote coral bleaching in Hawaiʻi
- Highest ranking management interventions were herbivore management areas and parrotfish size limits
- This approach could be adapted to other coral reef regions, supporting transparent and systematic management decisions

1. Introduction

Climate change is affecting coral reefs worldwide in several ways including more frequent and severe bleaching events, where corals expel zooxanthellae in response 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.

1.1 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 or 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.

1.2 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 Hawaiʻi'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 Hawaiʻi. 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 Hawaiʻi 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.

2. Methods

2.1 Identifying Hawaiʻi-relevant Management Interventions

First, a list of twelve interventions was created that managers in Hawaiʻi could implement to promote coral recovery following a bleaching event. The list was derived from a preliminary review of the literature, suggestions from Hawaiʻi's coral reef managers, interventions previously prioritized in a management response workshop with Hawaiʻi-based researchers and coral experts, interventions already in use in Hawaiʻi, 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 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 1 here

2.1 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 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 1 here

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.

2.3 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). Each paper included in the systematic review was assigned a point value ranging from -6 to 6 based on this evidence hierarchy.

Figure 2 here

2.5 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.

3. Results

3.1. 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

3.2 Distribution of Evidence across Evidence Hierarchy Categories

The number of papers varied by each of location, scale, and type of data collected (Figure 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 3 here

3.3 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 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 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 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 4c). The tool to "Enhance enforcement" had a relatively high proportion of papers based on theoretical evidence.

Figure 4 here

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 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 5 here

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). ‘Prohibit laynets’ had the lowest combined score (0.02).

Table 2 here

Recovery and management ranking scores differed between all management interventions (Figure 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 6 here

4. Discussion

This study compared and evaluated the effectiveness of a wide array of coral reef management intervention options to promote coral bleaching recovery in Hawaiʻi. 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 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.

4.1 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 Hawaiʻi’s herbivorous fish species, and previous success of herbivore management areas in Hawaiʻi. In the first six years of the Kahekili Herbivore Fisheries Management Areas on Maui, Hawaiʻi 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 Hawaiʻi 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 create new space for coral settlement, and these relationships have been confirmed in Hawaiʻi (Jayewardene 2009). Specifically, scrapers (*Chlorurus spilurus*, *Chlorurus perspicillatus*, and *Scarus rubroviolaceus*) were most strongly associated with Hawaiʻi'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 Hawaiʻi, 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 Hawaiʻi, 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.

4.2 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 Hawaiʻi, 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 Hawaiʻi have been 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.

4.3 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 in 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.

4.4 Difference between Global and Hawaiʻi-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 Hawaiʻi. The review identified one intervention ("Prohibit all use of laynets") that had only one study inside Hawaiʻi and another ("Replant bleaching resistant corals") that had zero studies inside Hawaiʻi. This ultimately affected the ability to measure the difference of place-based weighting on the results because there were insufficient papers from Hawaiʻi.

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.

4.5 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 both creating a large and mixed pool of evidence through which to navigate as well as potentially ignores the breadth of interventions to be considered. Lastly, scientific literature disproportionately reports complete studies with significant outcomes - publication bias. 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 Hawaiʻi 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 Hawaiʻi 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.

5. Conclusions

This work expands the application of resilience-based management to promote coral bleaching recovery by developing a systematic review framework (Figure 1). That framework was then applied to the case study of Hawaiʻi, where managers were seeking to identify effective management tools following a recent mass bleaching event. The review process was tailored to the Hawaiʻi example by identifying 12 place-based interventions and weighting the evidence of effectiveness so that evidence from Hawaiʻi 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 Hawaiʻi 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 Hawaiʻi 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.

Acknowledgements

This research was funded by the NOAA Coral Reef Conservation Program and the Department of Land and Natural Resources, Division of Aquatic Resources (NA15NOS4820037). The funding sources did not have a role in the preparation of this manuscript. Special thanks to Charissa Minato and Pamela Fujii and the entire staff from the Hawaiʻi Coral Reef Initiative for their invaluable support as well as to the staff at the Division of Aquatic Resources for their feedback and contributions to this work.

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Supplemental Information

Table 3. 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,
Ban all parrotfish	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

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

Figure 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 Hawaiʻi. 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.

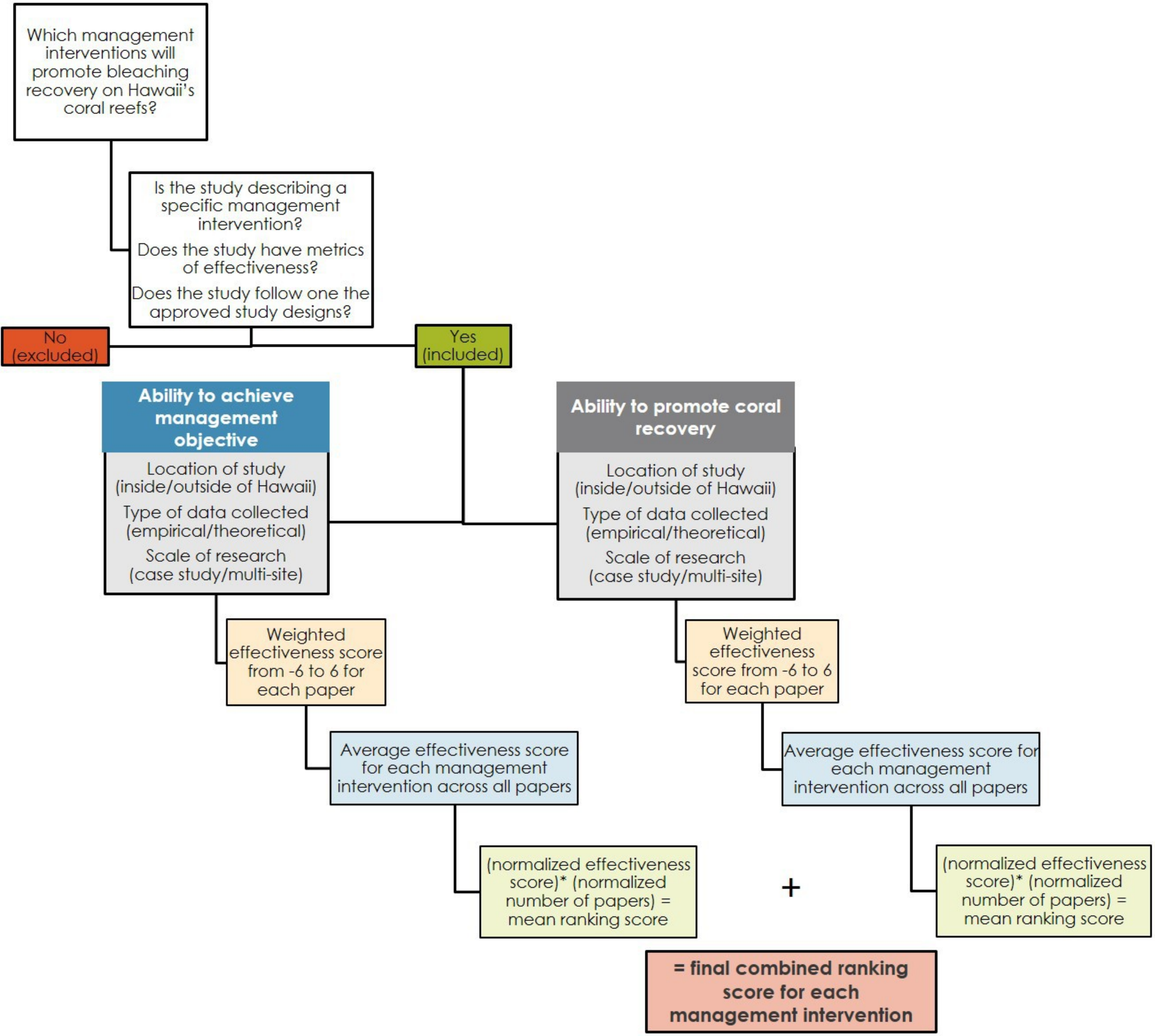
Figure 2. Evidence hierarchy used to assign score values to each paper included in the systematic review based on the type of data, scale, and location of the evidence.

Figure 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.

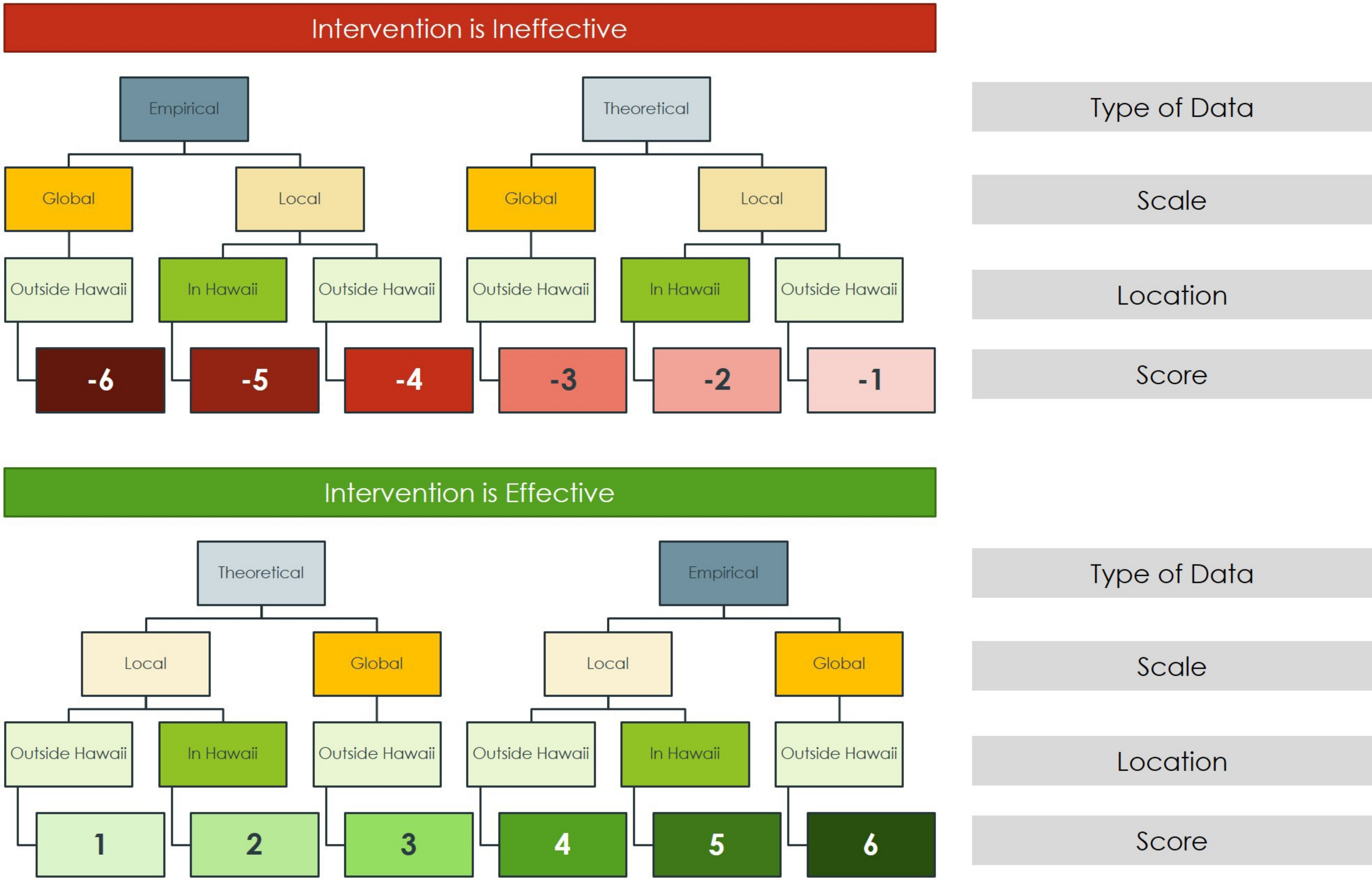
Figure 4. The distribution of papers collected across each intervention indicating the number of papers by a) the location of the research, b) the scale of the research, and c) the type of data collected.

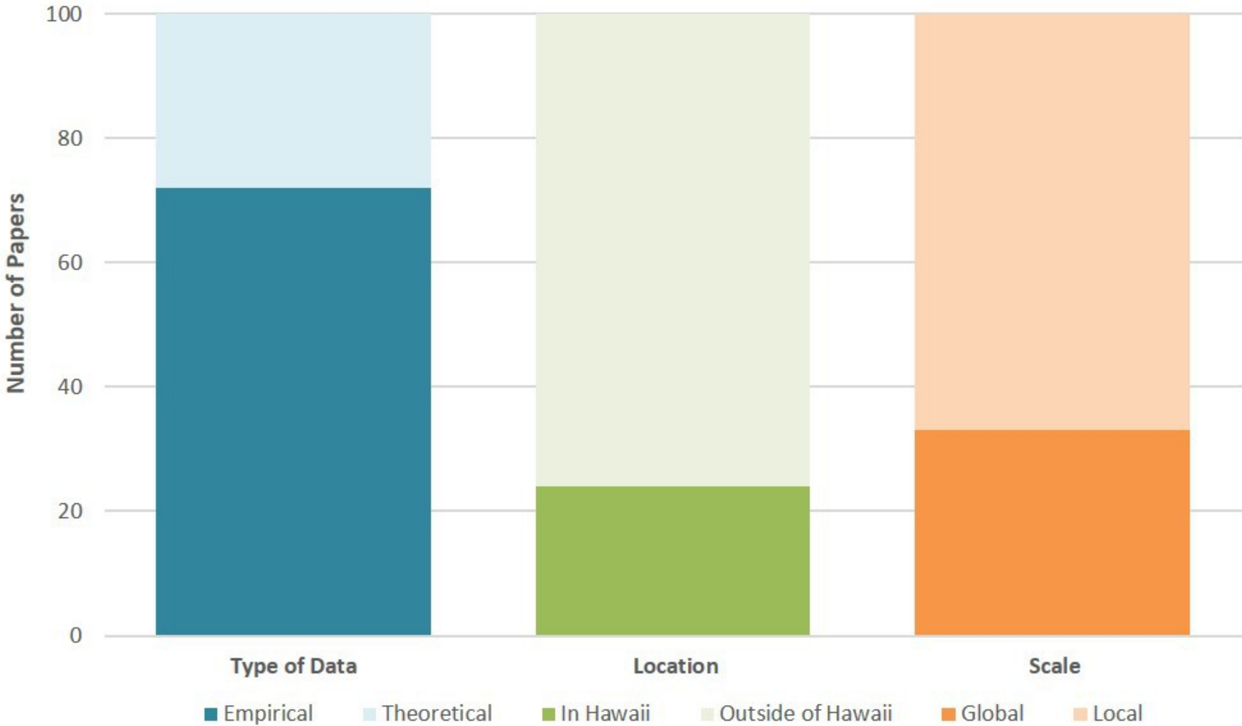
Figure 5. The total number of papers for each management tool that described either limiting or supporting evidence. Colors indicate the score categories that papers for each tool were categorized into ranging from -6 to 6.

Figure 6. The management and recovery ranking score as well as the final combined ranking score for each management intervention.

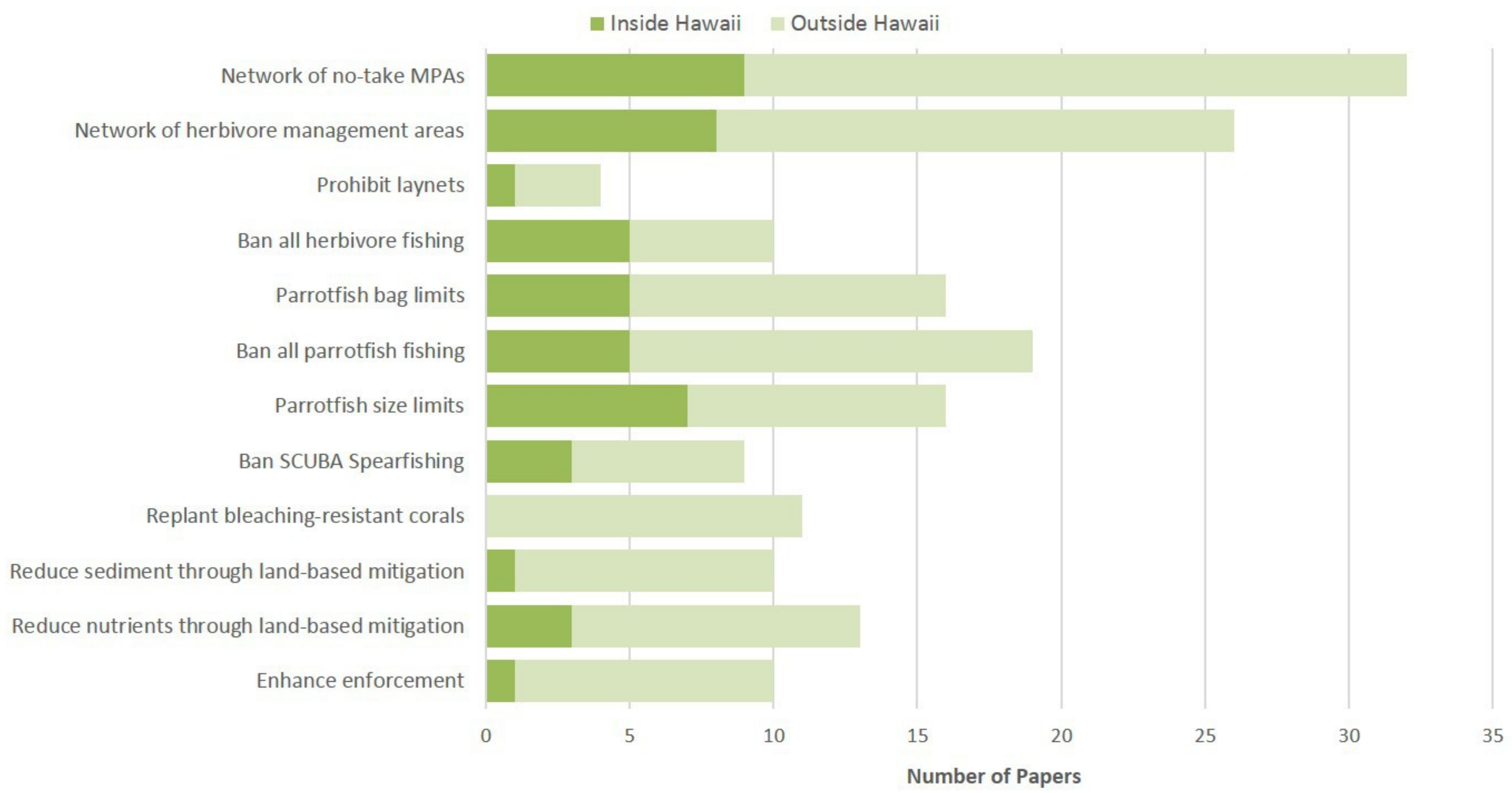


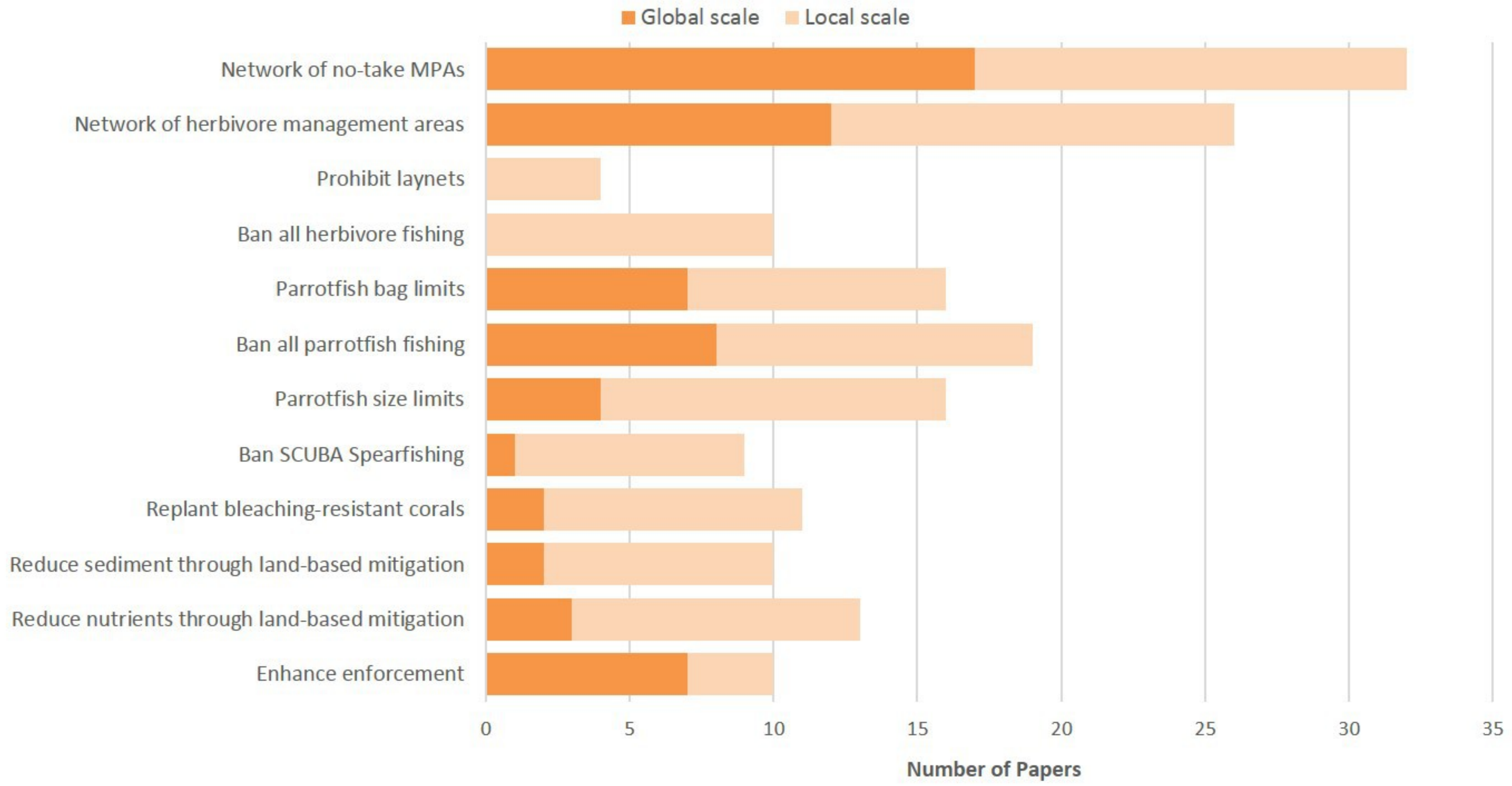
Which management interventions will promote bleaching recovery on Hawaii's coral reefs?
Is the study describing a specific management intervention?
Does the study have metrics of effectiveness?
Does the study follow one the approved study designs?
No (excluded)
Yes (included)
Ability to achieve management objective
Location of study (inside/outside of Hawaii)
Type of data collected (empirical/theoretical)
Scale of research (case study/multi-site)
Ability to promote coral recovery
Location of study (inside/outside of Hawaii)
Type of data collected (empirical/theoretical)
Scale of research (case study/multi-site)
Weighted effectiveness score from -6 to 6 for each paper
Weighted effectiveness score from -6 to 6 for each paper
Average effectiveness score for each management intervention across all papers
Average effectiveness score for each management intervention across all papers
(normalized effectiveness score)* (normalized number of papers) = mean ranking score
+
(normalized effectiveness score)* (normalized number of papers) = mean ranking score
= final combined ranking score for each management intervention

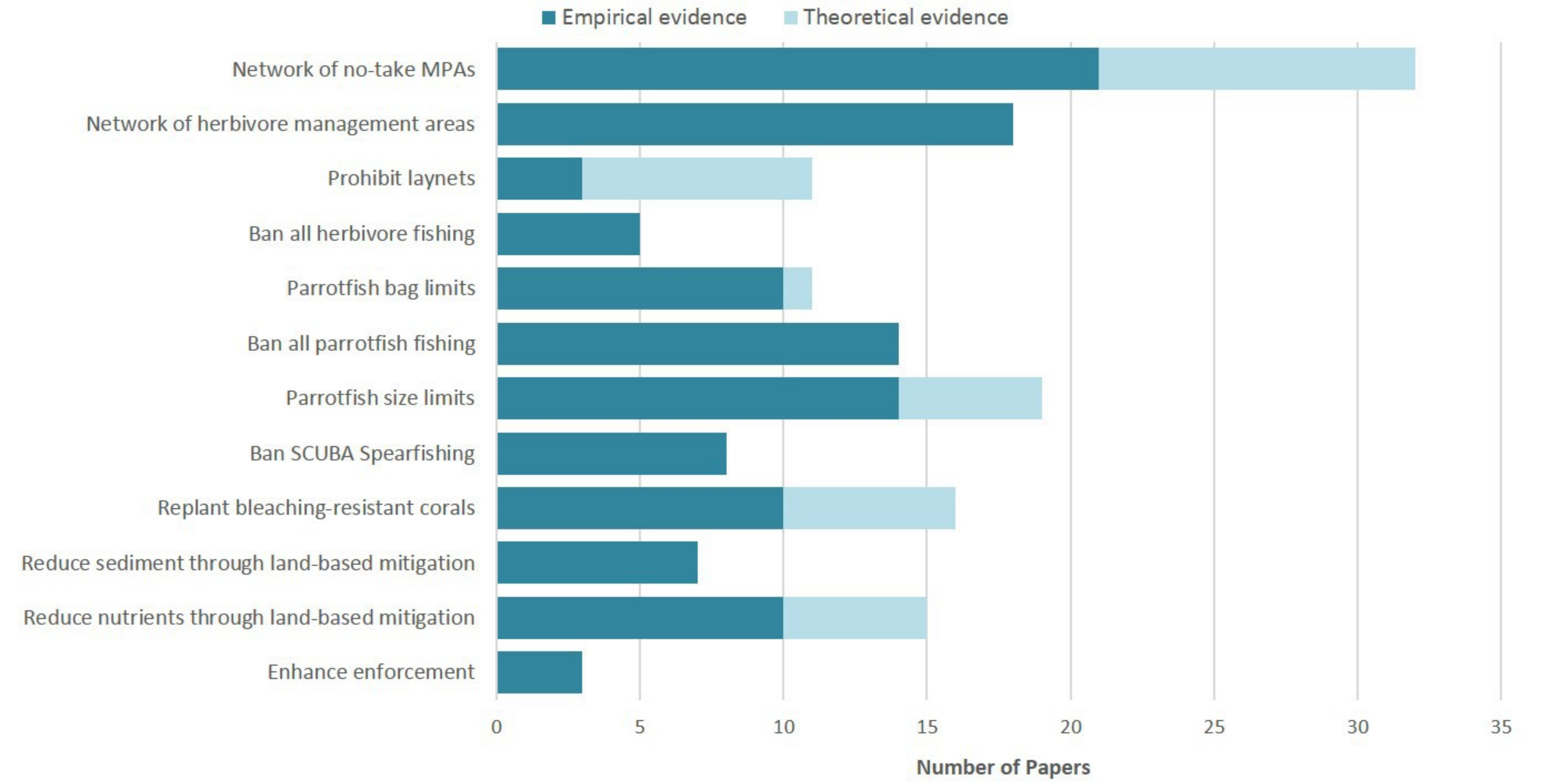

Intervention is Ineffective
Empirical
Theoretical
Global
Local
Global
Local
Outside Hawaii
In Hawaii
Outside Hawaii
Outside Hawaii
In Hawaii
Outside Hawaii
-6
-5
-4
-3
-2
-1
Type of Data
Scale
Location
Score
Intervention is Effective
Theoretical
Empirical
Local
Global
Local
Global
Outside Hawaii
In Hawaii
Outside Hawaii
Outside Hawaii
In Hawaii
Outside Hawaii
1
2
3
4
5
6
Type of Data
Scale
Location
Score



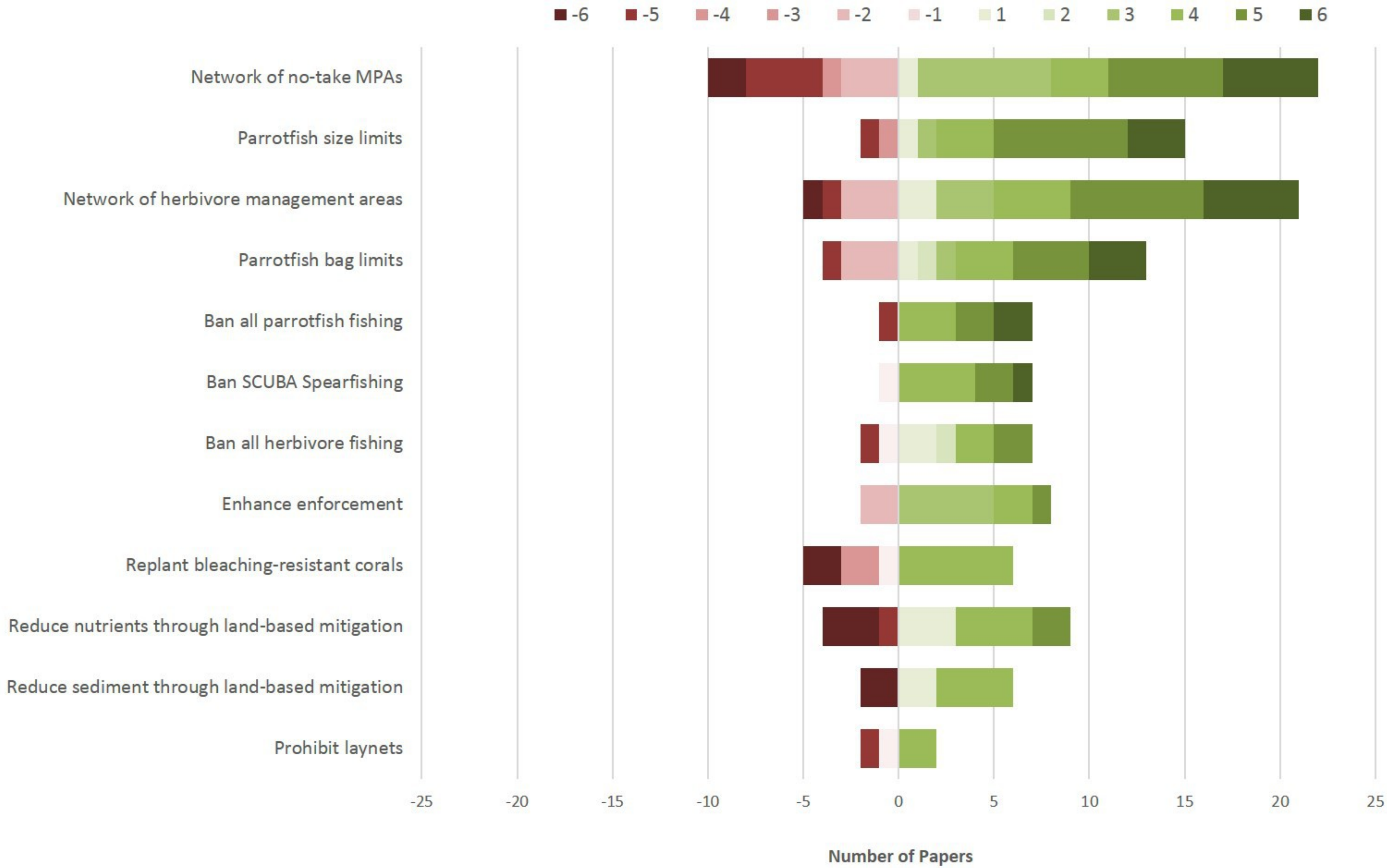
100
80
60
40
20
0
Number of Papers
Type of Data
Location
Scale
Empirical
Theoretical
In Hawaii
Outside of Hawaii
Global
Local


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

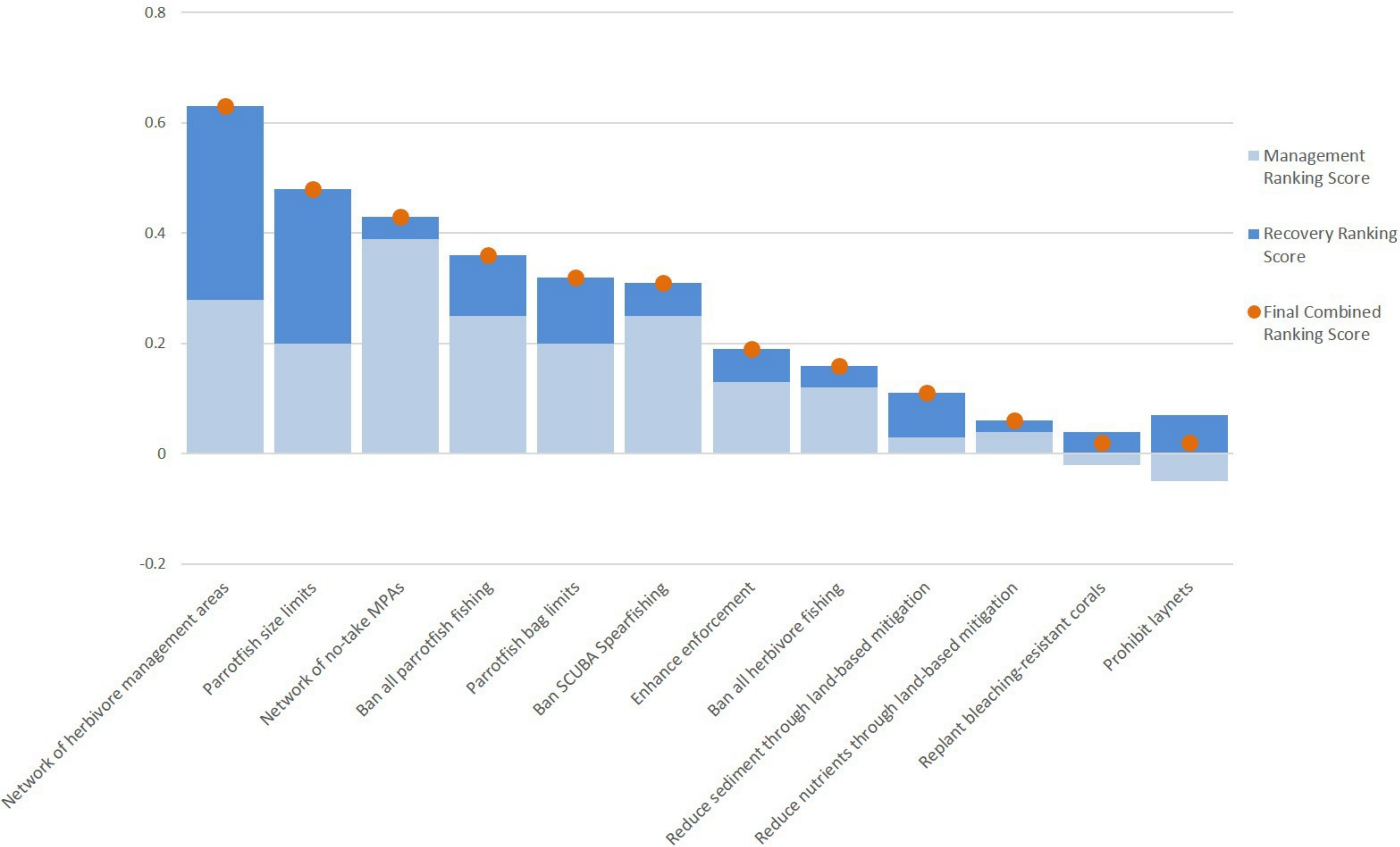

Global scale
Local scale
Network of no-take MPAs
Network of herbivore management areas
Prohibit laynets
Ban all herbivore fishing
Parrotfish bag limits
Ban all parrotfish fishing
Parrotfish size limits
Ban SCUBA Spearfishing
Replant bleaching-resistant corals
Reduce sediment through land-based mitigation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



Empirical evidence
Theoretical evidence
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



-6
-5
-4
-3
-2
-1
1
2
3
4
5
6
Network of no-take MPAs
Parrotfish size limits
Network of herbivore management areas
Parrotfish bag limits
Ban all parrotfish fishing
Ban SCUBA Spearfishing
Ban all herbivore fishing
Enhance enforcement
Replant bleaching-resistant corals
Reduce nutrients through land-based mitigation
Reduce sediment through land-based mitigation
Prohibit laynets
-25
-20
-15
-10
-5
0
5
10
15
20
25
Number of Papers



0.8
0.6
0.4
0.2
0
-0.2
Management Ranking Score
Recovery Ranking Score
Final Combined Ranking Score
Network of herbivore management areas
Parrotfish size limits
Network of no-take MPAs
Ban all parrotfish fishing
Parrotfish bag limits
Ban SCUBA Spearfishing
Enhance enforcement
Ban all herbivore fishing
Reduce sediment through land-based mitigation
Reduce nutrients through land-based mitigation
Replant bleaching-resistant corals
Prohibit laynets

Table 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 rules relating to coral reef recovery.	Increase in compliance to coral reef-related rules.	Increase in coral cover, increase in coral reef ecosystem health	Stakeholder suggestion

Table 2. Final combined ranking scores of potential management interventions to promote coral recovery in Hawaiʻi.

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