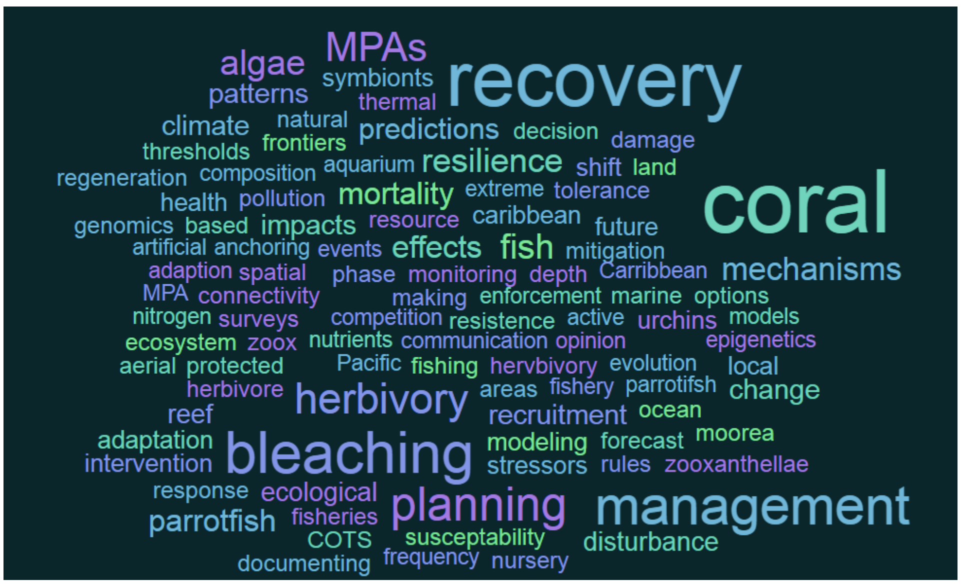
Analysis of Global Coral Bleaching Literature:

Efforts to Promote Recovery and Resilience



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May 2016

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Contents

Cover photo: word cloud of keywords and terms tagged in the reviewed literature

Executive Summary

Coral mortality caused by frequent coral bleaching events leads to systematic changes in the structure of tropical ecosystems. The frequency and severity of these events are predicted to increase. Despite the pressing consequences of these events, direct management interventions to promote recovery and increased resilience. Work is needed to increase the application of reef resilience theories and develop innovative techniques to promote coral recovery. This project collected and analyzed information from scientific literature that will inform a decision-making process to promote recovery in Hawaii through policy-making. This effort sought to outline types of restoration strategies present in the literature, synthesize evidence of support relevant to each strategy, and describe specific instances of management interventions following bleaching events.

Primary literature and management reports were gathered from multiple sources and collated using *Zotero*, a research software tool. If an entry discussed management actions following a bleaching event, it was categorized by 'type of action' (monitoring, bolstering existing management, or active recovery). Within these management actions, five recovery strategies were recorded: 1) stimulating new coral settlement 2) stimulating coral regrowth 3) replacing dead coral 4) preventing additional damage to coral 5) and controlling algae overgrowth.

A total of 207 papers were reviewed as part of this effort. Slightly more than half (52%) of papers discussed management actions and the majority of these (56%) discussed bolstering existing management. A smaller portion of the papers (74 papers, 36%) discussed one of the five recovery strategies. Recommendations in the literature for preventing additional damage to coral were the use of Marine Protected Areas (MPAs) and reduction of harmful activities. To control algal overgrowth, there is a body of evidence for the protection of herbivores through fisheries management – especially parrotfish. Factors to stimulate new coral settlement into a damaged area include protection of larval sources, ensuring adequate settlement substrate, and reduction of anthropogenic factors that affect early life stages of coral. Lastly, to replace dead coral, transplantation of fragments from healthy reefs and the farming of bleaching resistant genotypes is discussed. Four examples were found of managers intervening following a coral bleaching event: 1) creation of a no-anchor zone, 2) transplantation of corals, 3) closure of popular dive sites, and 4) a self-moratorium on aquarium collecting.

Based on the literature, managers should consider two main questions: "is there capacity for natural recovery of the system?" And, "is the natural rate of recovery sufficient to regain ecosystem function?" Based on these answers, managers are able to navigate whether it would more appropriate to pursue monitoring, bolstering existing management, or active recovery. Before management decisions can be made for corals affected by bleaching in Hawaii, a few key pieces of information are needed, including context-specific information on recovery rates of Hawaii coral and information on the ecological contribution of reef herbivores. To focus management interventions geographically and strategically, managers could use a number of theoretical decision-making tools. Lastly, this review revealed that although there continues to be substantial discussion regarding ecological factors that confer resilience in coral reef ecosystems, there remains very few examples of the use these strategies. When the State of Hawaii takes additional steps to promoting reef recovery, it will be among the first governments to take an active approach to address the effects of climate change in its waters.

Objective

The objective of this report is to review and analyze global bleaching literature with particular emphasis on management efforts to promote recovery and resilience, as well as other studies relevant to outcomes of the Coral Bleaching Recovery Survey (for example herbivory, land-based pollution).

- Gather scientific literature and management reports
- Incorporate literature in a searchable reference manager
- Extract, summarize and synthesize possible coral bleaching recovery and resilience strategies applicable to Hawai'i

Introduction

Coral mortality caused by frequent coral bleaching events leads to systematic changes in the structure of tropical ecosystems (Ainsworth et al 2015, Graham et al 2013, Roff et al 2012, Hughes et al 2010, Hughes et al 2007, Bellwood et al 2006, Bellwood et al 2004). The rate of increase in Sea Surface Temperatures (SST) driven by global climate change has made it likely that bleaching will become a chronic stress on corals in the near future (Hooidonk et al 2013, Hoeke et al 2006, McWilliams 2005, Jokiel and Coles, 1990). Mass coral bleaching events are occurring with more severity and frequency, negatively affecting coral reefs worldwide with both short and long-term impacts (Ateweberhan et al 2013, Ateweberhan et al 2011, Frieler et al 2012, Baker et al. 2008, Hoegh-Guldberg 1999).

Despite the pressing consequences of frequent coral bleaching events, direct management interventions to mitigate the effects of a coral bleaching in progress are extremely limited (McClanahan et al 2012, Aeby et al 2009, Baker et al 2008, Marshal and Schuttenberg, 2004). Major gaps between the science of coral reef resilience and the management of reefs facing the effects of climate change have been identified, including 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 (Magris et al 2014, McClanahan et al 2012, Heller et al 2009, Hughes et al 2003). Work is needed to practically increase the application of reef resilience theories and develop innovative techniques to promote coral recovery (Aswani et al 2015, Maynard et al 2014).

Planning for the results of coral bleaching in Hawaii was initiated with the development of the Rapid Response Contingency Plan in 2009. The plan outlines a framework for responding to bleaching events, primarily by monitoring its effects and communicating the results to stakeholders and the public (Aeby et al 2009). Studies of coral bleaching in Hawaii have mainly focused on physiological processes including acclimation potential (Putnam and Gates 2015, Coles and Jokiel 1978), mechanisms and breakdowns in coral metabolism (Grottoli et al 2016, Gates et al 1992), and the role of reef environmental parameters and reef morphology on coral bleaching patterns (Jokiel and Brown 2004).

There remains a gap in a review of efforts to promote the recovery and resiliency of coral reefs following a bleaching event. This project collected and analyzed information from scientific literature that will inform a decision-making process to promote recovery through policy-making. This effort sought to outline types of restoration strategies present in the literature, synthesize evidence of support relevant to each strategy, and describe specific instances of management interventions following bleaching events.

Methods

Primary literature and management reports were gathered from the Coral Bleaching Working Group, the Web of Science database, Google Scholar, and the Reef Resilience Network. Database search terms included 'coral bleaching AND management', 'coral bleaching AND recovery', and 'coral bleaching AND intervention.' Papers were collated and sorted using *Zotero*, a research software tool. The *Zotero* list was copied to an Excel spreadsheet, where it was first organized by author's last name, then by publication year. Each paper was given keywords, or tags, summarizing the main topics covered. The location of each study was also recorded. Each entry was then categorized by type of paper. The paper categories were a review, a case study, an experiment, a response plan, a theoretical piece, or a survey (Table 1).

Table 1 Categories for the types of papers included in this literature review

Type of Paper	Description
Review	A synthesis of several papers summarizing the current understanding on a topic related to coral bleaching
Case Study	A description of a particular instance of coral bleaching including recovery/degradation patterns or the effects on the ecological structure of a given area
Experiment	A manipulation either in the laboratory or field to test a hypothesis
Response Plan	A document written to guide the management and/or scientific response to a coral bleaching event
Theoretical	Research that is theoretical in nature including decision-making tools, spatial modeling, forecasting, and mathematical modeling
Survey	An inquiry and analysis of the opinions, beliefs of a certain group of people

If the paper discussed taking action following a bleaching event, the type of action was recorded (Table 2). Types of actions were active recovery (actively manipulating the environment including coral transplantation or habitat enhancement), monitoring (recording data on the effects of bleaching on the ecosystem), and bolstering existing management (building off of or strengthening pre-existing rules and management programs).

Table 2 Management actions included in this literature review

Type of Management Action	Description
Active Recovery	Actively manipulating the environment including coral transplantation or habitat enhancement
Monitoring	Recording data on the effects of bleaching on the ecosystem
Bolstering Existing Management	Building off of or strengthening pre-existing rules and management programs

Within the type of management action discussed, the actions were categorized by type of recovery strategy. Recovery strategies were stimulating new coral settlement, stimulating coral regrowth, replacing dead coral, preventing additional damage to coral, and controlling algae overgrowth (Table 3).

Table 3 Recovery strategies included in this literature review

Type of Recovery Strategy	Description
Stimulating new coral settlement	Encouraging the settlement of new coral larvae
Stimulating coral regrowth	Accelerating the regrowth of remnant coral within the area affected by bleaching
Replacing dead coral	Replacing coral that died from bleaching with new coral
Preventing additional damage to coral	Preventing additional stress or physical injury to naturally recovering coral
Controlling algal overgrowth	Managing the growth of turf algae following a bleaching event, which can overcrowd coral for space

If the paper specifically called out certain actions that were taken, those actions were recorded along with the outcome (did coral recover because of these actions?) and the timescale (how long did it take to measure a change, either positive or negative, in the coral?).

Results

A total of 207 papers were reviewed as part of this effort. Publication dates ranged from 1978 to 2016, though the majority of papers were from 2013 to present. The reviewed articles originated from 33 countries, the most common being Australia and the Caribbean. There were a total of 432 authors named on these works. All five types of papers were represented in the review. The most common type of paper was a case study (38%), followed by theoretical papers (25%), experiments (15%), reviews (15%), response plan (4%), and surveys (3%).

Types of Management Actions

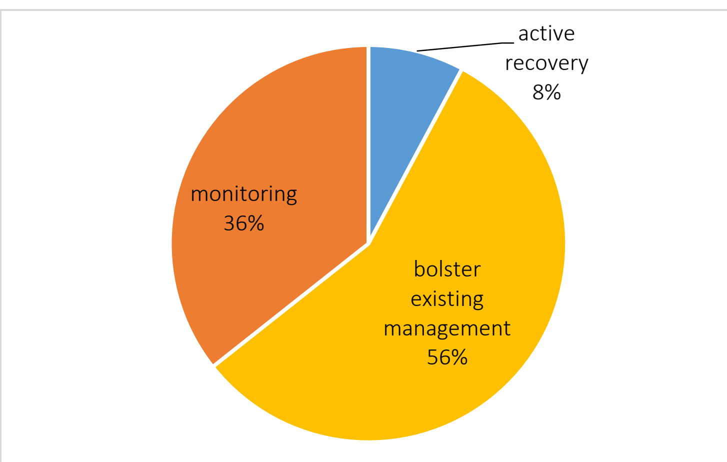

Figure 1 Types of management actions described in the reviewed literature

Slightly more than half (52%) of papers mentioned some type of management action. The majority of these (56%) discussed bolstering existing management regimes (Figure 1). An example of bolstering existing management is a recommendation to establish Marine Protected Areas (MPAs) in areas of low thermal stress to protect reefs that are not as exposed to temperature anomalies (Mumby 2008). Another example discussed using fisheries rules to protect parrotfish, which controls algae and thus creates more space for natural re-colonization of bleached areas (Mumby 2006). An example of a monitoring effort reported measuring rates of bleaching mortality across a geographic region (Ateweberhan et al 2011). An example of an active recovery effort included a review discussing reef shading, coral polyp feeding, and electro-chemical stimulation (Baker et al 2008).

Types of Recovery Strategies

A smaller portion of the papers (74 papers, 36%) discussed a more specific recovery strategy (Figure 2). Of these papers, the most common strategy discussed was preventing additional damage to coral (43%), followed by controlling algal overgrowth (36%), stimulating new coral settlement (12%), replacing dead coral (8%), and stimulating coral regrowth (1%). An important note is that most of these papers discussed multiple recovery strategies. The following sections go further in-depth into recommendations related to each restoration strategy.

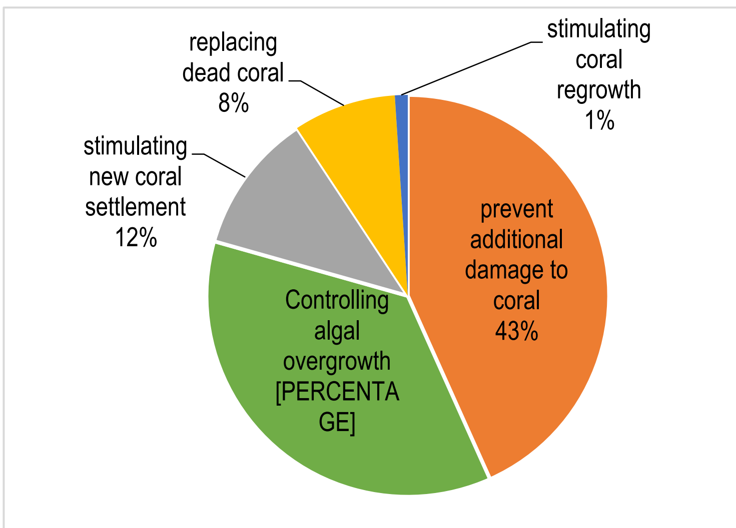

Figure 3 Types of recovery strategies discussed in reviewed papers

Recommendations to Promote Coral Recovery

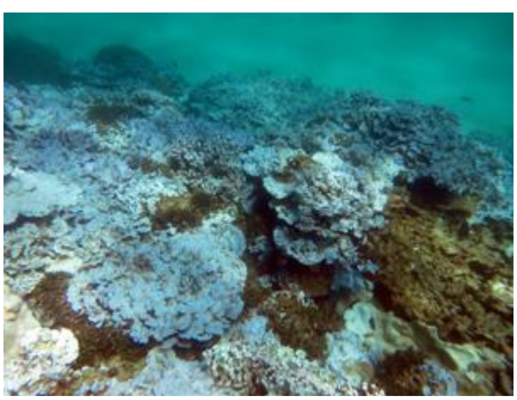

Figure 4 Coral bleaching in Papahanaumokuakea Marine National Monument, a Marine Protected Area (MPA) open to limited human entrance and closed to fishing activity, photo: NOAA

1. Preventing Additional Damage to Coral

The reasoning behind this strategy is to remove stressors aside from temperature stress, to allow for natural recovery of the bleached areas. The prevention of additional damage to bleached coral reefs was suggested for reefs where natural recovery is a promising outcome (Souter and Linden 2000). This intervention should also be scaled up or down according to the scale of the disturbance (Standish 2014). It has also been found that MPAs have high rates of coral loss following a bleaching event and recovery rates inside and outside of protected areas have been mixed (Ateweberhan et al 2011, McClanahan 2009). There were two main categories of strategies to reduce damage:

creation of marine protected areas and reduction of harmful human activities.

Creation of Marine Protected Areas

One recovery strategy to promote recovery following a bleaching event was to prevent additional damage to coral. The creation of areas closed from all human exploitation through a network of Marine Protected Areas (MPAs) was discussed (Rogers et al 2015, Aeby et al 2009, Dodge et al 2008), but the need for new approaches for exploited areas outside of MPAs were also acknowledged (Mumby and Steneck 2008, Dodge et al 2008). It was strongly suggested to place these protected areas surrounding reefs that have naturally lower vulnerability to bleaching events (Anthony et al 2015, Magris et al 2015, Pandolfi 2015, Magris et al 2014, Maynard et al 2012, Ban et al 2011, Baskett et al 2010, Keller et al 2009, McClanahan et al 2007, Obura 2005, Hansen et al 2003, West 2003, Done et al 2001, Westmacott 2000, Wilkinson 1992). Game et al 2008 presented an alternative viewpoint to protect areas and focus management actions on areas vulnerable to bleaching, while Baskett et al 2010 recommended placing protections around areas with high coral diversity. Aswani et al 2015 mentioned not to overlook hardy coral species living in marginal habitats, and McLeod et al 2009 presented a framework of MPAs stretching across a temperature regime.

Reduction of Harmful Human Activities

In addition to the creation of MPAs, it was also recommended to reduce human activities that harm corals. These activities include the creation of no anchor zones (Beeden et al 2014), a moratorium on all coral collecting (Goreau et al 2000), a self-moratorium on aquarium fishing (GBRA 2008), and closure of high-traffic SCUBA diving tourism sites (Hyde 2013). To identify these areas and activities, modeling has been used to pinpoint areas with high resilience potential and the most achievable management interventions (Maynard et al 2010). Targeting multiple, synergistic stressors were found to be more effective, including reducing land-based pollution (Brown et al 2013, Heller et al 2009). Reducing sediment and nutrients were in the top five actions recommended by coral bleaching and management experts in multiple studies (DAR 2016, McClanahan 2012). Wooldridge et al 2012 found that an 80% reduction in Dissolved Inorganic Nitrogen (DIN) buy an additional 50-60 years of reef-building capacity. Other pollution sources to target include sunscreen (Danovaro et al 2008) and wastewater discharge (Yeemin et al 2012). A recommended method of targeting specific pollution threats is the use of biomarkers, a way to measure the effect of pollution on the biology of corals and thereby identifying the specific contaminant.

2. Controlling Algal Overgrowth

Figure 5 A parrotifsh feeding on algae in the Carribbean, photo: Photostock

After an event that causes substantial coral mortality, like a bleaching event, there is a risk of an ecosystem shift from a coral-dominated environment, to an algal-dominated environment, which prevents the settlement of new coral recruits (Arnold et al 2010, Hughes et al 2007, Diaz-Pulido 2002, Westmacott 2000). It has also been found that when fish were abundant, algae was low and coral cover doubled due to new recruitment (Hughes et al 2007). It is important to avoid phase shifts, or if they occur to learn how to reverse them (Hughes et al 2003). Herbivores, or algae-eating species, have been found to be critical in maintaining a coral-dominated environment (Marshall et al 2004) and therefore the regulatory protection of herbivorous fish has been central in the discussion of management interventions to promote coral recovery following a disturbance (Mumby and Harborne 2010, Smith et al 2010). Pinpointing the threshold at which this ecosystem shift will occur has been found to be critical and to act before this transition takes place (Adam et al 2015, Standish et al 2014, Mumby et al 2007).

The lack of coral itself has also been found to affect fish populations through a lagged decrease in biomass due to natural mortality and lack of recruitment (Graham et al 2007). Adam et al 2011 found an herbivore population boom following a bleaching event due to food availability. It is also unclear whether herbivores are attracted to move to denuded areas from other places; there is evidence that rates of algae removal are similar on algae-dominated and coral-dominated reefs (Chong-Seng 2014) and that as hard coral declines that herbivore density increases (Russ et al 2015).

Protection of Herbivores through Fisheries Management

Protection of herbivores from fishing pressure has been projected to delay rates of coral loss even under the most extreme regimes of bleaching and other disturbance events (Edwards 2011). Even when significant coral has been lost, reduction in extraction through fisheries management has maintained populations in the absence of coral (Friedlander et al 2014). If fishing pressure on herbivores is high, two main strategies have been suggested. One strategy that has been suggested to accomplish this is through the use of MPAs focusing on the protection of herbivores (McClanahan 2014, Game et al 2009, Hughes et al 2007). This is a long-term strategy; McClanahan 2014 found that the rate of herbivory in a closed area peaks at 15-20 years after closure. A second strategy recommended is through regulation of herbivore populations – the International Coral Reef Symposium called for a ban on the harvest of herbivores commercially following (Dodge et al 2008). If fishing pressure is light, it may be possible to attract additional herbivores into a denuded area through providing artificial habitat structure and therefore increasing the architectural complexity of the area (Adam et al 2015).

The literature emphasizes that not all herbivores may have an equal effect on the rates of coral recovery and that managers need to target those species, functional groups, and sizes that have the greatest impact (Adam et al 2015, Cernohorsky et al 2015, Bonaldo et al 2014, Bellwood et al 2006).

The Protection of Parrotfish

Parrotfish (Scaridae) and their role in the removal of algae from coral reefs following disturbance have been a focal point for the scientific community. Like other herbivores, it has been found that their effect differs among species, functional groups, and sizes, with larger individuals contributing disproportionately to the benthic condition (Bellwood et al 2006). A recent action to protect parrotfish in Belize was found to have increased the resilience of surrounding reefs 6-fold (Mumby et al 2014). Regarding specific fisheries management objectives, it was found that corals can remain resilient to climate change disturbances if less than 10% of the parrotfish biomass is harvested and a minimum size of 30cm is implemented (Bozec et al 2016).

Global difference in the outcome of protecting herbivores

Although the relationship between protection of herbivores, and specifically parrotfish, and healthy coral reefs has been demonstrated in the Caribbean (Steneck et al 2014, Mumby et al 2010, Burkepile et al 2008), the evidence is not as clear for other parts of the world. In New Caledonia, no connection was found between protection status of a reef, coral recovery, and macroalgal development following a bleaching event (Carassou et al 2013). In Kenya, fisheries closures did not fare better than open areas (McClanahan 2009). One issue may be that managers are not addressing this issue at the appropriate scale (Mumby 2008). Additionally, herbivores are not a panacea, as they have been found to only be able to protect 10-30% of a structurally complex reef. Their management should be paired with additional management actions (Mumby et al 2006).

Other interventions to control algae overgrowth

In addition to herbivore protection, the reduction of anthropogenic factors that specifically influence the coral-algal relationship are critical (Baskett et al 2010). A novel approach of restocking grazing fish has been attempted only through a theoretical model (Obolski et al 2016). Their results suggest that applying this method in addition to protection, can be both ecologically and financially beneficial. There have been cases where coral naturally regenerates and outcompetes an algae boom (Diaz-Pulido et al 2009), the successful combination of traits was tissue regeneration, high competitive ability of the coral, and a seasonal die-back of a monospecific stand of seaweed.

3. Stimulating New Coral Settlement

Figure 6 Kaneohe Bay coral polyps, photo: DAR

It has been found that coral recovery from a bleaching event can be slow because of a decline in reproductive output of remnant corals (Hagedorn et al 2016, Chong-Seng 2014, Levitan 2014, Bair and Marshall 2002). Recovery will likely depend on an increase in larvae from other reefs (Souter and Linden 2000, Westmacott 2000). This is a slow process, dependent on natural recovery rates. Coles 2007 found that recovery following a storm in West Hawaii was cyclic on a decadal time-scale and correlated with species and site-specific time intervals. The study revealed that for this region, natural recovery rates were approximately 40 – 70 years.

Factors that influence new coral settlement

It has been recommended to secure larval connectivity for the affected area, or connection to larval sources (Aswani 2015, Baskett 2010). It is important to ensure that larval sources maintain a diverse gene pool to the settlement area (Hansen 2003). Adequate substrate is also imperative, measures should be taken to ensure hard-bottom habitat in the receiving site (Arnold 2010). There remains a need to bring together connectivity, larval settlement, and post-settlement mortality science to ensure that management targets the most valuable areas (Aswani 2015).

Mechanisms to stimulate new coral settlement

One mechanisms discussed to encourage settlement of new coral to bleached area is the use of MPAs to protect larval sources (Magris et al 2014, McLeod et al 2009). Amar and Rinkevich 2007 explored the use of active restoration to create coral nurseries as 'larval dispersion hubs.' These farmed colonies had 35% higher oocytes per polyp than their natural counterparts. Nursery-born planulae also developed faster in growing young coral colonies. A restoration effort in the Philippines following a dynamite blast used plastic mesh to secure loose substrate and found that coral recruitment and percent coral cover increased within 3 years (Raymundo 2007). Lastly, it has been found that anthropogenic effects are more influential for early coral life stages, so focusing on land-based pollution may also be a strategy (Baskett 2010).

4. Replacing Dead Coral

Figure 7 Transplanted corals in the Phillippines, described in Gomez et al 2014

Replacing the coral killed by a bleaching event with new coral from another location is a relatively novel active restoration method. The benefit of this method is the instant re-establishment of biodiversity in a damaged area. Research suggests it could be scaled up for global restoration projects (Rinkevich 2014). To use this method appropriately, it is recommended to assess the additional stressors present in the area and to identify specific restoration goals (Souter and Linden 2000). Many questions remain about this method and its use in restoring previously bleached areas (Yeemin 2012, Westmacott 2000). Two main methods are mentioned in the literature are: 1) collecting fragments from unaffected areas, and 2) farming bleaching-resilient genotypes to plant in the restoration area. Gomez et al 2014 collected fragments from unaffected reefs in the Phillippines following a bleaching event and transplanted them to the damaged area. After three years, they documented successfully increasing the coral cover and fish became attracted to the new reef. This gardening method has been used extensively in the Caribbean for the restoration of staghorn and elkhorn corals (Lirman et al 2010). Selecting and farming bleaching-resistant species is a relatively new phenomenon, but it is gaining momentum for Caribbean corals (Aswani et al 2015). The hope is also to target additional genotypes resistant to other stressors, like disease.

5. Stimulating Coral Re-growth

Figure 8 Dead coral skeleton following a beaching event, photo: Kristina Tietjen

A few papers documented instances where corals recovered from remnant live tissue following a bleaching event. On the Great Barrier Reef, a certain coral species was found to recover quickly (less than one year) due to rapid regeneration and competition with invasive algae (Diaz-Pulido et al 2009). Roff et al 2014 described a phenomenon called the 'phoenix effect,' where patches of live tissue in a French Polynesia lagoon environment overgrew dead coral substrate. Finally, Graham 2013 described how if detrimental human impacts could be reduced in the area, that pulsed disturbance events could 'jump-start' a return to a coral-dominated state.

Examples of Direct Management Interventions

In the 207 papers that were reviewed, there were four examples of managers directly intervening following a bleaching event to assist in the recovery of those reef areas (Table 4).

Table 4 Case studies of direct management interventions following a coral bleaching event

Publication	Location	Type of recovery strategy	Specific Strategy Discussed	Outcome	Time Scale
Beeden et al 2014	Great Barrier Reef, Keppel Islands	Preventing additional damage	Creation of no-anchor zones	Reduced anchor damage from ~80 to less than 10, coral continued to decline	4 years
Gomez et al 2014	Philippines, Bolinao	Replacing dead coral	Transplantation of coral fragments to degraded, formerly bleached area	After 12 months, recorded high survivorship (~95%), extensive coral cover, after 16 months more transplanted colonies were fusing and reef fish using the new habitat	3.5 years
Hyde 2013, Yeemin et al 2012, Tun et al 2010	Malaysia, Thailand	Preventing additional damage	Closure of high-traffic dive sites	No biological outcome could be found, some conflict between managers and dive site users resulted	4 – 14 months
GBRMPA 2008, Bonin et al 2016	Great Barrier Reef, Keppel Islands	Preventing additional damage	Self-moratorium on aquarium collecting	No biological outcome could be found; MPA network supports larval dispersal	8 years

Beeden et al 2014 - Creation of no-anchor zones on the Great Barrier Reef

Figure 9 No anchor sign in the Keppel Islands

Following the 2008 coral bleaching event and a damaging hurricane season, the Great Barrier Reef Marine Park Authority (GBRMPA) established a no-anchor zone in the Keppel Islands, a group of 16 islands 15km off the coast of Yeppoon in the southern Great Barrier Reef (GBR). The area has high coral cover and also high incidence of anchor damage as it is popular with boaters. Following the bleaching event, a working group was formed including local managers, community members, and regional natural resource management bodies to examine strategies to enhance the resilience of vulnerable coral reef ecosystems. The locations of the no-anchor zones were selected based on a resilience assessment (Maynard et al 2010). Sites had to meet four criteria: 1) low to medium resilience relative to other sites, 2) high levels of anchor damage, 3) high usage and good visibility to the public and 4) high accessibility for managers and rangers to install buoys. Despite a reduction in anchor damage at all monitored sites, coral continued to decline from 2010 – 2012 (Beeden et al 2014). This project represented the first time that supporting reef resilience was explicitly the motivation for local-scale management on the GBR.

Gomez et al 2014 – Transplantation of coral fragments in the Philippines

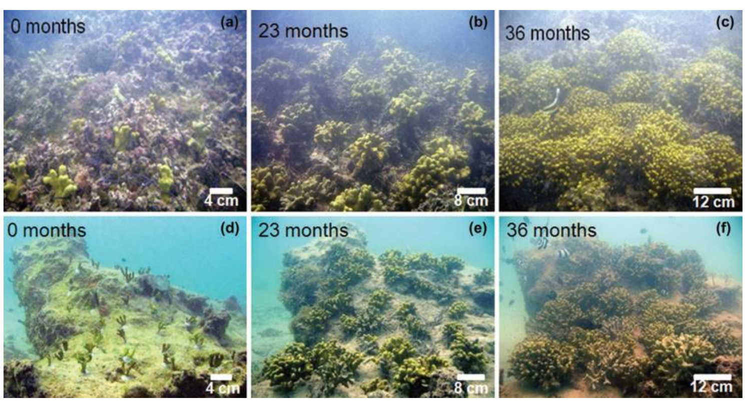

Figure 10 *Porites cylindrica* transplants 0, 23, and 36 months post-transplantation from Gomez et al 2014

The restoration area described in this study is part of a reef complex around Bolinao, Pangasinan in the northwestern Philippines. The area was described to be in a degraded state following a 1997-1998 bleaching event. The project used 960 pieces of *Porites cylindrica*, (a previously dominate coral species) from asexual fragmentation of donor colonies. Transplantation was chosen because of the lack of available substrate for new coral larvae. After 20 weeks, high rates of survival (80-95%) were maintained. There were no significant differences in the density of transplants, although shallower transplants fared better than those in deeper water (Gomez et al 2014). Implications for future practice were: use coral species that demonstrate resilience under a wide range of environmental conditions, density of transplants is of minor significance to growth and survival, some species will be successful despite being moved to a different substrate or orientation, greatest success comes when corals are transplanted to similar environments as the original source area, and it is not necessary to use artificial substrates (cement, tiles, etc.).

Hyde 2013, Yeemin et al 2012, Tun et al 2010 - Closure of high-traffic dive sites in Southeast Asia

Figure 11 Map of close dive sites in Malaysia

Southeast Asia, including Malaysia, Indonesia, and Thailand suffered from the 1998 coral bleaching event and resulting mortality was estimated at 18% (Tun et al 2010). In an unprecedented decision to minimize stress, the Malaysian Department of Marine Parks closed 12 of 83 dive sites in marine parks in Peninsular Malaysia from July – October 2010, where coral bleaching was estimated at 60%. Thailand instrumented a similar policy closing 18 popular dive sites for 14 months (Tun et al 2010). The Department of Marine and Coastal Resources in Thailand held a workshop to develop a coral reef management strategy in response to the coral bleaching crisis (Yeemin et al 2014). A list of potential management interventions were analyzed as well as a list of pressing research questions. No specific outcome of this effort could be found, however advice for managers includes ensuring clear communication of management actions, consultation of all stakeholders, and examination of local versus global impacts on reefs (Hyde 2013).

Great Barrier Reef Marine Park Authority 2008 – Self-moratorium on Aquarium Collecting

Figure 12 A cinnamon clownfish (*Amphiprion melanopus*) on the Great Barrier Reef

In January 2008, licensed Queensland aquarium fish collectors agreed to self-impose a moratorium on the collection of cinnamon clownfish (*Amphiprion melanopus*) and their associated anemone habitat. This effort represented the world's first climate change initiative taken by the aquarium industry. It was a pro-active measure and a direct reaction to the coral bleaching event in the Keppel Islands (the same region as the no anchor zone effort). No biological data could be found on the impact of this moratorium on clownfish population size. Bonin et al 2016 did mention the moratorium and evaluated how a network of MPAs supported *Amphiprion melanopus* larval dispersal within the Keppel Islands. Their findings suggest that the network is fully connected via larval dispersal and one MPA in particular was identified as a critical source of larvae.

Discussion

This effort synthesized evidence for five restoration strategies that managers could pursue following a bleaching event: preventing additional damage to coral, controlling algae overgrowth, stimulating new coral settlement, stimulating coral regrowth, and replacing dead coral. The largest portion of this literature discussed strategies to prevent additional damage and to control algae overgrowth and the central mechanisms for these strategies are the creation of MPAs, reduction of harmful human activities, protection of herbivores through fisheries management, and reduction of anthropogenic factors that promote algal growth.

Based on this evidence, managers that are faced with the need to implement recovery strategies should consider two main questions: is there capacity for natural recovery of the system? And is the natural rate of recovery sufficient to regain ecosystem function? Based on these answers, managers are able to navigate whether it would more appropriate to pursue monitoring, bolster existing management, or initiate active recovery (Figure 13). Other considerations include that the reviewed interventions must be context and site-specific based on local reef and environmental conditions, political and regulatory frameworks, and biology of the affected coral species.

Before management decisions can be made for corals affected by bleaching in Hawaii, a few key pieces of information are needed. Context-specific information on recovery rates of Hawaiian coral species need to be synthesized. Additional information on the ecological contribution of reef herbivores should be analyzed. To focus management interventions geographically and strategically, managers could use a number of decision-making tools described in the literature:

- Coral Reef Ecosystem Simulation Model (CAFFEE) – Used to help managers to evaluate the effects of fisheries management options considering climate change (Sebastian et al 2012).
- Atlantis Ecosystem Model – used to quantify the effects of climate change and current levels of LBSP and fishing. These analyses offer ways to quantify impacts and interactions of particular stressors in an ecosystem context (Weijerman et al 2015).
- Resilience Based Management (RBM) – Derived management recommendations from a resilience assessment around the Commonwealth of the Northern Mariana Islands (CNMI). The model combined larval connectivity simulations and identify priority sites for six types of management actions (Maynard et al 2015).

Lastly, this review revealed that although there continues to be substantial discussion regarding ecological factors that confer resilience and coral reef ecosystems, there remains very few examples of the use of these strategies—especially the effectiveness of these efforts. Four examples were found of managers intervening following a coral bleaching event. Tools are needed to operationalize reef resilience concepts and transfer knowledge from coral conservation concepts to practical interventions and strategies. This is beginning to take place as additional regions including Australia and the South Pacific experience extreme bleaching events in 2016. When the State of Hawaii takes additional steps to promoting reef recovery, it will be among the first governments to take an active approach to address the effects of climate change in its waters.

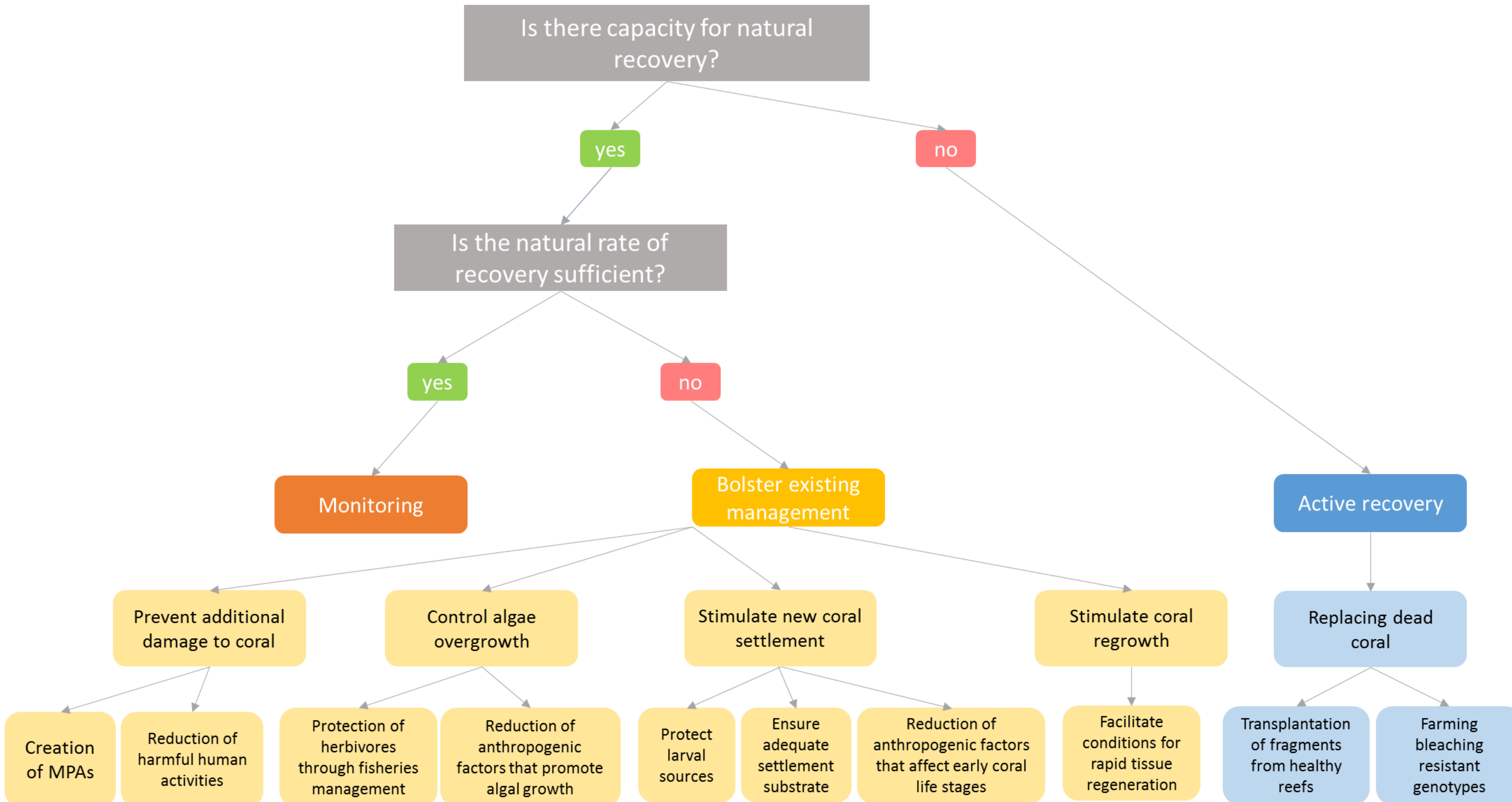

Figure 13 Decision making framework for management interventions to promote coral recovery following a bleaching event

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