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ARTICLE

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Using the Resist-Accept-Direct management framework to respond to climate-driven transformations in marine ecosystems

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Abstract

Climate change is impacting natural ecosystems and the services they provide at an unprecedented rate, yet management is not keeping pace with radical ecosystem transformations. Management in marine systems is primarily designed to regulate fishing pressures, which may be of limited use in addressing large-scale climate impacts. The Resist-Accept-Direct (RAD) is a flexible, novel framework that gives managers a way to structure and plan how to respond to radical shifts/transformations in ecosystems. We present marine case studies of broad scale impacts and outline how the responses may fit into the RAD concept. We use the RAD framework to address the collapse of the kelp forest in northern California and examine how potential policy guiding restoration strategies can be organised. We conclude that the response to most marine ecosystem transformations has been to use the *resist* strategy that includes adaptive management, and we suggest that for the kelp forests in California the *resist* strategy provides the best option for moving forward. The RAD framework will be useful for marine ecosystem transformations in which systems have reached their tipping points and now require novel restoration tools and thinking as we face climate change stressors and an unpredictable future.

KEYWORDS

climate change, regime shift, restoration, sea urchin barrens, tipping points

1 | INTRODUCTION

As global warming and extreme weather increasingly threaten our terrestrial, freshwater and marine ecosystems (Ummenhofer and Meehl 2017), it has become imperative for us to develop an effective framework for environmental management in response to climate disasters. Unfortunately, our knowledge about how to respond to climate impacts in the oceans lags behind terrestrial systems despite the known impacts to humans and critical ecosystem services (Allison and Bassett 2015). Anthropogenic stressors including increased greenhouse gas emissions, global warming, decreased migration corridors, overharvesting/overfishing, altered precipitation and increased fires and storm patterns are occurring and their impacts on the oceans are well documented (Doney et al. 2012; IPCC, 2013; Roberts et al. 2017). Human activities have impacted our current planet, and studies predict global mean temperatures will increase from 2°C to over 5°C by 2100, compared with the 1°C rise we are experiencing at present (Nunez et al. 2019). Further marine heatwaves will increase the negative impacts of global warming with additional heat stress (Frölicher et al. 2018, Arafeh-Dalmau et al. 2020). Intensifying anthropogenic stressors are resulting in radical ecosystem shifts that are occurring at accelerating rates (Solomon et al. 2009, Hoegh-Guldberg et al. 2010, Wernberg et al. 2013). Historically stable environments are reaching their tipping points and are undergoing unprecedented regime shifts to alternative states (Figure 1) (Scheffer et al. 2001, Waycott et al. 2009,

FIGURE 1 Collapse of the bull kelp forest, Salt Point, northern California, USA. Source: C. Catton

Rogers-Bennett and Catton 2019). Traditional management actions, such as adjusting fishing pressures (management lever), may be grossly insufficient for addressing climate-driven ecosystem collapse. Because of these radical, non-linear shifts, natural resource managers will require new ways of thinking about the problems, novel approaches and a policy framework to guide best management practices for ecosystems that are now transformed.

The Resist-Accept-Direct (RAD) decision-making framework (NPS 2020) allows policy makers and resource managers to employ effective environmental management when faced with radical, sudden ecosystem transformations (Schuurman et al. 2020, Lynch et al. 2021, Thompson et al. 2021, Schuurman et al. 2022). The purpose of this framework is to provide resource managers with three different management perspectives for responding to nonstationarity or radical ecosystem shifts (Schuurman et al. 2020). A consortium of five federal agencies joined together in the Federal Navigating Ecological Transformation working group to create the RAD framework (Schuurman et al. 2020). Using this framework, ecosystem transformation may be responded to with three strategies: (1) *resisting the transformation*, such that managers choose to maintain current or historical conditions of the ecosystem's structure; (2) *accepting the transformation*, where managers allow current drivers to alter ecosystem conditions. This may be because change is not significant enough to justify a response, current conditions are already sufficient or preferable, or effective change is not achievable; and (3) *directing the trajectory of the transformation* towards an alternate state that is more viable for the future than either accepting its current state or maintaining historic conditions. This new framework may be an important tool for considering how to proceed with the conservation of our ecosystems in the midst of unprecedented global temperature increases and escalating environmental transformations (Solomon et al. 2009).

Climate-driven changes to marine systems provide challenges that current conservation models are not well suited to address as many rely on conserving and restoring ecosystems to their pre-disturbed state in a "stationary," or fixed, climate rather than a warming one. Current conservation efforts that focus on mitigating impacts to the environment include creation of protected areas that reduce fishing and hunting, habitat restoration, bioremediation, reduction or control of local disturbances, and removal of invasive species. These methods aim to relieve anthropogenic impacts on the ecosystem and return it to its previous state. While most conservation efforts may help restore some aspects of the ecosystem, the current conservation model does not account for the rapidly accelerating human-induced effects that are radically altering ecosystems. For example, sea-level rise is projected to trigger major changes/transformations (tipping points) in shallow sandy beaches and tidal wetlands (Barnard et al. 2021). Furthermore, once ecosystems have been "restored," they will continue to face a changing climate and the organisms that were once there may no longer be able to survive. With today's rates of global warming and its intensifying effects, previous fishing pressures may no longer be sustainable if the productivity of the resources has been diminished. Similarly, current conservation efforts may become less successful over the long term as the climate changes the ecosystem. New, more adaptive management measures may be needed for both sustainable extraction and conservation (Malhi et al. 2020).

In this paper, we examine examples of radical changes in nearshore marine ecosystems and identify some of the management actions taken to address the declines. We examine these restoration actions through the lens of the RAD management framework identifying realistic management objectives. We outline a number of declining marine ecosystem case studies to identify restoration strategies for declines in (1) coral reefs, (2) eelgrass habitats, (3) native fishes due to invasive lionfish, (4) corals due to crown-of-thorns sea star population explosions and (5) sea star die off along the Eastern Pacific. Once the restoration actions for these case studies have been identified using the RAD framework, we go on to use this framework to identify management objectives for the bull kelp deforestation in northern California. The sudden decline in 2014 of >90% of the kelp forest in northern California from a healthy state such as that in 2008 (Rogers-Bennett and Catton 2019) has led to massive ecosystem changes, which we are still working to understand and quantify. As of 2020, the kelp forest ecosystem is still struggling to recover and it is unknown when many of the ecosystem services such as recreational and commercial fisheries will recover.

Furthermore, we identify a need for rigorous continued monitoring to adapt management to be responsive to this rapidly changing, dynamic ecosystem. Given the magnitude and the temporal extent of the kelp forest decline, we use the RAD management framework to aid in identifying restoration objectives, promote adaptive management and make recommendations for moving forward.

2 | GLOBAL MARINE CONSERVATION CASE STUDIES

As the changing climate continues to alter environmental conditions at an alarming rate, marine ecosystems across the globe are impacted. Marine ecosystems are affected by climate change at a higher rate than terrestrial organisms due to their inability to avoid environmental pressures such as the increase in ocean temperatures and how it affects their overall fitness (Antão et al. 2020). A species unable to shift in range will be put under stress and can exhibit diseases or mass mortality events, aka unusual mortality events (McCauley et al. 2015; Rogers-Bennett and Catton 2019). Furthermore, the health and reproductive capacity of survivors within collapsed ecosystems may also be impacted (Rogers-Bennett et al. 2021). The warming of ocean temperatures shifts, and many times constricts, the range of native marine organisms and allows nonindigenous species to invade new communities (Stachowicz et al. 2002; Ruiz and Carlton 2003; Sorte et al. 2010). There are countless examples of climate-induced disasters in marine populations from around the globe, and here, we present a number of examples (Case Studies 1–6).

2.1 | Case study 1: coral bleaching and declines worldwide

Coral reefs around the world are declining at an alarming rate. For example, coral reefs have been listed as one of the most vulnerable ecosystems to climate change (Gattuso et al. in IPCC, 2014). This is due to coral bleaching, a process that happens when warming ocean temperatures disrupt the symbiosis between coral and zooxanthellae, a photosynthetic symbiont that supplies coral with food (and their bright colours). Rising water temperatures stress the coral reefs physiologically, so they expel their beneficial zooxanthellae giving the coral a white, or "bleached" look (Figure 2). Without this symbiont that provides food and energy, the coral will die. The IPCC (2018) predicts with very high confidence the loss of more than 99% of coral reefs by a warming of 2°C under SR1.5 (IPCC, 2018). The SR1.5 is a special report by the IPCC that assesses the impacts of 1.5°C global temperature warming above pre-industrial levels. It is because of this that more adaptive restoration efforts are necessary in order to conserve coral reefs.

Coral restoration efforts include culturing coral fragments and stocking them on the natural reef. While these efforts have proven to be locally effective in reef regrowth, the changing climate will subject the planted corals to experience the same thermal stress as

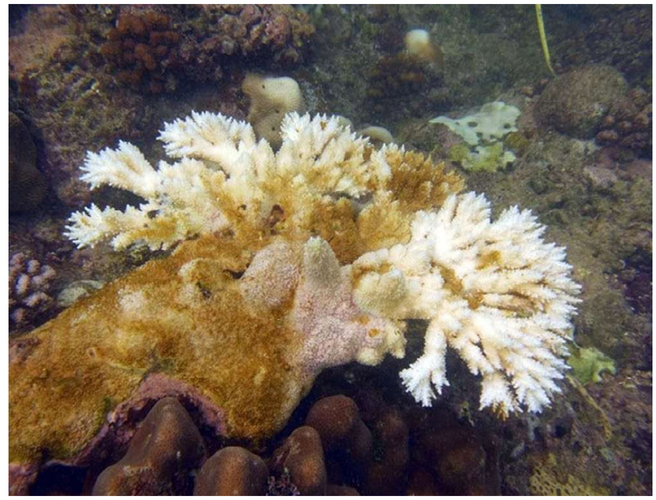

FIGURE 2 Bleached corals in Guam. Source: National Park Service

the rest of the reef from which they were taken, potentially killing them if global warming surpasses 1.5°C (IPCC, 2019). In this case, climate-smart restoration could include planting local coral that is naturally more resistant to warmer water (Dias et al. 2018) and selectively culturing these species or genetic families that are more heat-resistant. These strategies could be seen as *resist* if the families are more resilient, or *direct* if a new suite of corals is selected for planting on the reef, changing the community structure to be more resilient. Furthermore, there is the potential to culture more heat-tolerant coral symbionts to improve the chances of survival (Chakravarti and Van Oppen 2018, Cunning and Baker 2020). This, too, could be seen as *direct* if the symbiont species are different from those that are currently present.

A number of other different strategies are being used to promote coral restoration and combat the negative impacts of climate change on coral reefs. The mass removal of coral predators such as crown-of-thorns sea stars is being conducted (Hoey et al. 2016) and is considered a *resist* strategy for the coral reefs. We will discuss the crown-of-thorns starfish in more detail below (Case Study 4). Another example of a *resist* strategy is the development of coral safe sunscreens, such as Stream2Sea, that do not contain harmful chemicals like Oxybenzone that are known to degrade corals (Danovaro et al. 2008; Downs et al. 2015).

2.2 | Case study 2: eelgrass ecosystem management

Like kelp forests, eelgrass is an ecosystem engineer that provides habitat, food and a variety of ecosystem services through its establishment (see Figure 3). However, eelgrass ecosystems are declining around the world largely due to human impacts. To better understand how to restore these vital foundation species, a compilation of literature reviews on the restoration efforts for eelgrass ecosystems along the west coast of the United States was assessed

(Beheshti and Ward 2021). In total, 51 eelgrass restoration projects were analysed with their restoration efforts being categorised into four different types: active mitigation, active non-mitigation, passive mitigation and passive non-mitigation (See Beheshti and Ward 2021 for criteria).

We can think about these four categories of restoration efforts in terms of RAD. Because non-mitigation efforts were performed for purposes other than to mitigate the loss of eelgrass and focused only on experiment- or goal-oriented outcomes from predefined management targets, we have categorised all non-mitigation efforts under *accept*. Passive mitigation falls under the *resist* category, as these efforts mainly focus on maintaining historic conditions such as restoring the hydrology and water quality of the ecosystem and removing trash. Active mitigation would be classified under *direct*, where there is direct transplanting of new eelgrass shoots where different seeding techniques are used to promote new growth. Out of the 51 restoration projects, 6% are *resist*, 41% are *accept*, and 53% are *direct*. Given these data, *directing* is the more common method; however, the success of various restoration methods (best practices) depends mainly on environmental conditions and must be re-evaluated over time (Morris et al. 2019; Beheshti and Ward, 2021).

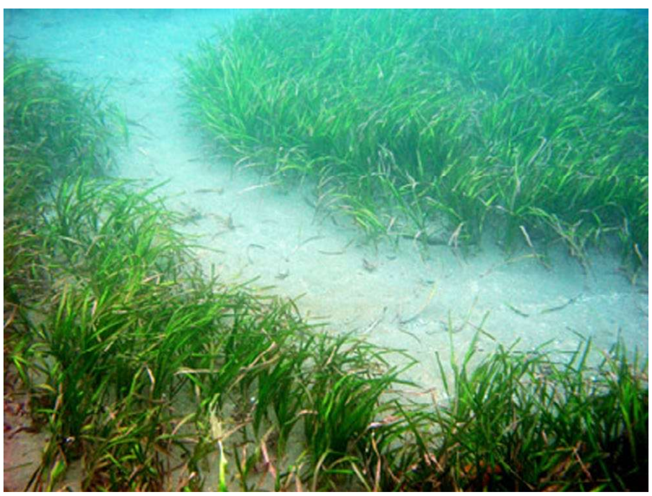

FIGURE 3 Eelgrass bed at Santa Cruz Island, Channel Islands, California, USA. Source: National Park Service

2.3 | Case study 3: overpopulation of lionfish in the caribbean

Lionfish, *Pterois volitans* (Oken) and *P. miles* (Bennett), are native to the Indo-Pacific region, but over the past decade have become established in the north Atlantic, Gulf of Mexico and the Caribbean, migrating as far south as the northern coast of South America (Whitfield et al. 2014). The invasion is thought to be due to releases of unwanted aquarium fish by aquarium owners and was first observed in 1985 in the western Atlantic Ocean or an unplanned aquarium release following a bad storm. In the Florida keys, lionfish were thought to have escaped from an aquarium during a massive storm around 2005 and were commonly seen on the reef by 2009 (P. Gross pers. comm. Force Blue). These invasive predators are considered a major threat to reef fishes due to their lack of natural predators and their generalist diet, consuming more than 50 different species of fish (NOAA, 2021). The success and recent overpopulation of lionfish in these northern invaded regions can be linked to climate change, as one of the few factors limiting lionfish distribution is water temperature (Whitfield et al. 2014). As northern waters become more tropical, lionfish are able to invade and establish their populations. With the absence of natural predators and an abundance of new prey, the lionfish populations are able to thrive. With the recent overpopulation of these species in the Caribbean, the coral reef ecosystems have changed dramatically with major reductions in native fishes (Whitfield et al. 2014).

Efforts to mitigate lionfish overpopulation have centred on lionfish fishing, including "lionfish derbies" (Figure 4a). Group dive events target lionfish and have been successful in reducing the population in localised areas. Commercial divers get around US$5 per pound of lionfish, and NOAA has issued permits even inside no-take marine reserves (Figure 4b). In addition, there is now a seafood market for lionfish, which is a delicate white meat served in some restaurants. This is an example of the *resist* strategy, yet there is the knowledge that fishing alone will not be sufficient to totally remove lionfish from cryptic or deep-water habitats where fishers are less effective. We use the RAD framework to examine restoration actions to control invasive lionfish. Therefore, we can think of the thinning of lionfish

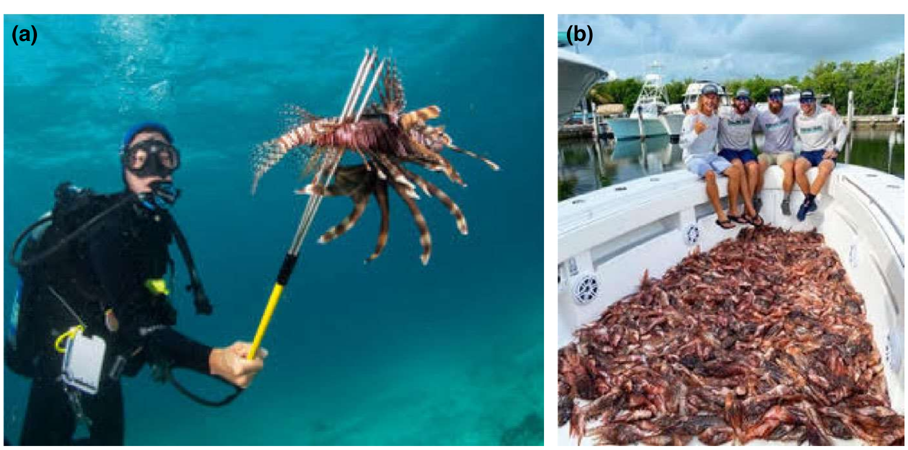

FIGURE 4 (a) Lionfish captured by diver Patti Gross. Photograph credit: David Gross. (b) Spear fishing boat during lionfish derby in Florida Keys, USA. Photograph credit: Tony Young, @ Foreveryoung as an *accept* strategy since we are working to accept the invasion along with the creation of a lionfish fishery.

Current efforts such as targeted fishing of lionfish and the creation of a viable seafood have proven to be successful at reducing their population. Similarly, the Lionfish University and NOAA are partnering to develop traps that attract and capture lionfish at depths too deep for divers. Because ocean temperature is a primary limiting factor in the spread of lionfish and ocean warming is intensifying, *accepting* and *resisting* the invasion of lionfish will need to be an ongoing adaptive restoration strategy. Given that the seafood market is viable, the fishery may prove to be a workable long-term management solution.

2.4 | Case study 4: crown-of-thorns sea stars in Australia

Coral-eating crown-of-thorns (COT) sea stars *Acanthaster planci* have a population outbreak about once every 17–18 years in Australia (Pratchett et al. 2019). However, these outbreaks are occurring with greater frequency and severity due to anthropogenic impacts such as nutrient inputs enhancing larval survival and removal of COTs predators by overfishing (Babcock et al. 2016). It is unlikely that any single factor is responsible for outbreaks, but acting in concert, these multiple stressors drastically increase both the frequency and magnitude of outbreaks. Today, COTs outbreaks are estimated to be the second greatest threat to corals on the Great Barrier Reef (Hoey et al. 2016) in combination with climate change. While COTs are native to Australia, when their population is in high densities, they have devastating effects on the reef as they consume coral faster than they can grow (Hoey et al. 2016). The rapid decline in the reefs in Australia due to COTs outbreaks, paired with climate change-driven ocean acidification and low oxygen, suggests there are multiple threats for coral ecosystems. Some management practices to mitigate overgrazing by COTs incorporate a culling programme using a lethal bile salt injection (Hoey et al. 2016) when there are outbreak events. Other long-term efforts to reduce COTs include water quality improvement, establishment of MPAs, and manual control, which has had the most success controlling COT numbers (Westcott et al. 2020).

Looking at management of COTs using the RAD framework, manual culling of adult COTs through lethal injection has proven to be the most effective at reducing populations and increasing coral cover (Westcott et al. 2020) (see Figure 5). This strategy attempts to *resist* change; however, it only responds to outbreaks and does not address the root cause of recurring events. *Accepting* the rise in COTs densities would certainly wreak havoc on the coral reef ecosystem, so it is not an option in this case. *Resisting* seems to be the chosen strategy for the long-term health of the reef. A biosecurity method developed by Hoey et al. (2016) details a forecast warning system that can activate the culling response in the affected zone when COT populations rise. The response activates a range of biocontrol measures, from alerting the Minister of the Environment to enabling a community team to perform mass lethal injections (Hoey et al. 2016). This forecast method could be used to proactively control adult COT densities and try to push the ecosystem back towards a more coral reef supportive state. This *resisting* approach in combination with local recruitment monitoring programmes, research on COTs reproduction and establishing a predatory giant triton *Charonia tritonis* stocking programme, could all help *resist* COT overgrazing.

2.5 | Case study 5: sea star mass mortality

Sea stars suffered mass mortalities along the Eastern Pacific starting in 2010–2013. One large, important predatory star, the sunflower sea star *Pycnopodia helianthoides*, suffered mass mortalities and have yet to recover (Figure 6a). Sunflower stars play an important role in maintaining kelp forests (Hamilton et al. 2021). The loss of sunflower stars preceded an ocean warming event, which is thought to have exacerbated the decline in the stars and their possible recovery (Hamilton et al. 2021). The epidemic known as sea star wasting disease (SSWD) plagued over 20 species of sea stars ranging from the Aleutian Islands to Mexico, triggering a mass mortality event (Harvell et al. 2019). Of these 20 species, the sunflower star population was decimated by the disease and are now listed as critically endangered by the IUCN (Gravem et al. 2020). These stars are now functionally extinct in the southern portion of their range between Baja California, Mexico and Oregon, the USA with declines of 99%–100% in some regions (Hamilton et al. 2021) (see Figure 6b). With the severe drop in sunflower star numbers, the temperature of ocean water has become a determining factor in the success of the remaining individuals. Efforts to re-establish sunflower star populations are being put into motion (J. Hodin pers. comm. Friday Harbor Labs); however, if climate change intensifies and ocean temperatures continue to warm, the southern portion of the population may not be able to recover even after stocking of captive-reared juveniles. It is unknown if the disease responsible for the declines is still active and present in the southern portion of the sea stars range.

Using the RAD framework, we examine the sunflower star restoration programme and categorise management options. Without human intervention, the population may have poor recovery in the southern portion of the range (>1000 km of coastline) as there has not been any evidence of natural recovery (Hamilton et al. 2021). *Accepting* the change in population numbers may lead to their continued local extinction in the southern portion of the range, loss of genetic diversity and potentially negative impacts to kelp forests when there is sea urchin overgrazing. *Resisting* or *directing* the changes may be a better option given that trophic cascades can occur with the loss of a key mesopredator in kelp forest ecosystems (Burt et al. 2018). One example of the *resist* strategy is the partnership between the Nature Conservancy and University of Washington who are establishing the first captive breeding programme for sunflower stars (J. Hodin pers. comm. Friday Harbor Labs). If large-scale stocking programmes are found feasible, reintroduction of juveniles and translocation of adults to areas where they are locally extinct

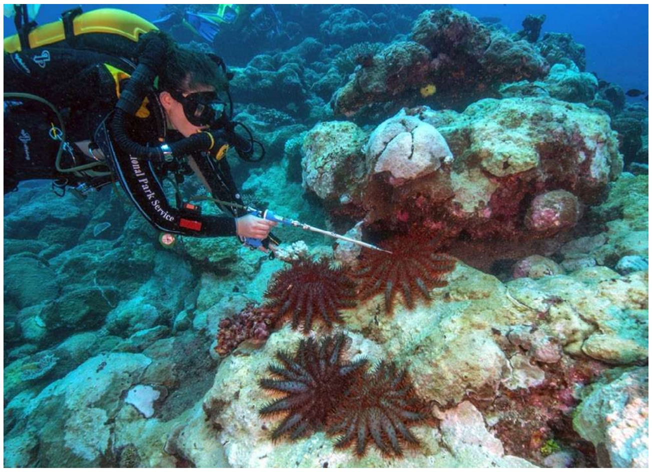

FIGURE 5 Lethal injection to COTS in Australia, Source: National Park Service

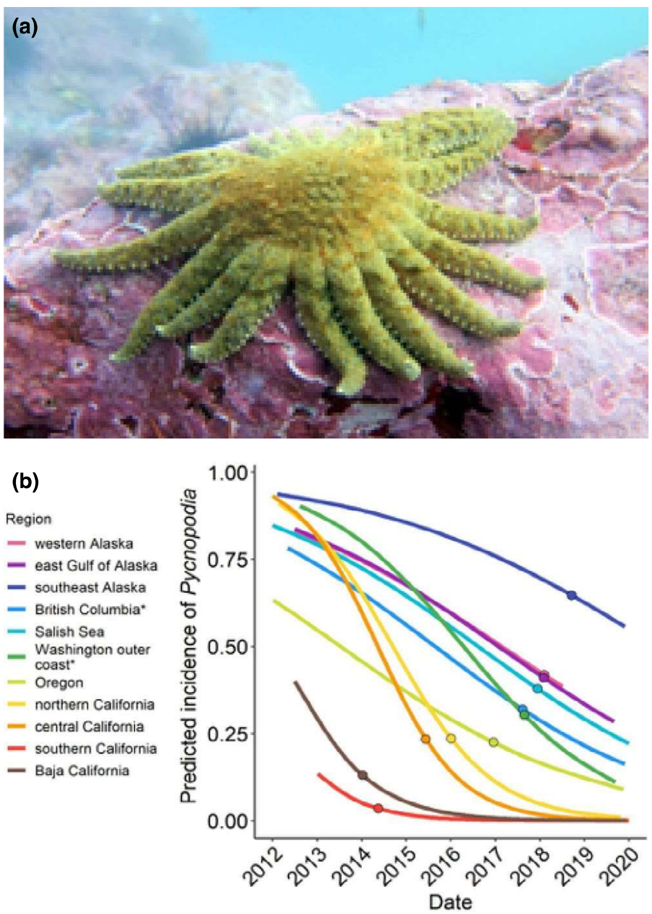

FIGURE 6 (a) Sunflower sea star *Pycnopodia* in northern California. Credit: Athena Maguire. (b) Declining predicted occurrence of *Pycnopodia* over time in different native regions. Source: Hamilton et al., 2021

are some *resisting* recovery strategies being considered. In addition, there are suggestions for supporting the population through genetic strategies. Selective breeding of more disease-resistant sunflower stars for stocking is one option for *resisting* change. As with any endangered species, the establishment of long-term monitoring programmes is also a key part of the recovery strategy. Trying to find more disease-resistant sea star species that have similar diets to sunflower stars would be an example of *direct*, moving the system to one with different species of stars. In these ways, *resisting* and *directing* the recovery of sea star populations can serve to preserve the trophic interactions limiting herbivores which can promote a healthy kelp forest community.

2.6 | Case study 6: kelp deforestation

Northern California is home to lush bull kelp *Nereocystis luetkeana* forest ecosystems that provide critical habitat and food resources for nearshore marine organisms. North of San Francisco, the most dense kelp forests are along the Sonoma and Mendocino County coasts where nutrient rich, cold water (García-Reyes et al. 2010) supports this fast growing annual species. The northern California kelp forest supports commercially important species such as the red sea urchin *Mesocentrotus franciscanus*, which provides jobs and revenues in excess of US$3 M per year. Kelp is also the main food source for the recreationally important red abalone *Haliotis rufescens* that provides fishing opportunities to 34,000 participants per year and was worth US$44 M when the fishery was healthy and active (Reid et al. 2016).

This once thriving, kelp forest ecosystem has been transformed by massive fields of purple sea urchins *Strongylocentrotus purpuratus* following the loss of sunflower stars and marine heatwave (Rogers-Bennett and Catton 2019). Since 2014, the combination of the climate change-induced marine heatwave and increase in sea urchins has resulted in the continued decline of the kelp, which has persisted due to overgrazing by herbivorous sea urchins (Figure 7). The decline in the once resilient kelp forest (McPherson et al. 2021) has led to the closure of the recreational red abalone fishery and an 80% decline in the commercial red urchin fishery from a healthy state before the marine heatwave in 2014 (Rogers-Bennett and Catton 2019). This large-scale loss of kelp forests has drastically altered the ecosystems and resulted in the loss of a suite of species and other ecosystem services. Declines in kelp forest ecosystem engineers can impact nutrient cycling, carbon sequestration, coastal protection, primary production, water and sediment flow, and economically valuable species (Rogers-Bennett and Catton 2019) such as abalone, urchins, lobster, rockfish and more. Because of the suite of ecosystem functions that kelps provide, the near-complete loss of kelp forests in northern California for the past six years has resulted in cascading effects leading to regime shift/ecosystem transformation (Rogers-Bennett and Catton 2019).

Using the RAD framework for the kelp forest example clearly shows that there are more and less desirable ecosystem outcomes (Table 1). It seems clear that humans will not be able to remove all the excess sea urchins from 350 km of coastline but that small restoration areas/patches may be a goal that is achievable. *Resisting* the transformation to sea urchin barrens in this case may be a manageable

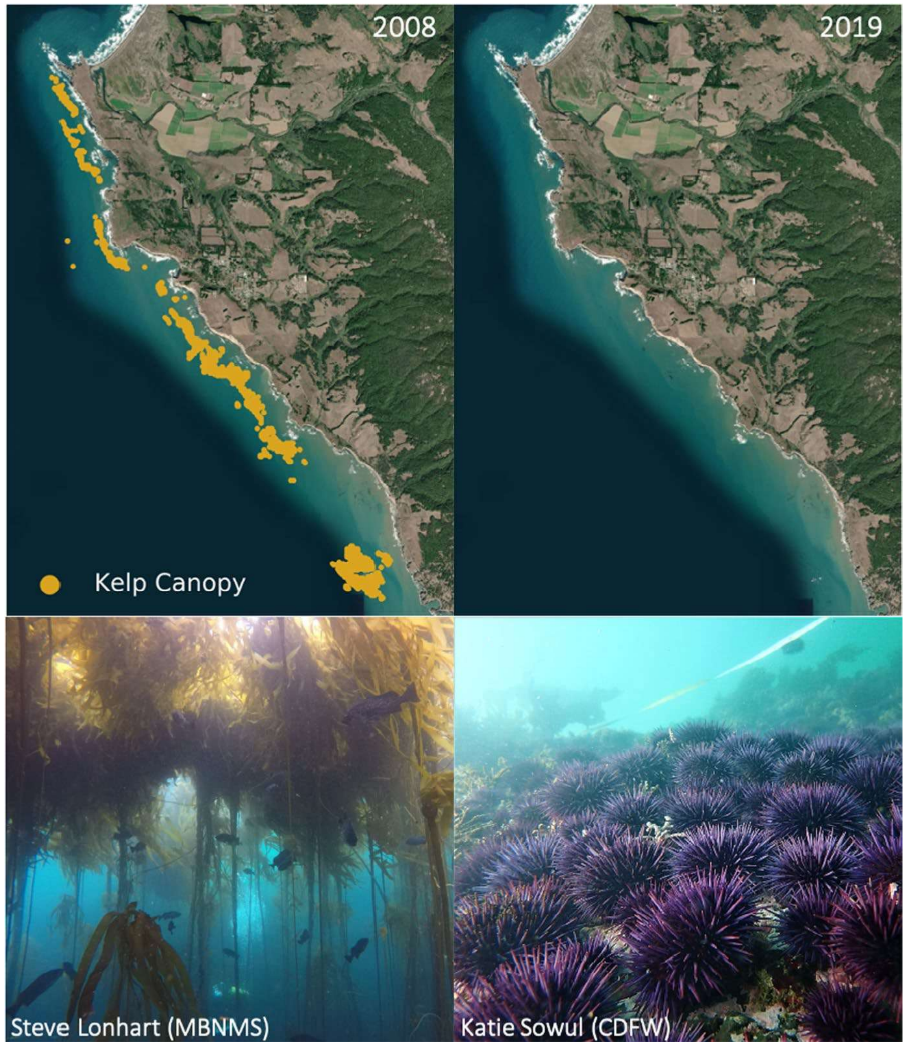

FIGURE 7 Satellite imagery of northern California showing the loss of kelp canopy since 2008 and established urchin barrens

goal only in small areas, whereas *resisting* across the broad scale is not feasible. Clearly, *accepting* is not desirable but it may be that over the short time scale we may not have much choice as action requires resources, which can be slow to mobilise (take more than 3 years) (Allen and Gunderson 2011). In this case, a combination of small-scale *resisting* and *accepting* appears to be the most feasible actions to achieve kelp forest conservation goals.

The urgent need to restore the kelp forest is a top priority for the state (S. Oh, pers. comm. Dir. CA Sea Grant), and one that requires both the best available science and policy work. Marine resource management and policy are guided in California in part by the Marine Life Management Act (MLMA), which mandates that fishery management shall strive to be sustainable (Weber et al. 2018). In this case, however, reducing fishing may not be the primary driver of the decline in kelp forests, and so this may not lead to kelp forest recovery. However, reductions in fisheries will be necessary as productivity of kelp dependent resources has declined dramatically. The second major piece of legislation in California is the Marine Life Protection Act (MLPA) that was enacted to conserve and protect marine biodiversity inside marine protected areas (MPAs). This, too, functions as a mechanism to buffer against overexploitation of marine populations. The MLPA was designed to establish a network of MPAs in California to support marine ecosystems by limiting fishing in no-take and limited-take marine reserves (Kirlin et al. 2013). Both acts were implemented in 1999, yet they provide little guidance for grappling with marine ecosystem transitions due to large-scale impacts such as from climate-driven stressors including ocean warming, hypoxia and ocean acidification. A novel framework is needed to help guide possible solutions to large-scale marine ecosystem disasters.

The concept of *resist* may be complicated in systems that have lost top level carnivores. In northern California, sea otters *Enhydra lutris nereis* were hunted in the fur trade that led to their local extinction about 150 years ago. Recent studies suggest that sea otters may enhance the persistence of patches of kelp forests (i.e. a method of *resisting*), but are not effective in reducing the abundance of urchin barrens as the urchins are likely starving and not developing full gonads, therefore unpalatable (Smith et al. 2021). While there are no efforts to reintroduce sea otters in northern California, natural northern expansion back into their native range could occur (Tinker et al. 2008); however, this would be catastrophic for local shellfish fisheries (Fanshawe et al. 2003; Carswell et al. 2015). Since this species is endangered and protected, this expansion would not be controlled and, using RAD, would be *accepted*. Shellfish populations coexist with sea otters in central California (Rogers-Bennett 2007); however, there is

TABLE 1 Application of the RAD framework to the Bull Kelp forest transition to sea urchin barrens in northern California

Strategy	Climate impact	Desired future condition	Actions
PROMOTE Resist: Promote Bull Kelp Restoration. Manage urchin levels to previous conditions and reintroduce urchin predators and competitors	Effort and resources must be allocated to restore previous environmental conditions	Broad scale restoration of previously robust kelp forest ecosystem	- Large-scale bull kelp restoration actions - Large-scale culling urchins by commercial fishermen and recreational divers - Removing urchins for food, compost and ranching - Stocking bull kelp genotypes that may be more resilient to warm water - Widespread restoration of sunflower sea stars to recover their role as predators - Widespread restoration of abalone as competitors with sea urchins
DO NOT Accept: Allow current conditions to persist	Loss of carbon sinks, continued loss of biodiversity, loss of fisheries and economically valuable species	Allow widespread sea urchin barrens to persist	- Monitoring levels of sea urchin, kelp, and temperature changes - Kelp forest and urchin barren research - Pre-existing management goal e.g. restoration
DO NOT Direct: Introduce an entirely new kelp forest ecosystem that will better adapt to current and future climate change scenarios	Deter the predicted, undesirable effects of climate change while maintaining similar ecosystem services from novel ecosystem	The transformed ecosystem will transition to having species that differ from before	- Introducing novel sea stars as predators of sea urchins - Mass culling of sea urchins - Stocking alternative kelp species to determine the best fit in current climate change scenarios

TABLE 2 Summary of restoration strategies using the RAD framework for six marine case studies

Marine case study	Strategy
Coral bleaching and declines worldwide	Planting local coral naturally resistant to warm water (Resist) Culturing species or genetic families that are more heat-resistant (Resist) Coral-safe sunscreens that do not degrade corals (Resist)
Eelgrass ecosystem management	Restoring hydrology and water quality and removing trash (Resist) Transplanting of new eelgrass shoots (Resist)
Overpopulation of lionfish in the Caribbean	Lionfish fishing derbies (Resist) Seafood marketing for lionfish (Resist) Permits to fish in no-take marine reserves for lionfish (Resist) Implement lionfish fishery and lower population levels in the wild (Accept)
Crown-of-thorns sea stars in Australia	Manual culling of adult COTs through lethal injection (Resist) Biosecurity forecast method (Resist) Collaborating with local recruitment monitoring programmes (Resist) Establishing a predatory giant triton stocking programme (Resist) Research on COTs reproduction (Resist)
Sea star mass mortality	Captive breeding programme for sunflower stars (Resist) Selective breeding of more disease-resistant sunflower stars for stocking (Resist) Establishment of long-term monitoring programme (Resist) Establishing alternative sea star species that are more disease-resistant with similar diets to sunflower stars (Direct)
Kelp deforestation	Large spatial-scale culling of urchins by commercial fishermen and recreational divers (Resist) Stocking juvenile bull kelps (Resist) Establish alternative sea star species, more disease-resistant, with similar diets (Direct) Restoration of sunflower sea stars (predators) and abalone (competitors) (Resist) Stocking kelp of various, foreign species to determine best fit in current climate change scenarios (Direct)

no surplus productivity to support human fishing. Additionally, it is unknown how well sea otters would survive in the north with the lack of kelp, extreme storms and increased predation by great white sharks *Carcharodon carcharias* (Linnaeus) (Tinker et al. 2016).

In response to the collapse of the bull kelp forest and loss of these critical ecosystem services, the Kelp Recovery Working Group drafted the Sonoma-Mendocino Bull Kelp Recovery Plan (Hohman et al. 2019) and the Kelp Forest Protection Interim Action Plan (OPC 2021). The recovery plans have two main goals: (1) enhance kelp recruitment and growth and (2) reduce purple urchin grazing pressures. These plans will help guide policy recommendations in the state and focus funds on projects to support kelp restoration. Furthermore, the recovery plans aim to address knowledge gaps in kelp forest ecosystem dynamics, fund solution-oriented research projects, support kelp restoration and urchin control, and develop policy for kelp forest recovery across the state. In addition to these action plans, Representative Jared Huffman (D-San Rafael) introduced the Keeping Ecosystems Living and Productive (KELP) Act in July 2021 (H.R. 4458). This act allocates resources towards bull kelp restoration along the north coast and provides a new NOAA grant programme that focuses on projects promoting the conservation and recovery of bull kelp forest ecosystems.

3 | DISCUSSION

A review of the marine case studies suggests that the most commonly used method for addressing major ecosystem transitions has been the *resist* strategy (Table 2). In this case, we are considering the possible use of more warm tolerant genotypes to be part of the *resist* strategy. We also observe that the transitions appear to result in very unfavourable conditions for biodiversity and a range of other ecosystem services. For many of these, cases that suggest that the *accept* strategy is not acceptable. Furthermore, the *direct* strategy looks to be very challenging as novel communities made up of different species with perhaps similar ecological functions do not appear to be occurring in the marine case studies examined here. We suggest that the application of the RAD framework will be useful for examining other marine ecosystem transitions to determine whether the patterns revealed for these marine ecosystem examples holds for other marine systems.

3.1 | RAD and adaptive management

The RAD framework is a useful tool for managers to conceptualise responses to radical ecosystem transformations brought on by climate change, and here, we apply it for the first time to marine ecosystems (Figure 8). This range of management responses can be implemented based on monitoring, learning and then adapting the response to the transformed ecosystem (Thompson et al. 2021). Adaptive management involves an iterative approach of first conceptualising management goals, designing an action plan, implementing the strategies, monitoring conditions and then making adjustments to the plan as needed to achieve the desired management goals. The complimentary concept of structured decision-making where a few alternative restoration options are examined closely to weigh the costs and benefits prior to selecting the best alternative will also need to take into account and changing future. Ecosystems are changing so rapidly and dramatically that constant monitoring and assessments will be required to examine historic baselines and implement restoration options. Assuming that the future ecosystem will look like the past may not be a realistic trajectory for many of these transformed ecosystems. Monitoring can give feedback to compliment restoration work. Furthermore, transformed ecosystems may require additional work by managers in the form of experiments, pilot studies and bet hedging to inform decision-making in transformed and unfamiliar ecosystems (Lynch et al. 2022). The RAD framework will require continual monitoring as these processes are not one-time events but ongoing. Long-term monitoring programmes are invaluable for giving scientists a better understanding of how baselines have changed due to anthropogenic impacts to inform the development of marine policies that are flexible and climate-smart (Navarrete et al., 2010). Surveying the most recent conditions in changing ecosystems is critical since climate change can alter ecosystems rapidly in unpredictable ways.

This RAD management strategy is useful in the kelp forest example to help think through options and approaches. This helps us pose questions such as can kelp rebound by itself if the water temperature is cool and there a less sea urchins or do humans need to intervene and stock kelp? Just recently, small patches of kelp have begun (summer 2021) to recover suggesting kelp spore banks robust enough to rebound on their own. Working to remove sea urchins to defend these newly recovering patches of kelp would be one way to implement adaptive management. This could be accomplished by examining fine-scale drone surveys from the north coast to help pinpoint healthy patches of kelp. This could guide sea urchin removal efforts to maximise their effectiveness at promoting kelp restoration. Continued monitoring of sea urchin health will also be critical for tracking possible expansion of sea urchin diseases, which can spread in high-density populations. Monitoring the recruitment of newly settled sea urchins to quantify the abundance of new sea urchin settlers (Okamoto et al. 2020) and new kelp sporophyte settlers are both ways to inform which kelp sites should be prioritised as active restoration sites.

3.2 | Partnerships

Strong partnerships will be required for long-term monitoring programmes. One example is the partnership with the National Parks Service, researchers, docents and citizen scientists that have all worked together to address deforestation from climate impacts (Schuurman et al. 2020; Morton and Magness). We have seen examples of this with eelgrass restoration projects, "lionfish derbies," the sunflower star breeding programme, and the Bull Kelp Recovery Plan. In the Bull Kelp restoration case, organisations such as the Ocean Protection Council, Gulf of the Farallons Assoc. National Oceanic and Atmospheric Admin., Cal. Sea Grant and Cal. Dept. Fish and Wildlife

FIGURE 8 RAD management framework for marine ecosystems

have banded together to establish kelp restoration plans backed by credible, scientific research. The drastic decline in white abalone *Haliotis sorenseni* also demonstrated how partnerships between researchers and policy officials are needed. The White Abalone Recovery Consortium is a partnership composed of government scientists, university researchers, aquaculture organisations and public aquaria, which together encompass the elements needed to implement the recovery plan for this critically endangered marine species (Rogers-Bennett et al. 2016). This programme has been successful at captive spawning, hatchery distribution, health assessments and in 2019 for the first time, stocking juveniles into the wild.

3.3 | Marine spatial planning

Spatial management of marine systems has been primarily to control fishing effort, shipping, oil drilling and other anthropogenic activities. One spatial planning tool is the establishment of marine protected areas (MPAs). There have been renewed calls for the use of MPAs as partial solutions to climate change in marine environments (Keppel et al. 2015; O'Leary et al. 2016; Roberts et al. 2017). Clearly, climate stressors such as marine heatwaves will impact communities inside and outside MPAs (Freedman et al. 2020). One perspective about MPAs is that they will be more naturally resilient (Holling 1973) to climate change, so no actions are needed in these areas. Using this concept, MPAs may help resist changes or are thought to be better able to adapt to the new conditions brought on by climate change. We know, for example, that abalone reproduction inside MPAs, with larger females, did better than fished sites when these areas were exposed to hypoxia in Baja California, Mexico (Micheli et al. 2012).

It will be useful to think through our notions of the benefits of MPAs as they relate to RAD. Continued monitoring inside and outside MPAs will help inform management goals and what is possible as climate change impacts marine systems. For example, will we work to restore degraded habitats inside MPAs (Abelson et al. 2016)? Will we want to stock captive-reared animals (conduct enhancement) to historic levels inside MPAs? Will we exclude all conservation measures from MPAs? In Florida, managers have decided to allow fishing of invasive lionfishes inside MPAs (P. Gross pers. comm. Force Blue). In northern California, will managers allow purple sea urchin culling inside no-take MPAs? Will managers allow the stocking of kelp in MPAs? What happens in cases where there is no more resilience left in the system? For example, whether there has been local extinction and there are no more propagules or larvae. Would we know when this endpoint occurs? Would this be a time for humans to intervene inside MPAs? Another perspective is that either restoration actions within sea urchin barrens will be fruitless or provide for much-needed starting points for recovery. There is theoretical evidence for both these conclusions such that restoration actions in large homogenous landscapes could either fail or lead to a transition back to a desired state (van de Leemput et al. 2015). There are many questions that managers of MPAs and other parks or natural spaces will need to think about in terms of the RAD lexicon. Are we seeking to restore to pre-impact state and is this even possible now? Has the system changed so much that stocked organisms may no longer survive in the new ecosystem? Thinking through our goals using the RAD framework language can help clarify our restoration goals and recommendations.

3.4 | Climate-ready restoration

Climate-ready actions may be a combination of human restoration actions and natural recovery. Recovery of many marine systems may lie not in their ability to recover but in their ability to resist degradation (Darling and Cote 2018). An example of resistance in natural systems may come from resistant species or family lines such as "super corals" that resist bleaching (McClanahan 2017; Van Oppen et al. 2017). Another avenue for resistance would be areas in the ocean that are naturally more resistant such as cooler areas due to water circulation patterns called "climate refugia" (Wilson et al. 2020). Marine areas that stay cooler than surrounding habitats may act as climate refugia sites for habitat-forming seaweeds as has been observed in the Mediterranean Sea (Verdura et al. 2021). Measuring the velocity of change may also aid in marine spatial planning for climate refugia (Arafeh-Dalmau et al. 2021). In a review of experts from multiple marine ecosystems, O'Leary et al. (2017) were able to identify "bright spots" that were able to resist degradation. They attributed these "bright spots" to a suite of factors including remaining biogenic habitat (such as kelps), enhanced recruitment, species movement, physical dynamics and local management. Modelling areas that are "bright spots" where species may expand under climate stress and then protecting them may help *resist* change and aid marine spatial planning (Queirós et al. 2021, see also Feiner et al. concurrent submission). Determining species such as abalones that may be particularly susceptible to range reductions due to climate change and providing climate-smart restoration for these species (Rogers-Bennett 2007) can help support climate resilience. Furthermore, we know that future marine ecosystems will continue to be impacted as climate change worsens, so we will need to promote resilience of not only biological ecosystems but also the people whose livelihoods depend on the oceans (Darling and Cote 2018; Queirós et al. 2021).

4 | ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to the first author.

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CONFLICT OF INTERESTS

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

The three authors wrote the first draft of the paper and the final drafts. All authors agree to submission.

ETHICAL APPROVAL

This publication does not involve human subjects or confidential data N/A.

DATA AVAILABILITY STATEMENT

Please contact the first author with data requests.

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