Received: 22 August 2016 | Revised: 26 February 2017 | Accepted: 27 February 2017
DOI: 10.1111/gcb.13698

RESEARCH REVIEW

WILEY Global Change Biology

Avoiding a crisis of motivation for ocean management under global environmental change

Peter J. Mumby[1] | James N. Sanchirico[2] | Kenneth Broad[3] | Michael W. Beck[4] | Peter Tyedmers[5] | Megan Morikawa[6] | Thomas A. Okey[7] | Larry B. Crowder[8] | Elizabeth A. Fulton[9] | Denny Kelso[10] | Joanie A. Kleypas[11] | Stephan B. Munch[12] | Polita Glynn[13] | Kathryn Matthews[14] | Jane Lubchenco[15]

[1]Marine Spatial Ecology Lab & ARC Centre of Excellence for Coral Reef Studies, School of Biological Sciences, University of Queensland, St Lucia, Qld, Australia

[2]Environmental Science and Policy, University of California, Davis, CA, USA

[3]Abess Center for Ecosystem Science and Policy, University of Miami, Miami, FL, USA

[4]The Nature Conservancy & Department of Ocean Sciences, University of California, Santa Cruz, CA, USA

[5]School for Resource and Environmental Studies, Dalhousie University, Halifax, NS, Canada

[6]Department of Biological Sciences, Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA

[7]School of Environmental Studies, University of Victoria, Victoria, BC, Canada

[8]Center for Ocean Solutions & Hopkins Marine Station, Stanford University, Monterey, CA, USA

[9]CSIRO Oceans & Atmosphere, Hobart, Tasmania and Centre for Marine Socioecology, University of Tasmania, Battery Point, Tas, Australia

[10]Gordon and Betty Moore Foundation, Palo Alto, CA, USA

[11]National Center for Atmospheric Research, Boulder, CO, USA

[12]NOAA Southwest Fisheries Science Center, Santa Cruz, CA, USA

[13]The Pew Charitable Trusts, Washington, DC, USA

[14]Oceana, Washington, DC, USA

[15]Department of Integrative Biology, Oregon State University, Corvallis, OR, USA

Correspondence
Peter J. Mumby, Marine Spatial Ecology Lab & ARC Centre of Excellence for Coral Reef Studies, School of Biological Sciences, University of Queensland, St Lucia, Qld, Australia.
Email: p.j.mumby@uq.edu.au

Funding information
Pew Fellows Program in Marine Conservation; Herbert W. Hoover Foundation

Abstract

Climate change and ocean acidification are altering marine ecosystems and, from a human perspective, creating both winners and losers. Human responses to these changes are complex, but may result in reduced government investments in regulation, resource management, monitoring and enforcement. Moreover, a lack of peoples' experience of climate change may drive some towards attributing the symptoms of climate change to more familiar causes such as management failure. Taken together, we anticipate that management could become weaker and less effective as climate change continues. Using diverse case studies, including the decline of coral reefs, coastal defences from flooding, shifting fish stocks and the emergence of new shipping opportunities in the Arctic, we argue that human interests are better served by increased investments in resource management. But greater government investment in management does not simply mean more of "business-as-usual." Management needs to become more flexible, better at anticipating and responding to surprise, and able to facilitate change where it is desirable. A range of technological, economic, communication and governance solutions exists to help transform management. While not all have been tested, judicious application of the most appropriate solutions should help humanity adapt to novel circumstances and seek opportunity where possible.

KEYWORDS
Arctic, climate change, coral reefs, fisheries, resilience, tipping point

1 | INTRODUCTION

Global environmental changes combined with local and regional stressors are rapidly altering life in the ocean and the nature of the world's coastlines. Rising ocean temperatures are affecting the distribution and productivity of fisheries (Cheung et al., 2010; Simpson et al., 2011). Climate change and ocean acidification (hereafter simply "climate change") are impacting shellfish aquaculture (Bell et al., 2013; Pinsky & Mantua, 2014). Deoxygenation has led to acute "dead zones" and steady reductions of habitable area for commercial fish species (Booth et al., 2014; Chan et al., 2008; Dybas, 2005). Increases in flooding, erosion, inundation and saltwater intrusion are affecting coastal habitats and hundreds of millions of vulnerable people, important infrastructure and tourism, with significant losses to national economies and increased human suffering (UNISDR, 2011). However, some of the impacts of climate change create new opportunities and thereby generate benefits at least in the short term. For example, reduced Arctic sea ice presents new opportunities for shipping (US Coast Guard, 2013) and the poleward migration of various fishery stocks, such as pelagic shelf fishes (Cheung, Okey, Brodeur, & Pauly, 2015) and Humboldt squid (Field, 2008; Stewart et al., 2014) along the west coast of North America will allow some jurisdictions to increase their access to stocks, or lead to the emergence of entirely new fisheries.

The diversity of outcomes brought about by climate change has stimulated a sizeable literature on the implications for resource management, ecosystems and ecosystem services (Hoegh-Guldberg & Bruno, 2010; Levin & Lubchenco, 2008; Rogers et al., 2015). Most articles are orientated around either a particular impact, such as ocean acidification (e.g. Rau, Mcleod, & Hoegh-Guldberg, 2012), or sector, such as fisheries (Punt et al., 2014; Weatherdon, Magnan, Rogers, Sumaila, & Cheung, 2016), yet all make useful recommendations on how management might need to respond. In virtually every case, there is an implicit or explicit acceptance that resource management has a key role in helping humanity meet the challenges set forth by climate impacts on the oceans. Here, we begin by asking a fundamental question over the fate of resource management in general. Using diverse case studies, we argue that climate change could result in reduced government investments in resource agency budgets, monitoring and enforcement activities regardless of whether the perceived impacts of climate change are positive or negative. We then explore the likely consequences of a reduction in management investment and suggest that humans and environment are better served by smarter, more flexible, proactive investments that lead to adaptive approaches. Climate change presents some specific challenges for marine resource management, and we draw on our varied disciplinary backgrounds to identify a range of appropriate mechanisms and policies. We argue that solutions to climate change impacts can be drawn from disparate disciplines, but they must be used judiciously in order to be effective.

2 | CLIMATE CHANGE AND DRIVERS FOR AND AGAINST MANAGEMENT INVESTMENT

We selected five case studies that provide a range of perceived human impacts of climate change on marine ecosystems (Figure 1). In each case, we describe the drivers that might promote further investments or disinvestments in resource management and consider the possible consequences of each.

2.1 | Presiding over ecosystems in decline: coral reefs

Coral reefs are one of the ecosystems most susceptible to climate change, largely because corals are highly sensitive to fluctuations in temperature, and because ocean acidification interferes with the process of calcification that underpins reef formation (Hoegh-Guldberg et al., 2007; Kleypas & Yates, 2009). Science clearly shows that management interventions can improve reef ecosystems (McCook et al., 2010) and that significant investments in local management are needed to maintain reef functioning under climate change (Anthony, 2016; Kennedy et al., 2013). Yet, the trajectory of reef health has been one of decline in many parts of the world, even in relatively intensively managed systems like the Great Barrier Reef (De'ath, Fabricius, Sweatman, & Puotinen, 2012).

Given that management usually aims to maintain or restore healthy ecosystems, trajectories of decline are typically viewed as failures (Great Barrier Reef Marine Park Authority, 2014) even if causes were outside control of management. With price tags in excess of US$6.2 billion thought to be associated with restoration of the Great Barrier Reef water quality alone (Alluvium, 2016), the perceptions around management failure despite active management have the potential to cause a crisis of motivation for management,

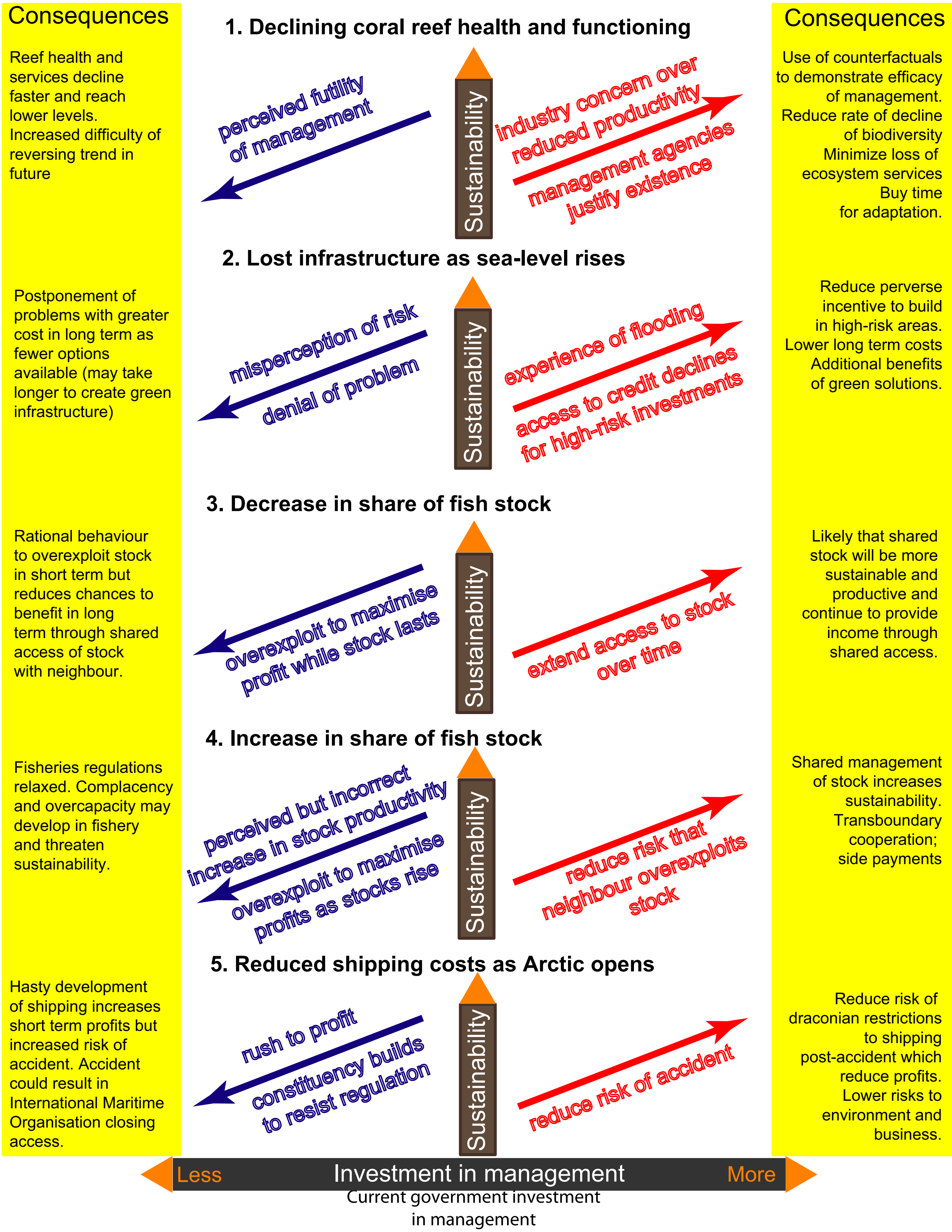

FIGURE 1 The effect of climate change on the willingness to manage marine ecosystems. Five scenarios are given spanning impacts that are usually perceived to range from beneficial to deleterious for society. In each case, the positive and negative drivers for management investment are identified and their consequences highlighted. [Colour figure can be viewed at wileyonlinelibrary.com]

making it difficult to justify continued – let alone increased – management investments from government. This problem is compounded if the public perception of coral reefs is also one of inevitable decline, which can be fuelled by pessimistic media coverage of climate change impacts and bleak projections. For example, some in the Caribbean island of Curaçao called for a reduction in funding for reef protection in response to media coverage of the impact of climate change on coral reefs. The true benefits of management, however, need to be evaluated against alternatives (counterfactuals), which include reductions in management (Fulton et al., 2015; Mumby & Anthony, 2015). For example, if a country wished to minimize the loss of biodiversity in order to meet the UN Aichi Targets, then proactive investments in well-regulated fisheries and improved water quality (Kennedy et al., 2013) might constitute a net benefit over a scenario of reduced management which would likely accelerate coral decline and increase the risk of failing to meet conservation objectives. Counterfactuals are useful in parameterizing adaptation pathways, which help identify time series of interventions for achieving desirable outcomes that consider both the historical inertia of the system's trajectory and how future global changes will shape system dynamics (Wise et al., 2014).

2.2 | Coastal protection and living in vulnerable areas

People have long been attracted to coastal zones because of the rich resources, access to trade, recreational opportunities and sense of place (Neumann, Vafeidis, Zimmerman, & Nicholls, 2015). Yet, the protective functions of the world's coastal habitats are degrading rapidly from development and climate change. Rising sea level compounds these risks yet development continues to push in to some of the most low-lying, exposed and high-risk areas often on top of or further degrading habitats that could provide a first line of defence (Gittman et al., 2015). Indeed, rates of human migration and population increase tend to be highest in climate change "hotspots" (Hugo, 2011), which exacerbates the societal impact of weakening coastal defences.

Despite increasing risk to coastal infrastructure from sea-level rise, rates of human population rise are highest in coastal areas (Neumann et al., 2015). A significant problem is that we do not assess risk well and we heavily discount the cost and price of this risk (NRC, 2014, UNISDR, 2015). One underlying issue is that humans tend to learn from experience and responses to future, anticipated threats tend to be weak if we are unable to draw on personal experiences, particularly when the risk does not evoke strong "dread" emotions (e.g. as nuclear accidents do) (Slovic, 1987). When faced with a decision that involves risk and uncertainty, people often rely on their rapid, instinctual responses. These are generated at a subconscious level and are swayed by emotional history packed with cognitive biases, ideological preferences and cultural specificity (Kahneman, 2011). Our individual decision making systems are not optimized for the often incremental, creeping, consequences of climate change, although we note that some communities are experiencing the direct effects of sea-level rise. Moreover, the communication of risk and uncertainty to policy makers and the public has had limited success, although the IPCC reports have made strong strides towards improving this (Budescu, Por, & Broomell, 2012).

Given our cognitive weakness with slow climatic processes, the severe economic consequences of losing coastal infrastructure, and the perverse incentives created by tax payers under-writing risk and reimbursing losses (e.g. the US Federal Emergency Management Agency, Lehrer, 2007), it is perhaps not surprising that common reactions to sea level rise are to do nothing. Psychological drivers of such behaviour include a lack of direct experience of flooding (Harvatt, Petts, & Chilvers, 2011), paralysis towards a wicked problem that affects our economic foundations (Albrecht, 2011) and psychological denial where problems are recognized but either generate too much fear (Reser, Morrissey, & Ellul, 2011) or create a cognitive dissonance because an awareness of responsibility for climate change and an inability to solve the problem constitute conflicting cognitions (Norgaard, 2012). Moreover, the preponderance of poverty in areas severely affected by climate change (Hugo, 2011), means that many people lack the opportunity to move away from coastal hazards. Collectively, a lack of action constitutes another driver of management decline when set against an increasing risk (Figure 1). When climate change is acknowledged, the long-term, uncertainty and global scale of required responses can be used by decision makers to avoid or delay actions (Barrett & Dannenberg, 2012). A good example is green infrastructure, such as the re-establishment of mangroves as a form of natural coastal defence, because such forests take years to establish (Ronnback, Crona, & Ingwall, 2007).

Green forms of coastal defence could not only help mitigate hazards, but could also provide conservation and resource management benefits tied to other ecosystem services (e.g. mangroves as fish nurseries). Thus, rather than investing purely in "grey infrastructure" such as seawalls, which further degrade coastal ecosystems (e.g. by enhancing erosion), environmental benefits can accrue from including coastal ecosystems as part of the solution for reducing risks. Increasing scientific and experiential (business) evidence shows that coastal habitats can be effective and cost-effective for reducing risks from coastal hazards (CCRIF, 2010, Cheong et al., 2013; Temmerman et al., 2013; Van Den Hoek, Brugnach, & Hoekstra, 2012). A greater appreciation of the risk-reduction benefits from such restored and healthy habitats should help motivate the investments needed to maintain and restore these ecosystems and the services they provide. There is also potential for these approaches to contribute directly to emerging and entrepreneurial green and blue economy opportunities such as carbon offset schemes. Integrating green engineering solutions will require clear demonstration projects, full assessment of the risks including climate change impacts on the ecosystem and the development of standard practices for coastal engineers.

2.3 | Loss of access to fish stocks as they move

Climate change will affect the catch potential of commercial fish species globally (Barange et al., 2014; Cheung et al., 2010), and poleward shifts in the distributions of pelagic fishes is occurring at a rapid pace (Cheung et al., 2015; Simpson et al., 2011). This is particularly troubling because poleward shifts away from tropical coastal areas are occurring (Barange et al., 2014), which are severely impacted by climate change (Wolff et al., 2015), will affect some of the poorest, most resource-dependent nations (Wheeler & Braun, 2013). Latitudinal gradients in fish age at maturation, natural mortality, growth rate and longevity are widespread and tend to be correlated with broad scale patterns in temperature. These observations suggest that predictable shifts in life history parameters such as earlier maturation or smaller adult size will continue to occur over the next several decades as the oceans continue to warm (Harborne & Mumby, 2011). Yet most conventional fisheries management approaches do not yet account for the influence of environmental drivers that can alter stock location and resilience, although exceptions exist (Hobday, Hartog, Spillman, & Alves, 2011; Pinsky & Mantua, 2014).

First, we consider the response of a country that knowingly begins to lose access to a fish stock (Figure 1). A potential noncooperative action on the part of the "loser" is to exploit the stock intensively while access remains to reduce any losses associated with the range shift. In many respects, a country faced with losing access to a resource stock is analogous to a firm extracting an exhaustible resource where the economically optimal solution is to use up the entire stock (e.g. Dasgupta & Heal, 1979). Whether exhaustion is optimal will depend on the rate at which the species range shifts relative to the costs of catching the fish as the stock size approaches low levels. Similar motivations are also occurring within tourism, with a significant proportion of visitors to iconic but vulnerable features – such as glaciers, Antarctic and the Great Barrier Reef – stating that they are motivated by a desire to experience it before it is lost (Piggot-Mckellar & Mcnamara, 2016).

With respect to fish stocks, a more sustainable and perhaps greater financial benefit might accrue from developing a new transboundary management arrangement with the "winner" country that is gaining greater access to the stock. A variety of mechanisms already exist for managing shared stocks including the making of compensatory side payments to the party set to lose access in return for them not overexploiting the stock. For example, for many years, Japan paid the former Soviet Union for the privilege to fish Pacific salmon in its waters (Dereynier, 1998). Similarly, fishers in the Faeroe Islands have been compensated by neighbouring jurisdictions for not fishing their quota of Atlantic salmon (Olaussen, 2007). However, while some successful side payment schemes exist, several mechanisms can preclude their uptake. A well-studied example is the incentives that drive Norwegian river owners to make side payments to commercial fishers in return for them not exploiting salmon in their marine phase prior to entering rivers where license fees from recreational fishers generate high levels of revenue (Olaussen, 2007). As it is impossible to predict which salmon in the marine phase will enter any given river, the practice of making a side payment to marine fishers might effectively subsidise access to fish for neighbouring river owners. A given river owner might achieve higher profits by not entering into an agreement and "free riding" on the payments made by others. Thus, while some Norwegian side payment schemes exist for salmon, such schemes need to be considered critically prior to adoption.

2.4 | Gains in the share of fish stocks

For every jurisdiction that loses access to a fish stock, another jurisdiction likely gains access. This is creating tension over appropriate management responses, whether to intensively exploit a new species to prevent its establishment and potential disturbance of the existing local ecosystem, or whether a more measured approach should be used to allow for the stock's secure establishment (Madin et al., 2012). Moreover, without sufficient understanding of the causes of the apparent "bounty," managers might assume – incorrectly – that the fishery is becoming more productive rather than simply migrating. Here, the risk is that a relaxation of regulations to boost harvest might actually increase the risk of overfishing. Better management would identify the cause of the fishery change and cooperate with partners to manage the stock sustainably as might happen with Iceland's access to mackerel fisheries that were historically exploited only by Russia, Norway, the Faroes and EU (Hannesson, 2013). Indeed, game theory predicts that international cooperation in treating the stock as a shared resource will likely result in a more sustainable outcome than each player maximizing their short-term profits without cooperation. In practice, we see that even quasi-cooperation can avoid total destruction expected by game theory as was seen in the Northeast Atlantic mackerel fishery (Hannesson, 2014). Geographic shifts in fish stocks can be monitored in near-real time by creating habitat models that utilize genetic sampling of stock identity, oceanographic remote sensing and satellite tracking of individual fish (Hobday et al., 2014). Cooperation has also been successful at promoting a sustainable outcome in dynamic ocean management. For example, numerous fisheries avoid closure through cooperative reporting of by-catch and dynamic mapping of suitable fishing grounds (Hazen et al., 2013). Similarly, commercial boats avoid ship strikes through voluntary closures or speed restrictions (Maxwell et al., 2015).

2.5 | Reduced shipping costs as the Arctic opens

As Arctic seasonal ice shrinks and open-water periods become longer, ships are beginning to transit the Arctic Ocean – an alternative that reduces the distance from Europe to Asia or to North America's Pacific coast via the Panama canal, by 25 percent or more (US Coast Guard, 2013). In 2009, successful use of the Northern Sea Route, the passage closest to Russia's northern coast, by commercial vessels produced an initial surge of shipping interest. The number of vessels transiting the Bering Strait doubled in 4 years, reaching 440 voyages in 2013 (Huntington et al., 2015).

The novelty of managing a new transoceanic route and the constituency created with the rush for profits by transnational shipping corporations could lead to delays in developing appropriate management and regulations such as the types of cargos and number of ships able to transit (Figure 1). However, an increase in traffic also carries elevated risk of environmental impacts. By 2020, Russia estimates a 50-fold increase from 2013 in the tons of cargo, primarily in the form of hydrocarbons, that will transit the strait, dramatically elevating the risk of oil spills (Haecker, 2013). Indeed, the high-latitude environment is especially hazardous for ships because of seasonal and drifting sea ice, harsh weather conditions, limited communications systems, lack of good charts and navigation aids, extreme cold that may hamper effectiveness of equipment and operating systems, and long distances from ports with capacity to provide assistance or accident response (US Coast Guard, 2013). Were an accident to occur, government could respond in an undesirable and draconian way, suspending all traffic until better regulations are in place, particularly if the accident could have been prevented by tighter regulations at the outset. Thus, industry might be better served by investing early in regulation, as this may increase long-term sustainability by reducing the likelihood of even harsher regulation were accidents to occur. At present, the International Maritime Organisation has adopted a Polar Code to address these regulatory issues (IMO, 2014) although it is not expected to become operational until 2017. Options include shipping lanes, areas to be avoided, communication measures and emergency response planning (Huntington et al., 2015).

3 | MANAGEMENT CHALLENGES UNDER CLIMATE CHANGE

While climate change can be thought of as “just another stressor” in the environment, it differs from many existing problems in that its onset is often slow and moderately predictable, albeit often impacting through high variability and extreme events or “flickering” from one state to another (Scheffer et al., 2009). In theory, this provides time for society to prepare. However, the often inadequate societal responses to other “predictable” stressors, even those that unfold rapidly such as ENSO events (Schreiber, Niquen, & Bouchon, 2011) suggest that there is much room for improvement. We have already argued that society will be better served by continued management investment. Here, we consider some of the key challenges in managing the impacts of climate change.

3.1 | Coping with surprise

Many aspects of climate change are unprecedented in human history and therefore generate surprise (Streets & Glantz, 2000). Surprises can be subjective because what might surprise a lay person might not surprise an expert. A climate surprise can be defined as the gap between one’s expectations about the likely climate and the actual climate (Bazerman, 2006; Streets & Glantz, 2000). Sometimes a surprise event can have both negative and positive impacts like (i) the enhanced upwelling in 2002 on the west coast of the USA which caused severe hypoxia resulting in crab and fish deaths off the coasts of Oregon and Washington but exceptionally high fisheries productivity further south in Monterey Bay, California (Chan et al., 2008; Grantham et al., 2004) or (ii) in larger scale shifts in distribution of abundance from climate regime shifts (Bakun & Broad, 2003). The problem presented by surprise is one of unpreparedness either to capitalize on beneficial events or mitigate/adapt to detrimental events.

An important means of reducing the risk of surprise is to ensure close and transparent communication between scientists and decision makers. Barriers to knowledge exchange persist as an issue, yet research on decision making is further supporting solutions such as knowledge co-production or the creation of boundary organizations to help broker information (Bednarek, Shouse, Hudson, & Goldberg, 2015; Cvitanovic et al., 2015; Fazey et al., 2013). In practice, some management agencies have taken an innovative approach to this by providing fellowships for academic scientists to work within government (AAAS Science and Technology Policy Fellows). Moreover, government scientists should be free to communicate their views even if politically unpopular and some agencies have introduced measures to support this (NOAA, 2011). Indeed, any practice that widens participation in decision making processes is also desirable in that a greater range of ideas are likely to be considered (Stirling, 2006; Wise et al., 2014). Decision making also needs to remain open to more extreme scenarios vs. a strict reliance on average outcomes as patterns shift (Kates & Clark, 1996). Effective communication management has been demonstrated to increase resilience when coping with surprise, with direct correlations between an organization’s internal coordination of crisis communication and the effectiveness of its leadership in crises ranging from natural disasters to disease outbreaks (Longstaff & Yang, 2008).

Much can be carried out to prepare for surprise including building precautionary buffers into management that cover a broad range of outcomes. Limitations in models can cause specific projections of the effect of climate change on certain stocks to fail, suggesting that management that accounts for broad forecasts in outcomes may be a preferred strategy (Punt et al., 2014). Actions such as setting fisheries harvest under maximum sustainable yield, and increasing the area of critical habitat under protection are examples of management that account for the uncertainty introduced (Hobday, Bell, Cook, Gasalla, & Weng, 2015; King, Mcfarlane, & Punt, 2015). Importantly, lessons from previous stock collapses justify shifting the burden of proof away from the conservation perspective to proving that more generous quotas are robust and warranted (Charles, 2002). A good example is the policy developed for Arctic fisheries by the U.S. North Pacific Fishery Management Council (NPFMC, 2009) – and approved by NOAA – such that new opportunities can only proceed once they have been demonstrated to be sustainable: an unprecedented level of precautionary management planning.

Shifting the burden of proof can also be useful in preparing for some forms of “ecological surprise” (Paine, Tegner, & Johnson, 1998). Many ecosystems exhibit alternative attractors and hysteresis, which can lock systems into what society considers to be unfavourable states and provide expensive obstacles for restoration (Suding, Gross, & Houseman, 2004). The existence of hysteresis is often controversial (Mumby, Steneck, & Hastings, 2013), yet the conventional burden of proof is usually to demonstrate the existence of hysteresis rather than its absence (Scheffer & Carpenter, 2003). This is an intrinsically risky strategy and the precautionary principle of management is better served by assuming the existence of hysteresis if it is suspected (Miller et al., 2010; Steele, 2004). Meanwhile, improvements in system monitoring and modelling can help provide early warning signs of impending regime change (Scheffer et al., 2012) and estimate the efficacy of management interventions to prevent the ecosystem crossing critical thresholds (Mumby, Wolff, Bozec, Chollett, & Halloran, 2014).

An important means of reducing the likelihood of ecological surprise is to understand the circumstances that lead to “unexpected” outcomes. While the study of “model ecosystems” that exhibit multiple attractors, including lakes, kelp forests and coral reefs, undoubtedly aids the creation of theory, much more could be made of empirical data in identifying previously unrecognized mechanisms that generate surprise. For example, recent analyses of large empirical datasets have plotted state variable against one another in an effort to seek break points that might be associated with threshold dynamics (Mcclanahan et al., 2011). These analyses are useful but provide an untapped opportunity to focus on outliers as sites of interest rather than statistical “noise” around a trend. The approach we articulate is conceptually similar to bright spot analysis (Cinner et al., 2016) but less concerned with statistical modelling per se and more precisely focused on identifying ecosystem states that defy current ecological model predictions. Do these sites experience apparently novel sets of physical or ecological interactions that generate outcomes that we cannot presently account for?

Appropriate monitoring can trigger action once an event appears to be underway, or imminent. Innovations in epidemiology, citizen science or crowd-sourced observation and surveillance could also be applied to monitoring of change in marine ecosystems. These can include surveillance of trending browser search terms, reported observations by fishers of new species, such as through Redmap (Redmap), where users can self-report sightings of marine species uncommon to Australia, and other crowd-sourced environmental observations and surveillance such as the LEO network (Leonetwork), where users self-report anomalous wildlife sightings or weather events. These crowd-source resources can directly help validate research relevant to management. For example, Redmap has been used to assist in assessing range expansions of marine species (Robinson et al., 2015)).

While we argue that greater investments in management might often be required, this does not necessarily mean further regulation. In most cases, management needs to be sufficiently flexible that it can respond to an event without incurring the delay of acquiring a new legislative authorization. The Peruvian government has faced this problem when ENSO events cause unpredictable levels of disruption to the anchoveta (*Engaulis ringens*) fishery. There, the fishery is not encumbered by complex legislation and managers can close the harvest of anchovy from a port within 2 days of the proportion of juveniles being landed exceeding 10% of the total catch (Schreiber et al., 2011). In contrast, Stoll, Beitl, and Wilson (2016) describe how decades of well-intentioned adaptive measures in the regulation of Maine fisheries have likely reduced the resilience of the wider fishery. Over time, the licensing of fishery access became ever more fragmented and specialized resulting in a plethora of licences and reduction in the variety of species an individual fisher can access, particularly given the difficulty of acquiring new licenses. This process might enhance regulation of specific fisheries in the short term, but might strangle the resilience of fisher livelihoods for several reasons. First, with a narrow portfolio of options, fishers are increasingly vulnerable to declines in the species they target (Steneck et al., 2011). Second, should profitably decline in the permitted fishery, it is increasingly likely that fishers will exhibit noncompliance and generate a culture of “avoidance entrepreneurs” (Porter, 1990) that undermines the wider fishery. Third, a lack of familiarity with different fisheries, brought about by path dependence, reduces the ability of fishers to adapt to new fisheries even if access is eventually granted. In short, while adaptation is rightly a central tenet of good governance (Gunderson & Holling, 2002; Walker & Salt, 2012), incremental fixes and adaptations can have unintended consequences on the system as a whole.

Much could be learned from agencies that deal with disaster management even when events are difficult to predict. For example, agencies like the Red Cross and the U.S. Federal Emergency Management Agency (FEMA) prepare for surprise through extensive planning, training and network building prior to an emergency. This process involves understanding human behaviour under stress (Perry & Lindell, 2003), utilizing emerging technology to better identify and protect vulnerable areas (Morrow, 2002; Perry & Lindell, 2003), and ensuring relevant parties are connected and able to react constructively to emergencies and surprises (Drabek, 1985). One of the major successes in disaster risk reduction is that fewer lives are now lost in natural disasters, in particular through the development of better early warning systems both in hazard detection and in stakeholder communication (GAR, 2011) coupled with ready-to-be-deployed action plans that have been practiced, with dedicated sources of disaster response funding to be tapped when needed.

The very concept of “surprise” is intrinsic to insurable risk. In the academic and NGO community, climate change has long been viewed as a “predictable surprise.” In the last few years, the predictable component of climate change impacts has been emphasized in some high profile court cases (McCoppin, 2014) and other more subtle institutional moves (Nelson, 2014), often related to what the reinsurance companies call emerging risks (and on which they capitalize). For example, sea level rise affects flood vulnerability and a central tenet of many municipal insurance policies is that the insurance is intended to cover unforeseeable events. Thus, large insurance companies are challenging municipalities regarding pay out for discrete flood events, arguing that these municipalities have ignored longstanding predictions of such events. In other words, climate change impacts will become increasingly difficult to insure against or there will be increased litigation over who is responsible for the cost of the damage. Indeed, some areas, such as flood prone regions of southeast Queensland, are now uninsurable (Bell, 2014). Further, some private insurers in Florida withdrew housing insurance for hurricane damage when the regulator disallowed risk-based rises in premiums in areas of high risk (Kunreuther, 2015).

3.2 | Facilitating change

Much of the dialog over climate change adaptation constitutes strategies to resist change. For example, reducing local stressors to enhance resilience of an ecosystem is primarily intended to alleviate total stress on the system being driven, in part, by climate change. There have, however, been a number of initiatives to facilitate change where it is desirable and faces natural barriers. A good example is “assisted colonisation” (also known as “managed relocation”) to overcome dispersal barriers as species’ ranges shift (Hoegh-Guldberg et al., 2008). Assisted migration can have benefits; for example, with the fishery of the southern rock lobster in Australia, assisted migration of approximately 10,000 climate-resilient lobsters produced a population with faster growth and higher fecundity (Green, Gardner, Linnane, & Hawthorne, 2010). However, the practice of assisted migration does not come without costs as possible stress from translocation caused a yearlong delay in fecundity for translocated populations (Green et al., 2010). Yet strategies and theory to operationalize assisted migration are in their infancy in the ocean even though they have considerable merit given the highly connected nature of marine ecosystems linked by larval dispersal (Kling, Sanchirico, & Wilen, 2016). Practical interventions might include targeting of management to maintain – or possibly create – critical stepping stones (habitat patches) to facilitate gene flow, or even translocations of native species, to more benign environments.

Although the process of assisted migration has its risks, there has been little consideration of more extreme measures such as re-engineering or rehabilitating marine ecosystems with similar, but non-native, species. In terrestrial ecosystems, the introduction of non-native megafauna has been argued for in order to prevent species’ extinctions in their native range and help rebuild the functioning of depauperate ecosystems where hunting has driven similar species to extinction (Donlan et al., 2005). Indeed, various forms of ecosystem rehabilitation are practiced on land and in freshwater environments. For example, managers have stocked lakes with non-native salmon to replace the predatory role lost by the overharvesting of native trout (Dettmers, Goddard, & Smith, 2012). They have introduced non-native tortoises to replace the functioning of extinct species in controlling invasive weeds (Griffiths, Hansen, Jones, Zuel, & Harris, 2011). In oyster restoration, where reef loss has been 85% globally (Beck et al., 2011), rehabilitation with non-native oyster has been practiced. This process is not without risks, for example, the possibility of non-native invasives hitchhiking on introduced hosts; however, there are cases where the ecosystem services may outweigh the costs and the benefit of non-native rehabilitation is often context dependent (Ruesink et al., 2005).

While we do not advocate such interventions in marine ecosystems, it might become increasingly important to consider such options if climate change exerts sufficiently profound impacts on ecosystem functioning. For example, the impacts of thermal and biogeochemical stress on an already depauperate coral fauna in the Caribbean might eventually lead to an almost obsolete set of coral-based functions such as providing habitat to support high biodiversity and fisheries, attracting tourism and providing a natural barrier to waves (Rogers et al., 2015). It is possible that introduction of hardy, fast-growing coral species from the Indian or Pacific Oceans might facilitate a net increase in native biodiversity by helping to re-engineer complex habitats. Such strategies are not usually countenanced because of the high risk of disrupting native food webs and biodiversity. Moreover, because decisions to introduce non-native species are usually taken at subnational (e.g. individual lakes) or national scales, there would be massive international opposition to introductions to marine ecosystems because their high connectivity would allow non-natives to spread and impact neighbouring jurisdictions where they were not permitted. Yet climate change is the only stressor that might feasibly compromise ecosystem functioning at a biogeographic scale, thereby raising the question of region-wide actions. To be clear, we do not advocate the introduction of alien species, but future societies will likely face a constrained menu of ecosystem services and have to consider an even wider range of management options (Rau et al., 2012).

3.3 | Judicious use of management tools

A range of tools exist to address the challenges presented by climate change with examples drawn from the fields of technology, governance, economics and decision sciences (Table 1). To address shifting fish stocks, for example, one might include remote sensing of pelagic fish habitat with dynamic ocean management (technological; Maxwell et al., 2015), early initiation of legislation when resistance is low (governance), and international fishing quotas (economic). Logically, the implementation of multiple solutions should improve management outcomes, but this is not as straightforward as it might appear. To explore this issue in more detail, we revisit part of the coral reef case study and construct a simple qualitative model of the system that includes climate change, reef state, management action, public perception and the valuation of ecosystem services (Figure 2).

We subject the model to loop analysis (Dambacher, Luh, Li, & Rossignol, 2003; Puccia & Levins, 1985), which has a rigorous mathematical foundation and allows us to evaluate the system’s behaviour with different combinations of solutions. Specifically, we can ask how the addition of multiple solutions is likely to influence the motivation for management under climate change. In some cases, the addition of a solution, such as the use of counterfactual modelling of alternative reef futures, might lead to an increase in management support, but in other cases, it might either provide no additional benefit or ambiguous benefits. An ambiguous prediction would occur if the number of positive and negative relationships between “climate change” and “management action” are roughly even, meaning that the net directionality is difficult to predict. Previous studies have found that a ratio of positive to negative relationships (or vice versa) of at least 3:1 is a reasonable indication that the dominant direction (that with at least three links to every one of opposite sign) will prevail (Dambacher et al., 2003).

TABLE 1 The diversity of solutions that can be brought to bear on problems created by of the effects of global environmental change on the oceans. Examples were selected on the grounds that the problems influence basic human needs (food, secure living environment, livelihoods). Solutions are disaggregated with the following superscripts: Technological [T], Governance [G], Economic[E], or Communication[C]

		Solutions		
Change	Problem	Increase resilience of human-ecological system	Early detection of changes	Facilitate rapid responses to a change
Location of pelagic fish stocks changing in response to rising sea temperature	Countries can both lose and gain fish stocks. Progressive migration of stock outside jurisdiction can lead to over-exploitation of departing stock, impacting the wider fishery	Industry collaboration in monitoring stocks[T] International fishing quotas[E] Dynamic ocean planning Ecosystem-based planning and management [G] Conservative buffers to reduce exploitation level (Precautionary Principle) [G]	Remote sensing of fish habitat [T] Genetic identification of fish stocks [T] Explore contrary assumptions in model (e.g., dispersal under antagonistic vs. synergistic impacts of warming on larval survivorship) [T]	Remote sensing of fish habitat [T] Initiate legislation early when little resistance[C] Adapt existing international agreements to suit purpose (e.g., North American Free Trade Agreement) [E] Dynamic ocean planning [G]
Rising sea level	Coastal infrastructure under greater threat and may become uninsurable; Current adaptation using concrete sea defense is expensive with high carbon footprint, and it degrades natural habitats and functions.	Implement managed retreat and associated watershed and coastal restoration where appropriate[C] Increase societal awareness and willingness to act on climate change issues (narratives, games, reframing problem) [C] Re-insurance industries tightening practicev Combine conventional grey infrastructure with green, ecosystem-based solutions [T]	Scientific freedom of expression[C]	Redefine insurable risk[E] Re-insurance industries tightening practice [T] Develop emergency response plans [T] Prepare certification and engineering standards for green solutions [G] Identify thresholds of change to trigger action and communicate altered risk perhaps using threat maps [T]
Reduced coral resilience because of rising thermal stress and ocean acidification	Difficulty of garnering support for management when presiding over system decline; Ecosystem services to society decline	Value and map ecosystem services[E] Model future ecosystem trajectories under alternate management scenarios [T] Protecting climate refugia from manageable stressors [T] Assisted migration of more resilient species [T]	Prioritize understanding of multiple stressors [T] Improved models of nonlinear dynamics [T] Monitor for early-warning signs even where they may be less likely [T]	Reward good governance [G] Convey immediate and long-term benefits of management with emotionally-salient information[C] Reverse the burden of proof: Assume that systems might exhibit hysteresis [T]

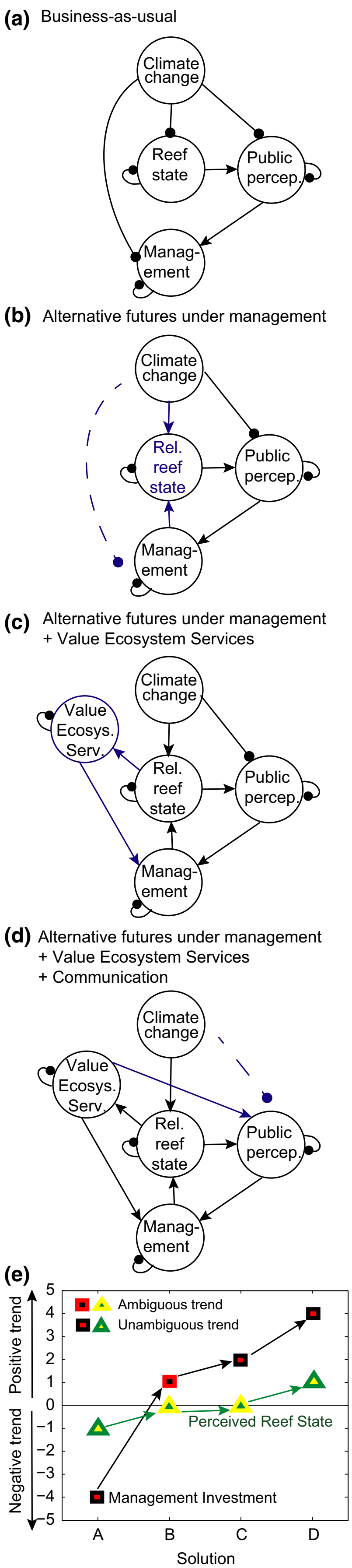

FIGURE 2 The effect of contributing additional solutions on garnering greater support for investments in the management of coral reefs under business-as-usual (a), consideration of counterfactuals (b), additional consideration of ecosystem services (c), and with the additional of communication strategies (d). In (e) we show the expected impact of climate change on management investment (black) and perceived reef state (green) for each scenario (a-d, now labelled A-D). Ambiguous trends (unclear whether positive or negative) identified as having red or yellow borders around points. [Colour figure can be viewed at wileyonlinelibrary.com]

Under a business-as-usual scenario, where management success is considered only in terms of reef state, the motivation for management is strongly negative because the ecosystem appears to be declining and media coverage of climate change is reinforcing the perception that management is futile (Figure 2a, e). We next add ecosystem models to express the success of management relative to unmanaged (or less managed) counterfactual (Figure 2b). Assuming that management improves the reef state relative to the unmanaged alternative, we can substitute "relative reef state" for "reef state," which essentially reverses the apparent relationship between climatic stress and reef state while also creating a visible feedback from management action to reef state. Managers now perceive a clearer benefit of action under climate change so the negative relationship of climate change on management motivation disappears. Under this scenario, predictions for climate change impacts on management interventions and reef state are highly ambiguous, so there is no compelling case for improved support for management (Figure 2e). We next add the valuation of ecosystem services, which reinforces the case for management, making it slightly positive (Figure 2c,e); although the perception of reef state still remains ambiguous. Lastly, we add an appropriate public communication strategy that raises awareness of the potential for losing ecosystem services and erodes the perception that management is futile under climate change (Figure 2d). The trend of management investment now becomes strongly positive, and the perception of reef state now becomes unambiguously, albeit weakly, positive.

Of course, the simple scenario modelled here is only intended to be illustrative that simply adding solutions does not necessarily increase the likelihood of a particular outcome. Nevertheless, qualitative models might be a useful early step in designing appropriate sets of solutions to a climate change problem (and identifying barriers to adaptation), just as they are used in designing fisheries management strategies (Dambacher, Gaughan, Rochet, Rossignol, & Trenkel, 2009). Such models allow managers to evaluate the risk, institutional barriers and social acceptability of a suite of solutions that in turn allow managers to evaluate the cost-benefit of a suite of solutions (Hobday, Chambers, & Arnould, 2015).

4 | CONCLUDING REMARKS

Climate change is a wicked problem but scientists are attempting to tackle some of the most serious associated challenges. One of the most difficult problems is how to incentivize human behaviour to act when (i) the risk appears low, (ii) the hazard is perceived too uncertain, low probability, far in the future, and not all that scary, (iii) other urgent issues compete for peoples' attention (Weber, 2006) and (iv) where the risk is high and well-known but adaptation options limited. Thus, simply undertaking more biophysical research to reduce scientific uncertainty over the future is unlikely to shift the perception of risk that motivates individual and societal preparedness. Rather, communication strategies need to tap into the affective and analytical aspects of human decision making by presenting climate change in a form that people can relate to on the timescales they care about and at relevant spatial scales (O'neill & Nicholson-Cole, 2009). This includes reframing the problem in terms of contemporary, local impacts and diverse ideological norms, employing narratives in lieu of statistical descriptions for public consumption, and utilizing advances in computer technology and access to let people play simulation games where their futures can be made explicit (Meyer, Broad, Orlove, & Petrovic, 2013). Yet even when people are aware of climate change and have experienced impacts first hand, there is often a tendancy to avoid thinking about it or console oneself with apparent claims to virtue such as "there are worse polluters" (Norgaard, 2012). Overcoming psychological hurdles to promote action remains an enormous challenge.

While reframing the climate change issue is important to gain greater traction today, another body of work is attempting to solve the temporal disconnect between the need to take action on climate change today given that the impacts accrue on generational timescales. Approaches to attain intergenerational equity include intergenerational discounting (Sumaila & Walters, 2005) and the development of approaches that provide representation to future generations in today's legal and political processes. These so-called Guardians of the Future are intended to ensure intergenerational equity by assigning present day "trustees" for future generation "beneficiaries" (as in the case of assets held in trust for minors). These ideas are related to the Public Trust Doctrine from Common Law. Under the Public Trust Doctrine, managers and policy-makers would have not only the authority to manage publically held resources, but also the responsibility (Turnipseed, Crowder, Sagarin, & Roady, 2009). In the United States, the Public Trust Doctrine exists at the level of states, but not at the Federal level. Some countries have formal Public Trust laws, but they vary vastly in their requirements and enforcement. So far, the idea has found little traction in the courts, but there are some isolated exceptions related to environment and human health and there is cause to believe that nontraditional coalitions and approaches can form as multisectoral impacts of marine ecosystem problems are realized (Anon 2008).

Climate change is most often and quite appropriately viewed as a major global threat to people and nature. This problem appears so large and intangible that many people and decision makers feel overwhelmed by it. We argue that new perspectives to this problem should include not only the threats from climate change, but also the opportunities that such change creates. But minimizing the dangers and capitalizing on opportunities requires fresh approaches. In particular, a natural tendency to reduce management would be counterproductive. Rational reactions to changing circumstances under climate change (Figure 1) are compounded by cognitive biases that have the potential to reduce management investment further. Psychological studies have found that some marine resource users tend to attribute the symptoms of climate change, such as shifts in species' ranges, to a failure of management rather than climate change itself (Van Putten et al., 2015). One reason for this is peoples' established mental model that may have already attributed declining species' abundance with overharvesting. Yet despite the risk of governments disinvesting in management, we draw on five case studies to argue that values to society increase through the creation of better, more responsive management while also developing a suite of solutions that foster a more profitable and environmentally sensitive path forward. There are increasing signs that stakeholders are becoming more involved with management, particularly where concerns are raised over the adequacy of government-funded management. For example, some rights-based approaches to fisheries have seen a reversal in responsibilities wherein fishers' are funding better stock assessments and taking a more precautionary approach by creating risk pools and voluntarily refraining from fishing areas where by-catch of "choke" species is likely to be high (Branch et al., 2006; Lewison et al., 2015). Of the many surprises that face us, we hope that a proactive and strategic human response is among the greatest.

ACKNOWLEDGEMENTS

We thank the Pew Fellows Program in Marine Conservation and Herbert W. Hoover Foundation for supporting and funding the workshops that led to this paper. We thank three referees for constructive feedback and suggestions on an earlier version of this manuscript.

REFERENCES

Albrecht, G. (2011). Chronic environmental change: Emerging 'psychoterratic' syndromes. In I. Weissbecker (Ed.), *Climate change and human well-being* (pp. 43–56). Springer.

Alluvium. (2016). *Costs of achieving the water quality targets for the Great Barrier Reef by Alluvium Consulting Australia for Department of Environment and Heritage Protection, Brisbane*, Brisbane, QLD: Alluvium.

Anon. (2008). *Models for protecting the environment for future generations*. The International Human Rights Clinic at Harvard Law School.

Anthony, K. R. N. (2016). Coral reefs under climate change and ocean acidification: Challenges and opportunities for management and policy. *Annual Review of Environment and Resources*, *41*, 59–81.

Bakun, A., & Broad, K. (2003). Environmental 'loopholes' and fish population dynamics: Comparative pattern recognition with focus on El Nino effects in the Pacific. *Fisheries Oceanography*, *12*, 458–473.

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., . . . Jennings, S. (2014). Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change*, *4*, 211–216.

Barrett, S., & Dannenberg, A. (2012). Climate negotiations under scientific uncertainty. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 17372–17376.

Bazerman, M. H. (2006). Climate change as a predictable surprise. *Climatic Change*, *77*, 179–193.

Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., … Guo, X. M. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience*, *61*, 107–116.

Bednarek, A. T., Shouse, B., Hudson, C. G., & Goldberg, R. (2015). Science-policy intermediary from a practitioner's perspective: The Lenfest Ocean Program experience. *Science and Public Policy*, *43*, 1–10.

Bell, J. D. (2014). *Climate change and coastal development law in Australia*. Annandale, NSW: Federation Press.

Bell, J. D., Ganachaud, A., Gehrke, P. C., Griffiths, S. P., Hobday, A. J., Hoegh-Guldberg, O., … Waycott, M. (2013). Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, *3*, 591–599.

Branch, T. A., Hilborn, R., Haynie, A. C., Fay, G., Flynn, L., Griffiths, J., … Young, M. (2006). Fleet dynamics and fishermen behavior: Lessons for fisheries managers. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*, 1647–1668.

Budescu, D. V., Por, H. H., & Broomell, S. B. (2012). Effective communication of uncertainty in the IPCC reports. *Climatic Change*, *113*, 181–200.

CCRIF. (2010). *Enhancing the climate risk and adaptation fact base for the Caribbean: Preliminary results of the economics of climate adaptation study*. Cayman Islands: Caribbean Catastrophic Risk Insurance Facility.

Chan, F., Barth, J. A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W. T., & Menge, B. A. (2008). Emergence of anoxia in the California current large marine ecosystem. *Science*, *319*, 920.

Charles, A. T. (2002). The precautionary approach and 'burden of proof' challenges in fishery management. *Bulletin of Marine Science*, *70*, 683–694.

Cheong, S.-M., Silliman, B. R., Wong, P. P., Van Wesenbeeck, B., Kim, C. K., & Guannel, G. (2013). Coastal adaptation with ecological engineering. *Nature Climate Change*, *3*, 797–791.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., & Pauly, D. (2010). Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, *16*, 24–35.

Cheung, W. W. L., Okey, T. A., Brodeur, R. D., & Pauly, D. (2015). Projecting future changes in distributions of pelagic fish species of the Northeast Pacific shelf seas. *Progress in Oceanography*, *130*, 19–31.

Cinner, J. E., Huchery, C., Macneil, M. A., Graham, N. A., Mcclanahan, T. R., Maina, J., … Mouillot, D. (2016). Bright spots among the world's coral reefs. *Nature*, *535*, 416–419.

Cvitanovic, C., Hobday, A. J., Van Kerkhoff, L., Wilson, S. K., Dobbs, K., & Marshall, N. A. (2015). Improving knowledge exchange among scientists and decisionmakers to facilitate the adaptive governance of marine resources: A review of knowledge and research needs. *Ocean & Coastal Management*, *112*, 25–35.

Dambacher, J. M., Gaughan, D. J., Rochet, M.-J., Rossignol, P. A., & Trenkel, V. M. (2009). Qualitative modelling and indicators of exploited ecosystems. *Fish and Fisheries*, *10*, 305–322.

Dambacher, J. M., Luh, H. K., Li, H. W., & Rossignol, P. A. (2003). Qualitative stability and ambiguity in model ecosystems. *American Naturalist*, *161*, 876–888.

Dasgupta, P. S., & Heal, G. M. (1979). *Economic theory and exhaustible resources*. Cambridge, UK: Cambridge University Press.

De'ath, G., Fabricius, K. E., Sweatman, H., & Puotinen, M. (2012). The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 17995–17999.

Dereynier, Y. L. (1998). Evolving principles of international fisheries law and the North Pacific anadromous fish commission. *Ocean Development and International Law*, *29*, 147–178.

Dettmers, J. M., Goddard, C. I., & Smith, K. D. (2012). Management of alewife using Pacific Salmon in the Great Lakes: Whether to manage for economics or the ecosystem? *Fisheries*, *37*, 495–501.

Donlan, J., Berger, J., Bock, C. E., Bock, J. H., Burney, D. A., Estes, J. A., … Greene, H. W. (2005). Re-wilding North America. *Nature*, *436*, 913–914.

Drabek, T. E. (1985). Managing the emergency response. *Public Administration Review*, *45*, 85–92.

Dybas, C. L. (2005). Dead zones spreading in world oceans. *BioScience*, *55*, 552–557.

Fazey, I., Evely, A. C., Reed, M. S., Stringer, L. C., Kruijsen, J., White, P. C. L., … Trevitt, C. (2013). Knowledge exchange: A review and research agenda for environmental management. *Environmental Conservation*, *40*, 19–36.

Field, J. (2008). *Part 11 Symposium of the calcon conference, 2007 Hubbs-Sea World Research Institute San Diego, California 26-28 November 2007 Jumbo squid (Dosidicus gigas) invasions in the Eastern Pacific Ocean*. *California Cooperative Oceanic Fisheries Investigations Reports*, **49**, 79–81.

Fulton, E. A., Bax, N. J., Bustamante, R. H., Dambacher, J. M., Dichmont, C., Dunstan, P. K., … Smith, D. C. (2015). Modelling marine protected areas: Insights and hurdles. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *370*.

Gar (2011). *Global assessment report on disaster risk reduction*. London, UK: United Nations.

Gittman, R. K., Fodrie, F. J., Popowich, A. M., Keller, D. A., Bruno, J. F., Currin, C. A., … Piehler, M. F. (2015). Engineering away our natural defenses: An analysis of shoreline hardening in the US. *Frontiers in Ecology and the Environment*, *13*, 301–307.

Grantham, B. A., Chan, F., Nielsen, K. J., Fox, D. S., Barth, J. A., Huyer, A., … Menge, B. A. (2004). Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature*, *429*, 749–754.

Great Barrier Reef Marine Park Authority (2014). *Great Barrier Reef Outlook Report 2014*. Townville, QLD: Commonwealth of Australia.

Green, B. S., Gardner, C., Linnane, A., & Hawthorne, P. J. (2010). The good, the bad and the recovery in an assisted migration. *PLoS ONE*, *5*, e14160.

Griffiths, C. J., Hansen, D. M., Jones, C. G., Zuel, N., & Harris, S. (2011). Resurrecting extinct interactions with extant substitutes. *Current Biology*, *21*, 762–765.

Gunderson, L. H., & Holling, C. S. (Eds.) (2002). *Panarchy: Understanding transformatoins in human and natural systems*. Washington, DC: Island Press.

Haecker, D. (2013). *Maritime symposium addresses increased Bering Strait traffic*. *The Nome Nugget*.

Hannesson, R. (2013). Sharing the Northeast Atlantic mackerel. *ICES Journal of Marine Science*, *70*, 259–269.

Hannesson, R. (2014). Does threat of mutually assured destruction produce quasi-cooperation in the mackerel fishery? *Marine Policy*, *44*, 342–350.

Harborne, A. R., & Mumby, P. J. (2011). Novel ecosystems: Altering fish assemblages in warming waters. *Current Biology*, *21*, R822–R824.

Harvatt, J., Petts, J., & Chilvers, J. (2011). Understanding householder responses to natural hazards: Flooding and sea-level rise comparisons. *Journal of Risk Research*, *14*, 63–83.

Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., … Block, B. A. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*, *3*, 234–238.

Hobday, A. J., Bell, J. D., Cook, T. R., Gasalla, M. A., & Weng, K. C. (2015a). Reconciling conflicts in pelagic fisheries under climate change. *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *113*, 291–300.

Hobday, A. J., Chambers, L. E., & Arnould, J. P. Y. (2015b). Prioritizing climate change adaptation options for iconic marine species. *Biodiversity and Conservation*, *24*, 3449–3468.
Hobday, A. J., Hartog, J. R., Spillman, C. M., & Alves, O. (2011). Seasonal forecasting of tuna habitat for dynamic spatial management. *Canadian Journal of Fisheries and Aquatic Sciences*, *68*, 898–911.
Hobday, A. J., Maxwell, S. M., Forgie, J., Mcdonald, J., Darby, M., Seto, K., ... Powers, A. (2014). Dynamic ocean management: Integrating scientific and technological capacity with law, policy and management. *Stanford Environmental Law Journal*, *33*, 125–165.
Hoegh-Guldberg, O., & Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science*, *328*, 1523–1528.
Hoegh-Guldberg, O., Hughes, L., Mcintyre, S., Lindenmayer, D. B., Parmesan, C., Possingham, H. P., & Thomas, C. D. (2008). Assisted colonization and rapid climate change. *Science*, *321*, 345–346.
Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., ... Hatziolos, M. E. (2007). Coral reefs under rapid climate change and ocean acidification. *Science*, *318*, 1737–1742.
Hugo. (2011). Future demographic change and its interactions with migration and climate change. *Global Environmental Change*, *21S*, S21–S33.
Huntington, H. P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., ... Stetsen, G. (2015). Vessels, risks and rules: Planing for safe shipping in Bering Strait. *Marine Policy*, *51*, 119–127.
IMO. (2014). *Development of an international code of safety for ships operating in polar waters (Polar Code)*. London, UK: International Maritime Organisation.
JAT, B., Woodson, C. B., Sutula, M., Micheli, F., Weisberg, S. B., Bograd, S. J., ... Crowder, L. B. (2014). Patterns and potential drivers of declining oxygen content along the southern California coast. *Limnology and Oceanography*, *59*, 1127–1138.
Kahneman, D. (2011). *Thinking fast and slow*. New York, NY: Macmillan.
Kates, R. W., & Clark, W. C. (1996). Environmental surprise: Expecting the unexpected? *Environment*, *38*, 6–34.
Kennedy, E. V., Perry, C. T., Halloran, P. R., Iglesias-Prieto, R., Schonberg, C. H., Wisshak, M., ... Mumby, P. J. (2013). Avoiding coral reef functional collapse requires local and global action. *Current Biology*, *23*, 912–918.
King, J. R., Mcfarlane, G. A., & Punt, A. E. (2015). Shifts in fisheries management: Adapting to regime shifts. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *370*.
Kleypas, J. A., & Yates, K. K. (2009). Coral reefs and ocean acidification. *Oceanography*, *22*, 108–117.
Kling, D., Sanchirico, J. N., & Wilen, J. E. (2016). The bioeconomics of managed relocation. *Journal of the Association of Environmental and Resource Economics*, *3*, 1023–1059.
Kunreuther, H. (2015). The role of insurance in reducing losses from extreme events: The need for public–private partnerships. *The Geneva Papers on Risk and Insurance Issues and Practice*, *40*, 741–762.
Lehrer, E. (2007). *Watery marauders: How the federal government retarded the development of private flood insurance*. Washington, DC: Competitive Enterprise Institute.
Leonetwork. Retrieved from www.leonetwork.org
Levin, S. A., & Lubchenco, J. (2008). Resilience, robustness, and marine ecosystem-based management. *BioScience*, *58*, 27–32.
Lewison, R. L., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., ... Crowder, L. B. (2015). Dynamic ocean management: Identifying the critical ingredients of dynamic approaches to ocean resource management. *BioScience*, *65*, 486–498.
Longstaff, P. H., & Yang, S. U. (2008). Communication management and trust: Their role in building resilience to "surprises" such as natural disasters, pandemic flu, and terrorism. *Ecology and Society*, *13*.
Madin, E. M. P., Ban, N. C., Doubleday, Z. A., Holmoes, T. H., Pecl, G. T., & Smith, F. (2012). Socio-economic and management implications of range-shifting species in marine systems. *Global Environmental Change*, *22*, 137–146.
Maxwell, S. M., Hazen, E. L., Lewison, R. L., Dunn, D. C., Bailey, H., Bograd, S. J., ... Crowder, L. B. (2015). Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy*, *58*, 42–50.
Mcclanahan, T. R., Graham, N. A., Macneil, M. A., Muthiga, N. A., Cinner, J. E., Bruggemann, J. H., & Wilson, S. K. (2011). Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 17230–17233.
Mccook, L. J., Ayling, T., Cappo, M., Choat, J. H., Evans, R. D., De Freitas, D. M., ... Williamson, D. H. (2010). Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 18278–18285.
Mccoppin, R. (2014). *Insurance company drops suit over Chicago-area flooding*. *Chicago Tribune*. Chicago, IL.
Meyer, R., Broad, K., Orlove, B., & Petrovic, N. (2013). Dynamic simulations as an approach to understanding hurricane risk response: Insights from the *Stormview* lab. *Risk Analysis*, *33*, 1532–1552.
Miller, K., Charles, A., Barange, M., Brander, K., Gallucci, V. F., Gasalla, M. A., ... Perry, R. I. (2010). Climate change, uncertainty, and resilient fisheries: Institutional responses through integrative science. *Progress in Oceanography*, *87*, 338–346.
Morrow, B. H. (2002). Identifying and mapping community vulnerability. *Disasters*, *23*, 1–18.
Mumby, P. J., & Anthony, K. R. N. (2015). Resilience metrics to inform ecosystem management under global change with application to coral reefs. *Methods in Ecology and Evolution*, *6*, 1088–1096.
Mumby, P. J., Steneck, R. S., & Hastings, A. (2013). Evidence for and against the existence of alternate attractors on coral reefs. *Oikos*, *122*, 481–491.
Mumby, P. J., Wolff, N. H., Bozec, Y. M., Chollett, I., & Halloran, P. R. (2014). Operationalizing the resilience of coral reefs in an era of climate change. *Conservation Letters*, *7*, 176–187.
Nelson, J. (2014). *Insurers must adapt to climate change*. *The Guardian*. Australia.
Neumann, B., Vafeidis, A. T., Zimmerman, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding – A global assessment. *PLoS ONE*, *10*, e0118571.
NOAA. (2011). Scientific integrity. In Administration NOaA (Ed.), *NOAA FORM 58-5 (4-04)*. (pp. Page). Silver Spring, MD: NOAA.
Norgaard, K. M. (2012). Climate denial: Emotion, psychology, culture and political economy. In J. S. Dryzek, R. B. Norgaard, & D. Schlosberg (Eds.), *The Oxford handbook of climate change and society*. Oxford, UK: Oxford University Press.
NPFMC. (2009). *Fisheries management plan for fish resources of the Arctic management area*. Retrieved from http://www.npfmc.org/wp-content/PDFdocuments/fmp/Arctic/ArcticFMP.pdf
NRC. (2014). *Reducing coastal risk on the East and Gulf coasts*. Washington, DC: The National Acadamies Press.
Olaussen, J. O. (2007). Playing chicken with salmon. *Marine Resource Economics*, *22*, 173–193.
O'neill, S., & Nicholson-Cole, S. (2009). Fear won't do it: Promoting positive engagement with climate change through visual and iconic representations. *Science Communication*, *30*, 355–379.
Paine, R. T., Tegner, M. J., & Johnson, E. A. (1998). Compounded perturbations yield ecological surprises. *Ecosystems*, *1*, 535–545.
Perry, R. W., & Lindell, M. K. (2003). Preparedness for emergency response: Guidelines for the emergency planning process. *Disasters*, *27*, 336–350.
Piggot-Mckellar, A. E., & Mcnamara, K. E. (2016). Last chance tourism and the Great Barrier Reef. *Journal of Sustainable Tourism*, *25*, 397–415.

Pinsky, M., & Mantua, N. (2014). Emerging adaptation approaches for climate-ready fisheries management. *Oceanography*, *27*, 146–159.

Porter, M. (1990). The competitive advantage of nations. *Harvard Business Review*, *68*, 73–93.

Puccia, C. J., & Levins, R. (1985). *Qualitative modeling of complex systems: An introduction to loop analysis and time averaging*. Cambridge, UK: Harvard University Press.

Punt, A. E., A'mar, T., Bond, N. A., Butterworth, D. S., De Moor, C. L., De Oliveira, J. A. A., . . . Szuwalski, C. (2014). Fisheries management under climate and environmental uncertainty: Control rules and performance simulation. *ICES Journal of Marine Science*, *71*, ru2208–ru2220.

Rau, G. H., Mcleod, E. L., & Hoegh-Guldberg, O. (2012). The need for new ocean conservation strategies in a high-carbon dioxide world. *Nature Climate Change*, *2*, 720–724.

Redmap. Retrieved from www.redmap.org.au

Reser, J. P., Morrissey, S. A., & Ellul, M. (2011). *The threat of climate change: Psychological response, adaptation, and impacts* (pp. 19–42).

Robinson, L. M., Gledhill, D. C., Moltschaniwskyj, N. A., Hobday, A. J., Frusher, S., Barrett, N., . . . Pecl, G. T. (2015). Rapid assessment of an ocean warming hotspot reveals "high" confidence in potential species' range extensions. *Global Environmental Change-Human and Policy Dimensions*, *31*, 28–37.

Rogers, A., Harborne, A. R., Brown, C. J., Bozec, Y. M., Castro, C., Chollett, I., . . . Mumby, P. J. (2015). Anticipative management for coral reef ecosystem services in the 21st century. *Global Change Biology*, *21*, 504–514.

Ronnback, P., Crona, B., & Ingwall, L. (2007). The return of ecosystem goods and services in replanted mangrove forests: Perspectives from local communities in Kenya. *Environmental Conservation*, *34*, 313–324.

Ruesink, J. L., Lenihan, H. S., Trimble, A. C., Heiman, K. W., Micheli, F., Byers, J. E., & Kay, M. C. (2005). Introduction of non-native oysters: Ecosystem effects and restoration implications. *Annual Review of Ecology Evolution and Systematics*, *36*, 643–689.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., . . . Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature*, *461*, 53–59.

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology & Evolution*, *18*, 648–656.

Scheffer, M., Carpenter, S. R., Lenton, T. M., Bascompte, J., Brock, W., Dakos, V., . . . Vandermeer, J. (2012). Anticipating critical transitions. *Science*, *338*, 344–348.

Schreiber, M. A., Niquen, M., & Bouchon, M. (2011). Coping strategies to deal with environmental variability and extreme climatic events in the Peruvian anchovy fishery. *Sustainability*, *3*, 823–846.

Simpson, S. D., Jennings, S., Johnson, M. P., Blanchard, J. L., Schon, P. J., Sims, D. W., & Genner, M. J. (2011). Continental shelf-wide response of a fish assemblage to rapid warming of the sea. *Current Biology*, *21*, 1565–1570.

Slovic, P. (1987). Perception of risk. *Science*, *236*, 280–285.

Steele, J. H. (2004). Regime shifts in the ocean: Reconciling observations and theory. *Progress in Oceanography*, *60*, 135–141.

Steneck, R. S., Hughes, T. P., Cinner, J. E., Adger, W. N., Arnold, S. N., Berkes, F., . . . Worm, B. (2011). Creation of a gilded trap by the high economic value of the Maine lobster fishery. *Conservation Biology*, *25*, 904–912.

Stewart, J. S., Hazen, E. L., Bograd, S. J., Byrnes, J. E. K., Foley, D. G., Gilly, W. F., . . . Field, J. C. (2014). Combined climate- and prey-mediated range expansion of Humboldt squid (*Dosidicus gigas*), a large marine predator in the California Current System. *Global Change Biology*, *20*, 1832–1843.

Stirling, A. (2006). Analysis, participation and power: Justification and closure in participatory multi-criteria analysis. *Land Use Policy*, *23*, 95–107.

Stoll, J. S., Beitl, C. M., & Wilson, J. A. (2016). How access to Maine's fisheries has changed over a quarter century: The cumulative effects of licensing on resilience. *Global Environmental Change-Human and Policy Dimensions*, *37*, 79–91.

Streets, D. G., & Glantz, M. H. (2000). Exploring the concept of climate surprise. *Global Environmental Change-Human and Policy Dimensions*, *10*, 97–107.

Suding, K. N., Gross, K. L., & Houseman, G. R. (2004). Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology & Evolution*, *19*, 46–53.

Sumaila, U. R., & Walters, C. (2005). Intergenerational discounting: A new intuitive approach. *Ecological Economics*, *52*, 135–142.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature*, *504*, 79–83.

Turnipseed, M., Crowder, L. B., Sagarin, R. D., & Roady, S. E. (2009). The silver anniversary of the U.S'.s Exclusive Economic Zone: Twenty-five years of ocean use and abuse, and the possibility of a blue water public trust doctrine. *Ecology Law Quaterly*, *36*, 1–70.

UNISDR. (2011). *Global assessment report on disaster risk reduction*. Vol 178. Geneva: United Nations International Strategy for Disaster Reduction.

UNISDR. (2015). *Making development sustainable: The future of disaster risk management. Global assessment report on disaster risk reduction*. Geneva: United Nations Office for Disaster Risk Reduction (UNISDR).

US Coast Guard. (2013). *The United States Coast Guard's Arctic Strategy*. Washington, DC.

Van Den Hoek, R. E., Brugnach, M., & Hoekstra, A. Y. (2012). Shifting to ecological engineering in flood management: Introducing new uncertainties in the development of a building with nature pilot project. *Environmental Science & Policy*, *22*, 85–99.

Van Putten, I. E., Frusher, S., Fulton, E. A., Hobday, A. J., Jennings, S. M., Metcalf, S., & Pecl, G. T. (2015). Empirical evidence for different cognitive effects in explaining the attribution of marine range shifts to climate change. *ICES Journal of Marine Science*, *73*, 1306–1318.

Walker, B., & Salt, D. (2012). *Resilience practice: Engaging the sources of our sustainability*. Washington, DC: Island Press.

Weatherdon, L. V., Magnan, A. K., Rogers, A. D., Sumaila, U. R., & Cheung, W. W. L. (2016). Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: An update. *Frontiers in Marine Science*, *3*.

Weber, E. U. (2006). Experience-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). *Climatic Change*, *77*, 103–120.

Wheeler, T., & Braun, J. V. (2013). Climate change impacts on global food security. *Science*, *341*, 508–513.

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, *28*, 325–336.

Wolff, N. H., Donner, S. D., Cao, L., Iglesias-Prieto, R., Sale, P. F., & Mumby, P. J. (2015). Global inequities between polluters and the polluted: Climate change impacts on coral reefs. *Global Change Biology*, *21*, 3982–3994.

How to cite this article: Mumby PJ, Sanchirico JN, Broad K, et al. Avoiding a crisis of motivation for ocean management under global environmental change. *Glob Change Biol*. 2017;23:4483–4496. https://doi.org/10.1111/gcb.13698