A Review of Potential Approaches for Managing Marine Fisheries in a Changing Climate

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ABSTRACT

Climate variability and change may affect marine fisheries by altering: ecosystem functions, fish abundance and productivity, species and fishery distributions, fish phenology, interactions with non-target species and bycatch rates and levels, and habitat use and/or availability (e.g., shifting nursery grounds). Because managers may not be aware of the many approaches available to respond to or plan for environmental change, we conducted a literature review and compiled a list of options. In general, management approaches can be either proactive and plan for change, or reactive and respond to change after it has occurred. Pro-active management alternatives can be implemented to increase resilience of stocks, species, ecosystems, and/or fishing businesses. Given the large uncertainties surrounding the effects of climate change, two good approaches are to either reduce the uncertainty, or embrace the uncertainty and rely on management options that will be robust to the given uncertainties. On a whole, management actions that seek to increase management flexibility and provide incentives to the fishing industry to try new approaches while preserving genetic diversity of the fished populations should prove to be beneficial. Ideally, the pros, cons, and tradeoffs associated with various management options should be evaluated to determine the best approach (or mix of approaches) given the information available. New approaches will continue to emerge as management across the globe grapples with this complex issue.

1.0 INTRODUCTION

As the climate changes, marine ecosystems will continue to undergo significant physical and chemical changes. Some of the anticipated shifts include: global increases in temperature, decreases in pH (acidification), changes in currents, rises in sea level, and changes to freshwater inputs (Stock et al. 2011; Rhein et al. 2013). These changes may in turn, affect species abundances and/or distributions, species phenology, marine habitats, marine communities, and the resulting ecosystem productivity and function (O'Connor et al. 2007; Badjeck et al. 2010; Ottersen et al. 2010; Pörtner and Peck 2010; Stock et al. 2011).

The effects of the changing climate on marine ecosystems are already being observed. Shifting distributions and abundances of fish species are being documented worldwide (Perry et al. 2005; Cheung et al. 2010; Hoegh-Gulberg and Bruno 2010), including several important commercial and recreational fish species in the United States (Nye et al. 2009; Hollowed et al. 2012; Mills et al. 2013; Pinksy et al. 2013). In addition, shifts in productivity have already been identified for some stocks (Fogarty et al. 2008; NEFSC 2012; Bell et al. 2014). Therefore, fishery managers and scientists need to be prepared to anticipate these changes even though they are typically making decisions on a much shorter timeframe (next 1–5 years) compared to interannual climate variability (1–50+ years) and climate change (projections are typically on a multi-decadal scale). Not anticipating or preparing for these biological, economic, and cultural changes could result in negative biological, social, and economic effects (Cooley and Doney 2009; Madin et al. 2012; Mills et al. 2013; Barange et al. 2014).

Environmental change is not new to fisheries. For example, anchovy and sardine populations have well-known oscillations that began prior to human exploitation (Baumgartner et al. 1992). However, climate change differs from past environmental change because, even though there will be variations in magnitude across years, the overall trends are drifting away from recent average conditions. The future may bring environmental conditions not yet experienced in the historical record, and the speed of these changes is predicted to be faster than at any time in history, challenging the adaptation capabilities of marine species. In addition, the uncertainty associated with when and how climate change will affect stocks, results in decreased confidence in stock projections through time. Biological, ecological, and social responses to these changes are hard to predict but have the potential to occur at any point in time. It is unclear whether the common approaches currently being used in fisheries management will be sufficient (Field and Francis 2002; Plaganyi 2011b; Tingley et al. 2014), or whether the magnitude of climate change will simply overwhelm the effectiveness of these management strategies (Daw et al. 2009).

The goal of this paper is to review peer-reviewed literature to outline suggested or implemented ideas for managing fisheries in a changing climate. In 2015, the National Marine Fisheries Service (NMFS) released their Climate Science Strategy (Link et al. 2015) that outlined seven objectives NMFS will tackle to increase the production, delivery, and use of climate-related science information needed to manage fisheries in a changing climate. Our paper builds off of the Climate Science Strategy by identifying possible management approaches that facilitate implementation of the Strategy. The intersection between science and management can be a thin line and a few of the approaches presented here lean to the science side. However, our objective is to delve more into management approaches as much of the science is covered by the Climate Science Strategy. Ideas provided here have not been evaluated for feasibility and applicability under current legal authorities, and inclusion of alternatives in this paper does not represent endorsement by NMFS.

We divide the management options into five main categories: 1) reactive management options, 2) proactive management options that increase species' resilience, 3) proactive management options that increase ecosystem resilience, 4) proactive management options that increase resilience of fishermen, and 5) recommended practices that improve management's ability to be successful in a changing climate (Table 1). Managers are encouraged to investigate the tradeoffs associated with each approach, and may determine a mixed approach to be the best option. For the most part, the alternatives discussed here are within the control of fisheries managers. However, a few approaches discussed may be outside the control of the managers and dependent on other Agencies or scientists for implementation. The alternatives included in this review do not represent an exhaustive list of options. Our hope is that this list of alternatives launches the conversation, and subsequent discussions or papers will expand on the alternatives included here. For a recent review that covers fisheries adaptation options for specific climate changes, see Pinsky and Mantua (2014). Climate change will also have impacts that will likely affect terrestrial components of marine fisheries, such as infrastructure (docks and processing facilities). These effects of climate change will not be covered here.

2.0 ADAPTATION

Adaptation strategies are adjustments to social or ecological systems that are specifically designed as a response to current and future expected environmental change, and can be applicable to biological, economic, and cultural systems (Stein et al. 2014). Climate change adaptation strategies should attempt to maintain key ecosystem functions (Moore et al. 2013) while managing for ecological change rather than maintaining the historical state (Stein et al. 2014). Adaptation strategies can include short to long term timeframes, minor adjustments to deep transformations, and may or may not in the end be successful at meeting the adaptation goals (Moser and Ekstrom 2010). An analogy for climate change adaptation is building a structure to provide protection from a storm: the structure does not stop the storm; it just lessens the impact (Grafton 2010).

Climate change adaption can be divided into two main alternatives: proactive or reactive management (Sumaila 2011; Frusher et al. 2014); however, these groups are somewhat arbitrary as what we describe as reactive options can also be used proactively, and vice versa. Reactive management focuses on responses to changes that have already occurred, while proactive management prepares for changes before their effects occur. Proactive management is often aimed at increasing the resilience of species, ecosystems or fishermen. Because adaptation actions can include costs (resources to implement adaptation actions, etc.), there are trade-offs between adapting now versus in the future (Grafton 2010). There is a balance between actions that occur too early or too late (Fussel 2007). Generally, the earlier we act, the more flexibility there is in the actions we can take, but there are consequences (e.g. economic impacts) of any management actions. Articulating what is at risk—and the consequences of proactive action versus reactive action or inaction—may result in different answers for different fisheries. No matter how proactive managers are in planning for climate change, there will still be a need for reactive management as scientists will be unable to predict all changes (Schindler and Hilborn 2015).

3.0 REACTIVE MANAGEMENT: ADAPTING CURRENT MANAGEMENT TO ACCOUNT FOR OBSERVED CHANGES

Following a reactive (also called adaptive) management approach—where management is rapidly updated in response to identified changes in the environment or resource—may be more successful than proactive management that depends on predictive modeling of future environmental–fisheries relationships that may or may not be accurate (Plaganyi 2011b, Schindler and Hilborn 2015). However, even in a reactive management framework, it can be useful to consider predictions about possible future states, and to develop management measures that are robust to future changes.

3.1 Creating Flexible, Nimble Management Systems

The key to successful management in a changing climate is a flexible, nimble, and adaptive management system. We need to create a system that identifies when management changes are needed and is able to implement these changes in a timely manner. Flexibility and adaptability will be necessary at all levels of management (Johnson and Welch 2010; Stein et al. 2013): within fisheries, between fisheries, and across jurisdictions. Julius et al. (2013, pg 12) note that "[i]ncentive systems that reward status quo while discouraging creative-but-risky ideas" can limit the adaptation of management systems. They suggest creating incentives that reward innovative ideas and policies to encourage local strategies and management actions while improving coordination and collaboration between regions and institutions. Other experts suggest managers should consider future costs associated with any proposed policy, including to the feasibility of altering or reversing the policy should the impacts prove to be different or greater than expected (Schindler and Hilborn 2015). In addition, more resources should be dedicated to monitoring indicators that answer specific questions about resource and ecosystem conditions (Schindler and Hilborn, 2015; see section 7.2 on monitoring for climate change).

The laws governing federal and state rulemaking processes can limit the adaptability and flexibility of fisheries management (MAFMC 2014). For example, amendments to U.S. fishery management plans (FMPs) take at least three years to review, analyze, and implement. One mechanism that may create shorter response times is "frameworking," whereby an amendment or regulation describes a shortened procedure for implementing future regulatory actions that are anticipated but cannot be predicted (NMFS 2015). The analyses associated with the action would be completed when creating the framework, front-loading the implementation process. For example, the Caribbean Fishery Management Council created a framework process for its Spiny Lobster Fishery Management Plan that includes a pre-determined set of reference points (e.g., maximum sustainable yield, overfishing limit, and minimum stock size threshold) and management measures (e.g., seasonal and area closures, trip/bag limit, and size limits) that may be more quickly modified via framework adjustments than via full FMP amendments (CFMC 2011).

Dynamic ocean management (DOM) is another example of a flexible management system. DOM is "management that uses near real-time data to guide spatial distribution of commercial activity," and examples exist from around the world (Lewison et al. in press). In the United States, DOM is primarily used to reduce unwanted bycatch (e.g., turtles in the tropical Pacific and yellowtail flounder in the northeastern Atlantic; Lewison et al. in press). For sea turtles and yellowtail flounder, bycatch advisories are provided to participating fishermen, who can then voluntarily avoid areas with higher probability of bycatch (Lewison et al. in press). In the Gulf of Maine, researchers use temperature to forecast increased catch rates of lobster in summer (GMRI 2016). Their hope is this information will allow fishermen to better prepare for the upcoming season. While there can be a disconnect between the timeframes associated with climate change and DOM, the approach may provide a mechanism for quickly adjusting fisheries management. For now the tool is used mainly to minimize unwanted interactions, but as with the lobster example above, managers may expand into other management challenges in the future.

3.2 Adjusting Reference Points after Changes in Species Productivity or Stock Structure Have Occurred

When environmental changes affect the long-term productivity of a stock, biological reference points (e.g., catch limits and rebuilding biomass targets) that are based on historical conditions may no longer be relevant, achievable, or appropriate (MAFMC 2014). Further, changes in biological stocks, such as splitting or merging of stocks, may affect stock identification, productivity, evaluation, and management success (Link et al. 2011). In theory, adjusting management to account for changes in productivity or stock structure makes sense and seems simple. However, it can be difficult to discern when changes in stock dynamics are simply due to normal variation around a historical average or the start of a more permanent regime shift that will cause the stock to drift away from previously observed states (Punt et al. 2014). If a regime shift is underway, waiting too long to implement management changes could result in negative effects on the resource. Brown et al. (2012) used simulation models to demonstrate how delaying management responses more than 5 years after a decrease in stock productivity occurs, results in a greater probability of stock collapse. Alternatively, overreacting to normal environmental variability could result in management practices that are unstable and "chasing noise" (MAFMC 2014).

Both yellowtail flounder in the northeast United States and jackass morwong in Australia have had their biological reference points adjusted to account for changes in stock productivity (NEFSC 2012; Wayte 2013). An analysis of the evidence used to determine whether these changes in productivity occurred found lower weight of evidence to support the management shift in yellowtail flounder than in jackass morwong (Klaer et al. 2015). Arnason (2012) notes that changes in stock productivity could theoretically lead to management implications that are counterintuitive: increasing catch on stocks decreasing in productivity and decreasing catch on stocks increasing in productivity. The former would allow fishermen to harvest as much food as possible from the biomass before it declines, and the later would provide the stock the biomass needed to reach its growth potential (Arnason 2012).

3.3 Adjusting Fisheries Allocations after Species Abundances or Distributions Have Changed

Changes in species distributions can create management challenges, particularly when they cross jurisdictional boundaries. As the abundance and/or distribution of fish species change, following the common practice of basing allocations on historical catch rates (Bailey et al. 2013) may no longer be appropriate. Fish may be in a new location because their distribution has shifted or because they are more abundant and have expanded into new habitat (Bell et al. 2014). Bates et al. (2014) have outlined a methodology for identifying species that have significantly shifted their geographical range. They noted their methodology only applies to abundant species, and that improved monitoring would be needed to document range shifts in rare species.

Fishermen who have become reliant on particular fish species are unlikely to willingly decrease their allocation as stock distributions shift out of their area. Similarly fishermen in areas that are being colonized by shifting stocks may want to increase exploitation of the species that are now readily available in their region. Both sides have valid claims to the fish, creating a political situation that could lead to overexploitation and compromise the sustainability of the fish stocks. A good example of this is the "Mackerel wars" between the European Union (EU), Norway, Iceland and the Faroe Islands. In response to warming waters, the Atlantic Mackerel stock has shifted their migration pattern to the north and into the waters around Iceland and the Faroe Islands (Jensen et al. 2015). Iceland and the Faroe Islands unilaterally decided to increase their harvest levels in response to the increased abundance present in their exclusive economic zone. However, the EU wanted to continue their historic catch levels, especially those from Scotland where fishermen are dependent on this species. The combined quota demands exceeded the sustainable harvest levels, creating a politically charged allocation dispute that included trade restrictions, landing bans, and ultimately a rejection of Iceland's application for full EU membership (Jensen et al. 2015). Multiple failed negotiations were attempted before a 2014 agreement was reached between Norway, EU, and the Faroe Islands. Iceland chose not to participate in this agreement and is thus still sanctioned by Norway and EU (Jensen et al. 2015).

The literature mentions multiple options for adjusting allocations as the distribution of fish species move into and out of adjacent areas or jurisdictions (management, state, or country boundaries). First, managers could create an allocation mechanism where annual allocations are based on the distribution of the stock that year (Bailey et al. 2013). For example, an agreement between tuna fishermen in the Western Pacific Ocean determines annual allocations on a combination of historical effort in a zone (50%) and estimated biomass in each zone each year (50%) (Dunn et al. 2006; Bell et al. 2013). Similarly, pre-arranged management responses (Brander 2010) can be negotiated that "clearly articulate a set of rules for adjusting quotas and allocations as a function of mutually agreed upon indicators of changes in the shared stock" (Miller and Munro 2004, pg 388). Finally, countries with abundant capital might purchase rights to access resources within another country's exclusive economic zone (Sumaila et al. 2011). Payments for those access rights can either be direct payments for fishing rights, or side payments in an allocation agreement (Miller and Munro 2004; Sumaila 2011; Bailey et al. 2013; Pinsky and Mantua 2014). Side payments—whereby parties that will benefit the most from the allocation agreement compensate[1] the parties that would benefit from breaking the agreement—can help improve compliance (Munro et al. 2004; Bailey et al. 2013).

3.4 Adjusting Fishing Practices or Gears as Fish Community Composition Changes

As species shift abundances and distributions in response to a changing climate, the mix of species caught in fishing gears will also change, potentially creating management issues when the overlap of targeted stocks with either non-target stocks or protected species increases. Fishermen can adjust their fishing practices or gears to minimize these interactions. Adjusting fishing practices/gears can be considered as reactive and proactive depending on the situation. It can be reactive if the changes are in response to a change that has already occurred, or proactive if it is in response to either a predicted change in catch composition or a need to improve the resilience of the ecosystem by reducing habitat or bycatch impacts (see section 5.1 on Protecting Key Habitats and Species). Even though there is limited discussion in the literature related to adjusting fishing practices as an adaptation for climate change, there is considerable literature available on how changes in fishing behavior (Abbott et al. 2015; Wallace et al. 2015) or changes in gear (Glass et al. 2000; Serafy et al. 2012; Lomeli and Wakefield 2013; Senko et al. 2014) can decrease habitat impacts, bycatch of sensitive stocks, or interactions with marine megafauna. However, there are trade-offs associated with switching behaviors or gears that need to be considered (Jenkins and Garrison, 2012). For example, positive impacts can include increased efficiency, decreased impacts on habitats and species, and increased sustainability of stocks (Jenkins and Garrison, 2012). Negative impacts can include the economic costs of buying new gear, as well as social impacts such as decreased safety, and changes to the social dynamics in associated fishing communities (Jenkins and Garrison, 2012). Compliance for using new fishing gears can be low (Lewinson et al., 2003; Orphanides and Palka 2013). Therefore, involving fishermen early in discussions and analyses of socio-economic and biological tradeoffs can improve the success of these initiatives (Jenkins and Garrison, 2012).

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[1] Munro et al. (2004) clarify that side payments do not have to be monetary (i.e., they can include trade concessions on products other than fish).

4.0 PROACTIVE MANAGEMENT: MANAGING TO INCREASE RESILIENCE OF INDIVIDUAL STOCKS OR SPECIES

Resilience is defined as the "capacity of an ecosystem [species, or industry] to absorb recurrent disturbances or shocks and adapt to change while retaining essentially the same function and structure" (McClanahan et al. 2012). Most discussions of resilience are at the scale of the ecosystem (Walker et al. 2004; McClanahan et al. 2012). However, the idea can be expanded to include resilience of a species, community, or industry to resist change as it occurs, and recover after a change has occurred.

4.1 Managing for Uncertainty- Scenario Planning

Given the uncertainties associated with climate change, managers can either work to reduce the uncertainty or they can embrace the uncertainty and adapt management options that will be robust to the given uncertainties (Basson 1999; Moore et al. 2013). Scenario planning is a methodology for identifying the uncertainties, articulating possible future scenarios, and determining options that will meet management goals across multiple possible futures (Moore et al. 2013). Scenario planning can range from low-tech options that articulate possible futures in a few sentences to promote brainstorming of adaptation options, to full implementation of management strategy evaluations that use sophisticated ecosystem models to analyze the success of different options in meeting specific management goals.

At a relatively simplistic level, written descriptions of possible scenarios can be used to describe how climate change could affect fisheries. A general guide for this type of scenario planning is available for marine resource managers (Moore et al. 2013). In four fisheries in Australia, stakeholders used short descriptions of possible futures to identify potential options for adaptation to climate change (Lim Camacho et al. 2014). Stakeholders then brainstormed possible adaptation options, including moving fisheries to more productive areas and improving the quality of their fishery products. Most adaptation options identified were described as being beneficial even in the absence of climate change (Lim Camacho et al. 2014).

Management strategy evaluation (MSE) is a more technical approach to answering the same questions. MSE is a general framework that uses simulation modeling to quantify how often management alternatives meet quantifiable management goals under specified uncertainties (Holland 2010). For example, Ianelli et al. (2011) simulated and tested multiple management alternatives for the Alaska pollock fishery given expected changes in sea surface temperature and a predicted functional relationship between sea surface temperature and recruitment. Results showed that the status quo management alternative resulted in lower catches and a higher risk of fishery closures than alternatives that allowed for adjustments in carrying capacity (Ianelli et al. 2011). The most sophisticated MSE analyses include potential socio-economic behavioral responses of the fishermen (Holland 2010). Punt et al. (2016) provides a good summary of MSEs completed to date and suggests best practices for completing future MSE analyses.

4.2 Managing to Promote Adaptive Capacity

Management decisions can have a direct impact on a population's ability to adapt as the climate changes (Munguia-Vega et al. 2015). Little is known about the adaptive capacity of marine fish and invertebrate populations, suggesting a priority for future research. There are three components to adaptive capacity: 1) ability to adjust to new conditions (i.e., plasticity in phenotypic response), 2) ability to relocate if or when conditions change (i.e., dispersal), and 3) ability to evolve strategies to survive in the new conditions (requires sufficient genetic diversity) (Beever et al. 2015). Management approaches are largely restricted to efforts that improve the genetic diversity of managed species, but management aimed at improving or assisting adult movement may also be useful.

Given the high rate of expected environmental change, genetic adaptation to climate change may be necessary, and management should aim to increase or preserve current genetic diversity. Recent investigations into the genetic diversity of abalone found that "management decisions are capable of increasing or decreasing genetic diversity over relatively short time scales" (Munguia-Vega et al. 2015, p 274). Since environmental stress can reduce genetic variation (Pauls et al. 2013; Munguia-Vega et al. 2015; Beever et al. 2015), an important management approach may be to decrease existing stressors (see above).

Another important management option is to protect populations with high genetic diversity or those that possess appropriate alleles (e.g., higher heat tolerance). For example, genetic diversity at the edges of a population may differ from the rest of the population. The rear edge often has high genetic diversity as it preserves historical alleles (Pauls et al. 2013). Conversely, even though the leading edge can contain lower diversity, it can also contain the alleles best adapted to the new conditions and are thus the "source for most of the surviving lineages and persisting alleles" (Pauls et al. 2013, p 927). Therefore, scientists have suggested that, as fish distributions advance or contract, it may be prudent to be cautious in our management of fish populations located at both edges of the species distribution (Brander 2010; Brown et al. 2011). Scientists suggest that decreasing fishing on these populations will help individuals with these advantageous adaptations survive and reproduce. In doing so the populations' ability to establish in new areas or remain viable in historical areas may be increased (Brander 2010; Pinsky and Fogarty 2012).

4.3 Protecting Age Structure and/or Old Females

Protecting or recovering the full age structure of a stock or population can increase that population's resilience to a changing environment. The importance of a full age structure (including the presence of large females) to a population is not new (Berkeley et al. 2004; Palumbi 2004; Planque et al. 2010); large females tend to have larger, healthier eggs and more of them, all of which contribute to the subsequent recruitment success of a population (Planque et al. 2010). However, newer research suggests that a full age structure is even more important for a population's persistence as it experiences environmental changes (Field and Francis 2002; Planque et al. 2010; Rouyer et al. 2011, 2012).

Environmental conditions have a stronger influence on recruitment variability in stocks with a truncated age structure. This is due to two main mechanisms. First, in many species, the older and larger fish spawn over a longer time period, depth gradient, and an extended area when compared to younger fish (Rouyer et al. 2011). Second, removal of larger, older fish can result in the loss of historical migration routes, concentrating the remaining individuals into fewer migration routes and spawning sites (Planque et al. 2010). Thus, the removal of large females can decrease the variety of conditions experienced by eggs and larvae, reducing the likelihood that some eggs and larvae encounter the necessary environmental conditions (Planque et al. 2010). While the theory and ecology behind the importance of age structure is clear, simulations that investigated the impact of population age structure on population health are less clear. Brunel and Piet (2013) found no relationship between age structure and population health, measured as deviation from the initial state when affected by a disturbance as well as recovery back to the initial state after the disturbance is over. Management options that may improve a population's age structure include: increased use of MPAs (see below), maximum size or slot limits, gear modifications (i.e., grates that stop large fish from entering nets), using gears that improve post-release survival, or closures during times and over areas when large individuals congregate.

4.4 Incorporating Environmental Parameters into Stock Assessments and Management Measures:

There is strong evidence to suggest that the productivity of many fish stocks is directly influenced by environmental variables (Vert-Pre et al. 2013; Szuwalski et al. 2014). For species whose productivity is known to be dependent upon environmental conditions, managers can integrate appropriate environmental parameters into stock assessments and/or management (Maunder and Watters 2003; Brander 2010; Plaganyi et al. 2011b; Punt et al. 2014; Pinsky and Mantua 2014; Wayte 2013). U.S. Pacific Sardine management directly incorporates temperature into management decisions. Recruitment of Pacific sardine is dependent on temperature (Lindergren and Checkley 2013); stock productivity is typically higher during warm water conditions (PFMC 2014). The management of Pacific sardine accounts for this temperature effect by using an environmentally dependent maximum sustainable yield parameter (E_{MSY}) and adjusting the catch quotas (harvest guidelines) depending on temperature (PFMC 2014). Adjusting harvest levels to match expected population size (based on temperature) should decrease the probability of large fluctuations in abundance (Lindergren and Checkley 2013). A good example of successfully incorporating an environmental parameter into a stock assessment is butterfish. Scientists have used water temperature to help predict pelagic habitat for butterfish along the U.S. east coast, which reduced uncertainty in the butterfish stock assessment and increased catch limits for this species (NEFSC 2014). For an overview of analytical methods for incorporating environmental variables into fisheries models, see Keyl and Wolff (2008).

However, multiple studies highlight challenges and indicate that there may be limited advantages for incorporating environmental parameters into stock assessments and management. Two separate simulation studies that link environmental parameters to recruitment found limited to no benefit to incorporating an environmental parameter into an assessment or management rule (De Oliveira and Butterworth 2005; Basson 1999). De Oliveira and Butterworth (2005) found the environmental index needs to explain at least 50 percent of the variance in recruitment before limited benefits of incorporating the index into the management process occur (e.g., a 2–4 percent increase in catch). Similarly, Basson (1999) found only minimal benefits (measured as increased yield or decreased probability of spawning stock biomass falling below a desired level) in even the best-case simulations (i.e., situations where the environmental factor can be well predicted and the interaction between the environmental factor and recruitment is strong). In situations with weaker relationships, adding the environmental parameter into management could actually decrease benefits (Basson 1999). Similarly, Punt et al. (2014) reviewed these simulation studies as well as current fisheries that incorporate the environment into assessments and found limited success: "…modifying management strategies to include environmental covariates did not improve the ability to achieve management goals over time scales relevant to short and medium term fisheries management decision making much, if at all. They did so only if information on environmental factors driving the system was well known" (Punt et al. 2014, pg 2217). Therefore, Punt et al. (2014), suggest that a better option is to consider all the broad, plausible climate forecasts to assess which management strategies are successful across multiple possible future conditions (see next section on scenario planning). However, as knowledge of relationships between managed fish stocks and environmental dynamics continues to improve, there will be more justification for incorporating environmental factors in stock assessment and management (Keyl and Wolff 2008). Also, as the ability to forecast environmental conditions on time scales that are most germane to fisheries management (e.g., seasonal to decadal) continues to improve, fishery managers will be more equipped to facilitate climate-ready fisheries management within existing management frameworks.

4.5 Decreasing Existing Stressors

One strategy for increasing resilience of stocks (and ecosystems) to climate change is decreasing existing stressors already impacting the stocks (Sumaila et al. 2011; Stein et al. 2013; Pinsky and Mantua 2014). Scientists theorize that species experiencing other stressors (cumulative impacts) are more likely to have faster and more acute reactions to climate change (Hsieh et al. 2008; Sumaila et al. 2011; Stein et al. 2013). Tingley et al. (2014) note that it is critical to consider climate change as well as other stressors when determining appropriate management responses. Stress on living marine resources can come from many sources, some of which are outside the direct control of fisheries managers (e.g. pollution, hypoxia). Some examples of existing stressors include: high fishing mortality, habitat degradation, invasive species, disease, pollution, and hypoxia. Location specific analyses can be completed to determine what stressors can be reduced, and to conduct trade-off analyses to determine if the effort to reduce stress is worth the resulting impact on the species (see section on Regional Planning).

Fishing mortality is one source of stress on stocks that is within the control of fisheries managers. Given that scientists are uncertain about how climate change will impact fish stocks, it has been suggested that managers be more precautionary in their decisions regarding catch limits. Increased precaution can include increasing the buffer around allowable catch limits to account for increased uncertainty (Johnson and Welch, 2010; Pinksy and Mantua 2014); however, not everyone supports this idea (Schindler and Hilborn 2015). Trade-offs between Economic, ecological and social impacts need to be considered (Johnson and Welch 2010).

4.6 Enhancing or Translocating Stocks

As climate change affects economically or ecologically important fish species, fisheries managers may want to consider more resource intensive options for sustaining these important species, including active enhancements and translocations of stocks (Koehn et al. 2011; Madin et al. 2012; Lorenzen et al. 2013; Tingley et al. 2014). To date, there are limited analyses of these options for marine systems.

Translocation, also called assisted migration, is: "the intentional translocation or movement of species outside of their historical ranges in order to mitigate actual or anticipated biodiversity losses caused by anthropogenic climate change" (Hewitt et al. 2011). Translocation was initially proposed for terrestrial species in 1985, but has only recently been identified as an option for marine species (e.g., Hoegh-Gulberg et al. 2008; Koehn et al. 2011; Madin et al. 2012). For example, in Tasmania, active translocation of rock lobster has been considered as a methodology for reducing the abundance of urchins that have recently expanded their range and are denuding important kelp habitats (Madin et al. 2012). Transloction is controversial because it creates complex scientific, policy, and ethical questions (Hewitt et al. 2011). There are concerns with unintended consequences, such as the spreading of disease, parasites, and invasive species (Hoegh-Gulberg et al. 2008; Tingley et al. 2014). Therefore, any translocations should be studied carefully to determine ecological and economic feasibility (Koehn et al. 2011). See Hoegh-Gulberg et al. (2008) for a decision tree that was developed to help managers determine when translocation might be beneficial.

Stock enhancement is defined as “a set of management approaches that involve the release of cultured organisms to enhance or restore fisheries” and can include sea ranching (release for direct re-capture), stock enhancement (continued release into wild stocks), or restocking (temporary releases aimed at building up wild stock) (Lorenzen et al. 2013). The use of stock enhancements as a response to climate change has not received much discussion, but Lorenzen et al. (2013) point out that traditional fisheries management measures may be insufficient to fully mitigate the broad changes coming. To date, there are only a few success stories associated with stock enhancements (e.g., salmon, oysters, and bay scallops), and stock enhancements tend to be controversial due to questions about system effects and genetic diversity. Improvements in the process continue. Lorenzen et al. (2010, 2013) have outlined a responsible approach to stock enhancement, and created modeling approaches that allow for appraisal of the costs/benefits of possible enhancement projects before implementation. Given the magnitude of expected climate change, stock enhancements of important species may increase in the future.

5.0 PROACTIVE MANAGEMENT: MANAGING TO INCREASE ECOSYSTEM RESILIENCE

Climate change is expected to increase the need to account for ecosystem interactions as productivity, distributions, species interactions, and habitats adjust to changing environmental conditions. Management that maintains ecosystem heterogeneity may better retain ecosystem functionality and improve the stability of the resources (Schindler and Hilborn 2015). As the climate changes, it may be unrealistic to preserve ecosystems in their historical state (Stein et al. 2014); instead, it may be more realistic to manage fisheries to maintain key ecological functions (Moore et al. 2013).

Scientists recommend moving toward Ecosystem Based Fisheries Management (EBFM) to increase the health and resilience of ecosystems, but a full discussion of EBFM is outside the scope of this paper. EBFM “is a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem ; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals” (NMFS 2016). Many of the management actions described in this article fall under the umbrella of EBFM (e.g., scenario planning, protecting age structure, protecting key habitats and species, designing appropriate marine reserves, and applying ecosystem models). Scientists and managers have the science and management tools to implement EBFM today (Link 2010; deReynier 2014; Patrick and Link 2015).

5.1 Protecting Key Habitats and Species

Because healthy marine ecosystems are more resilient to environmental changes, managers should consider regulations that protect key habitats and species. Gear modifications that reduce effects on habitats will result in a less stressed, more resilient ecosystem (Sumaila 2011). Where habitats have become degraded, active restoration or creation of new habitat may be a viable management option. Since climate change is expected to decrease important larval intertidal habitat by 20-70 percent over the next 100 years (Harley et al. 2006), adaptation efforts aimed at offsetting anticipated losses could be helpful (Gilman et al. 2008). Active wetland restoration programs not only address losses of key larval fish habitat, but they also provide a number of climate services, including carbon sequestration (M. Johnson, Habitat Conservation Division at NMFS Greater Atlantic Regional Fisheries Office, personal communication). Similarly, creating reserve zones behind current mangrove stands (Gilman et al. 2008) or rolling easements (Titus 2011) could allow larval habitats such as wetlands to migrate inland as sea level rises. In a more extreme example, van Oppen et al. (2015) suggest assisted evolution in habitat forming coral species may be necessary to help these vulnerable species adapt to climate change.

Focusing management on species fulfilling key ecological functions may be necessary for maintaining ecosystem function and resiliency as the environment changes (MacNeil et al. 2010; Staudinger 2013; Tingley et al. 2014). In the U.S. Caribbean, management has introduced regulations to reduce fishing pressure on important herbivores because of their functional importance at reducing the abundance of fleshy algae (Bellwood 2005; Nystrom 2006; Burkepile and Hay 2008; CFMC 2013). Key functional groups may differ between habitats and could include forage fish (Pikitch et al. 2014), keystone species (Paine 1995), predators (Bellwood 2005; Heithaus et al. 2008), or habitat-forming species such as corals and algae (Wilson et al. 2008). Improving our understanding about which species have important functional roles in an ecosystem and how these roles may change as the environment adjusts should be prioritized.

5.2 Applying Ecosystem Models to Better Understand Species' Responses

Modeling species and ecosystems will be an important component of managing fisheries in a changing climate. Ecosystem models are useful for improving our understanding of direct and indirect interactions between the environment, species and human beings (Plaganyi et al. 2011a, Link 2010). The "integrative power of models" allow scientists to review the health of entire ecosystems and determine if ecosystem overfishing is occurring (Link 2010). Once stock or ecosystem models exist, they can be integrated with management alternatives to test which alternatives best meet identified objectives of the fishery. In addition, models can help clarify interactions within the ecosystem and between the biological and human components of ecosystems, which are necessary when evaluating how management options will influence the resilience of natural resources (Plaganyi et al. 2011a). Hollowed et al. (2009) outline a framework that can be followed when modeling how fish species may respond to climate change, and Plaganyi et al. (2011a) provide a discussion about which ecosystem models are better suited for improving our understanding of the effects of climate change.

Even though models provide estimates of how stocks and ecosystems may change in the near future, limitations of the models also need to be considered. Sizable uncertainty exists in these models: uncertainty surrounding anthropogenic climate change scenarios is coupled with uncertainty in species responses to these changes (Plaganyi et al. 2011b, Schindler and Hilborn 2015). Models must balance competing goals of realism (number of underlying processes included in the model), precision ("exactness" of predictions), or generality (extrapolating to new conditions) (Dickey-Collas et al. 2014). If possible, creating and running multiple types of models is recommended, as this can provide competing perspectives and can increase confidence of the results if models agree in their general conclusions (Link 2010). Schindler and Hilborn (2015) argue that since we will never be able to accurately forecast the future, we should use models to capture uncertainty in our knowledge and determine what management will be robust across multiple plausible scenarios (see section on scenario planning). As computational power continues to grow, our ability to model complex systems will improve and the usefulness of these models should expand (Keyl and Wolff 2008; Link 2010).

5.3 Designing Appropriate Marine Reserves

Marine reserves (also called marine protected areas) are a tool that can help maintain ecosystem resilience in a changing climate (Bellwood et al. 2004; Micheli and Halpern 2005), but careful implementation is needed to ensure that the reserve will continue to be effective under changing conditions (Field and Francis 2002; Hobday 2011; Campbell 2013). In theory, protecting a subset of habitat and individuals from the effects of fishing or other human uses can increase the resiliency to climate effects of both the species being protected and the associated ecosystem (Bellwood et al. 2004). For example, reserves increase the abundance of older females, which in turn improve the age structure of a stock, and decrease the influence of environmental variability on stock abundance (Planque et al. 2010; Rouyer et al. 2011, 2012). In addition, because marine reserves protect multiple trophic levels, they can help retain the functional diversity of an area (Micheli and Halpern 2005), improving its ability to maintain basic ecosystem functions through a changing environment (Belwood et al. 2005). Marine reserves also provide locations to observe and study how ecosystems react to climate change without the added stress of fishing.

Managers should consider climate change effects on species and habitats when designing new reserves or assessing the effectiveness of established reserves, because the effectiveness of a reserve may change as habitats, ranges, and productivities shift (Field and Francis 2002; Tingley et al. 2014). There are three options for creating marine reserves that are effective even in the face of a changing climate. 1) Managers can locate reserves to include the habitat or species we currently want to protect in addition to the areas where we expect habitats or species to move (Hobday 2011). 2) Managers can periodically reexamine and modify closures to ensure they remain centered on core areas of stock distribution (Campbell 2013) and are maintaining their goals. 3) Managers can create reserves to be dynamic, where boundaries are tied to current environmental conditions (Hobday et al. 2010; Campbell 2013; Pinsky and Mantua 2014; e.g. dynamic ocean management discussed in the previous section on "flexible and nimble management systems").

6.0 PROACTIVE MANAGEMENT: MANAGING TO INCREASE RESILIENCE OF FISHING BUSINESSES

The idea of resilience can be expanded to include not only the fish species, but also the resilience of the fishery and fishing businesses (Pinsky and Mantua 2014). As fish stocks adjust their distributions and abundances, fishing effort may also have to adjust by changing the species targeted and the locations and times fished, as well as landing or processing locations (Haynie and Pfeiffer 2013). Communities that are reliant on more than one fishery, or that have alternative livelihood options will be better able to adjust as climate change impacts the marine resources (Jepson and Colburn 2013; Mathis et al. 2015; Barange et al. 2014). Similarly, overcapitalized fisheries operating with a thin profit margin will be limited in its ability to experiment with new practices or to remain viable as the environment changes. Management can be updated to improve the resilience of the fishermen and communities dependent on fishing; however, many relevant factors, such as dependence on the fishery and availability of alternative livelihoods, may be outside the control of fishery management (MAFMC 2014).

6.1 Expanding Flexibility in Fisheries Permitting

To adapt to a changing climate, fishermen will need the flexibility to adjust where, when, and what they catch (as well as the associated permits) depending on conditions (Miller and Munro 2004; MacNeil et al. 2010; Mills et al. 2013; Campbell 2013; Schindler and Hilborn 2015). In the past, fishermen have been able to adjust their fishing targets to match species with high abundances. For example, when crab fishing was not profitable, they switched to groundfish (Campbell 2013). In contrast, cod fishermen in Canada lost their livelihoods when the cod fishery collapsed. The removal of the cod allowed shellfish and shrimp to increase in abundance, but the regulations in place made switching fisheries difficult. Therefore the fishermen who benefitted from the increases in shrimp and shellfish were different than the fishermen put out of work by the loss of cod (Schindler and Hilborn, 2015). Fishermen need the ability to diversify their target stocks as changes in the climate, ecosystem, and fishery occur. Systems locking fishermen into specific species, locations or gears may reduce fishing flexibility (Grafton 2010, Schindler and Hilborn 2015), and options for amending or switching permits should be considered (Mills et al. 2013). For example, policies may need to be created that facilitate access to loans for operators who want to diversify by purchasing quota in other fisheries (Kasperski and Holland 2013) or by expanding their business to include aquaculture. In addition, including flexibility as a management goal in government policies and regulations may need to be considered (Badjeck 2010).

Recent regulations aimed at reducing the high competition associated with short fishing seasons (sometimes called the race to fish) have moved from open access fisheries (where anyone can fish) to limited access fisheries (a limited number of fishermen are allowed access) to rights-based management (a limited number of fishermen have access to an individual- or group-specific amount of the allowable catch). Some experts suggest that changing to rights-based management could increase the adaptability of fishermen (Grafton 2010; Sumaila et al. 2011), while others argue the opposite (Campbell 2013), highlighting the extreme opinions often associated with rights-based management programs. Differences in interpretation may depend on the design elements of the programs. Examples that limit flexibility include requirements to land fish in specific areas or for specific processors, high entrance costs into a fishery, and single-species permits. Alternatively, rights-based management provides fishermen incentives to experiment with alternative fishing methods that decrease the bycatch of overfished stocks (Kaplan et al. 2010; Holland and Jannot 2012) as catch composition shifts over time. Even though rights-based management can decrease the diversification of fishermen, it also provides the opportunity for fishermen to build a portfolio of harvest privileges that can reduce their income risk (Kasperski and Holland 2013).

Similarly, management that encourages ownership of quota (the right to catch a given percent of the allowable catch) within fishing communities could improve the resilience of fishermen and communities. Anchoring quota for many species within communities rather than individual businesses should create a robust system better able to adapt to environmental change (Schindler and Hilborn 2015). Permit banks, risk pools, and community quota entities have been implemented within the United States to anchor quota within communities (Stoll and Holliday 2014).

6.2 Providing Insurance for Fishermen to Cover Years with Poor Catch

Extending insurance to fishermen to cover years with low catch could increase financial stability for fishermen. Similar to crop insurance for farmers, an insurance program for fishermen run by the Federal Government has been discussed (Hermann et al. 2004; Mumford et al. 2009). Theoretically, fishing insurance could simultaneously improve managers' ability to meet a goal of sustainability as well as improve the fishing industry's goal of income security (Mumford et al. 2009). In brief, fishing insurance provides a program where fishermen pay an annual insurance premium that guarantees them some proportional payout if catch rates are low. The insurance program could provide more stability to fishermen because income would be less variable when poor years are supplemented with insurance payouts. Positive benefits to this stability include decreasing the incentives for fishermen to keep fishing when biomass is at low levels, as well as improved fishing practices if eligibility for insurance were tied to sustainable fishing practices (Mumford et al. 2009). Cons of fishing insurance include the possibility of fishermen reducing effort and "gaming" the system, and a decreased incentive to test new fishing practices that decrease catch on limiting species (Mumford et al. 2009).

Even if official forms of catch insurance are not available, fishermen who participate in rights-based fisheries have the option of creating their own catch insurance by joining together to create catch pools. Fishermen who participate in catch pools do so by pooling catch quotas and then pulling from the pool to cover quota needs. Catch pools can be organized to include all catch (Sethi et al. 2012), or just bycatch species that can limit a fisherman's ability to catch target species (Holland and Jannot 2012). Holland and Jannot (2012) outline general conditions that are amenable to bycatch pools, such as: bycatch species are rare and have a high variance, bycatch risk is uncorrelated with expected profits, bycatch risk is homogeneous across vessels, vessels have a low number of fishing events, and real-time information sharing is available. West Coast trawl businesses have successfully formed bycatch pools to help each other deal with bycatch in the West Coast Trawl Rationalization Program (Holland and Jannot 2012).

6.3 Improving Flexibility in the Supply Chain

Changes to the composition, magnitude, and timing of landings could be complicated if the shore-side processing and supply chain is not adaptable. For example, a 2012 heat wave in the Gulf of Maine led to an increase in American lobster landings, and the processing facilities and markets were unable to respond appropriately (Mills et al. 2013). Due to the lack of flexibility in the supply chain, fishermen experienced an unexpected decrease in the price they received for their catch, which resulted in severe economic hardships and the need to immediately reduce fishing effort and landings (Mills et al. 2013). Identifying key elements along a supply chain could help identify adaptation strategies that would improve the resilience of the markets to changes in supply or demand (Plaganyi et al 2014).

7.0 UNDERLYING PRACTICES THAT IMPROVE MANAGEMENT IN A CHANGING CLIMATE

In reviewing the literature on preparing fisheries for climate change, a few key practices are discussed as being imperative for climate-ready fisheries management: clarifying and updating management goals, monitoring the environment to detect changes, and creating regional management plans to address localized issues.

7.1 Updating and Clarifying Management Goals

Climate change will affect fisheries; therefore, management decisions need to be made with a clear understanding of the goals and priorities associated with the fishery and ecosystem. Often, goals and objectives for a fishery are articulated when the management of that fishery begins and are not re-assessed as the fishery matures. To prioritize adaptation options, management goals should be current, clear, measurable and forward-looking (Grafton 2009, Stein et al. 2013).

Fisheries goals can vary between biological goals, such as conserving the resource for future generations, to economic goals, such as maximizing catch or reducing negative effects on communities (Punt 2006). Attainment of multiple fisheries goals can be contradictory if achieving one goal affects the ability to achieve another one. When these trade-offs occur, clear articulation of current goals and priorities could aid in determining the best way forward. For example, complex ethical decisions—such as whether to concentrate on maintaining historic ecosystems or on protecting the new ecosystems that emerge (Madin et al. 2012)—may be easier if priorities are clearly articulated.

7.2 Monitoring for Climate Change

Monitoring will be an important component of many strategies related to managing fisheries in a changing climate (Madin et al. 2012; Plaganyi et al. 2013; Frusher et al. 2014). Monitoring is the collection of biotic, abiotic, and human social information to answer management questions (Levin 2013). "Accurate assessment of resource states and ecosystem services must be given high priority" (Schindler and Hilborn 2015, p 954). Plaganyi et al. (2013) compared management options across eight species of sea cucumbers and found that strategies that included monitoring resulted in decreased risk and increased profit compared to strategies without monitoring. Current monitoring programs could benefit from a re-evaluation of their design and scope in light of climate change (e.g., Bates et al. 2014).

Newer technologies could be considered when planning monitoring programs. For example, cell phones allow stakeholders to provide real-time catch or sightings information (e.g. http://www.redmap.org.au/), and satellite remote sensing results (e.g., chlorophyll density and sea surface temperature) can be used to estimate area-specific phytoplankton productivity and predict the fish distribution and abundance (Chassot et al. 2011). Development of new indicators—such as duration of spring blooms and the size composition of phytoplankton—could provide even better information relevant to predicting climate effects on fishing resources (Chassot et al. 2011).

Processes for identifying (Kershner et al. 2011) and selecting (Boldt et al. 2014) appropriate indicators are available. Recent research suggests that certain biological parameters could provide predictions about which stocks are experiencing a change in productivity due to changes in climate, habitat, or community interactions. For example, declines in mean weight at age often preclude stock collapse by several years, suggesting that monitoring age and length of an indicator species could predict future changes in stock abundance (Brander 2010). Another paper found that spatial variability in catches increased prior to stock collapse (Litzow et al. 2013); however, the authors caution that more studies are necessary to determine whether this indicator would be useful to management.

7.3 Using Regional Planning to Address Local Needs

Climate effects will vary significantly from one region to the next, so it will be important to develop regional management responses. For example, although ocean acidification is increasing globally there are also local contributors to coastal waters where acidification effects may disproportionately affect certain coastal communities (Kelly et al. 2011; Ekstrom et al. 2015). Incentives for implementing local storm water runoff protections or generally decreasing local stressors can be more successful than incentives for improving the global environment (e.g., reducing local pollution as opposed to reducing global greenhouse gas emissions) (Scheffer et al. 2015). Developing regional planning bodies or using existing regional frameworks might be helpful in developing a management response to the many effects on the marine environment from land-based sources. For example, a 2013 Washington State law established the Washington Marine Resources Advisory Council—composed of representatives from academia, government, nongovernmental organizations, tribes, and the private sector—that will implement local actions to combat ocean acidification that were identified during a 2012 Washington State Blue Ribbon Panel on Ocean Acidification (WSBRP 2012). Similarly, some of the adaptation options discussed by Pecl et al. (2009) for the Australian rock lobster fishery are local responses to possible changes. Options discussed include: reducing catch in areas where rock lobster prey (urchins) are expected to have a large negative effect; reducing high-cost input controls (such as trap limits and seasonal closures); and improving the quality of catch as quantity of catch decreases.

8.0 CONCLUSIONS

Climate change will continue to affect the abundance and distribution of fisheries resources. Because fisheries management occurs in an uncertain and changing environment, the foundation already exists for management to adjust as the climate changes.

The list of management alternatives provided here is not comprehensive, and there is no one "right" answer. Suitable approaches will differ depending on local conditions such as life history traits of the species being managed, the type of management being implemented, the fishing community, and the resources available for monitoring and modeling. In general, management actions that seek to increase management flexibility and provide incentives to the fishing industry to try new approaches while preserving genetic diversity of the fished populations should prove to be beneficial. Managers should consider the pros and cons of different alternatives when determining the appropriate mix of options for their situation, including estimates of the risks associated with each action (including inaction), where risk includes the probability as well as the consequence. Other questions that should be considered include: what are the associated costs and benefits, which options would be more acceptable to fishermen, which options require an update to federal mandates and which are feasible under current laws. Managers should involve constituents and discuss what mix of existing and new management options would be most appropriate for their fisheries.

This document is intended to assist managers facing this issue and to spur brainstorming about various management approaches and options. New research, ideas, and options should emerge as management across the globe grapples with this issue and determines what works and what does not work in each region.

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REFERENCES

Abbott, J. K, A. C. Haynie, and M. N. Reimer. 2015. Hidden flexibility: Institutions, incentives, and the margins of selectivity in fishing. Land Economics 91:169-195.

Arnason, R. 2012. Global warming: New challenges for the common fisheries policy? Ocean and Coastal Management 70:4-9.

Badjeck, M., E. A. Allison, A. S. Halls, and N. K. Dulvey. 2010. Impacts of climate variability and change on fishery-based livelihoods. Marine Policy 34:375-383.

Bailey, M., G. Ishimura, R. Paisley, and U. R. Sumaila. 2013. Moving beyond catch in allocation approaches for internationally shared fish stocks. Marine Policy 40: 124-136.

Barange, M., G. Merino, J. L. Blanchard, J. Scholtens, J. Harle, E. H. Allison, J. I. Allen, J. Holt, and S. Jennings. 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change 4:211-216.

Basson, M. 1999. The importance of environmental factors in the design of management procedures. ICES Journal of Marine Science 56:933–942.

Bates, A. E., G. T. Pecl, S. Frusher, A. J. Hobday, T. Wernberg, D. A. Smale, J. M. Sunday, N. A. Hill, N. K. Dulvy, R. K. Colwell, N. J. Holbrook, E. A. Fulton, D. Slawinski, M. Feng, G. J. Edgar, B. T. Radford, P. A. Thompson, and R. A. Watson. 2014. Defining and observing stages of climate-mediated range shifts in marine systems. Global Environmental Change 26:27-38.

Baumgartner, T. R., A. Soutar, and V. Ferreira-Bartrina. 1992. Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. CalCOFI Reports 33:24-40.

Beever, E. A., J. O'Learly, C. Mengelt, J. M. West, S. Julius, N. Green, D. Magness, L. Petes, B. Stein, A. B. Nicotra, J. J. Hellmann, A. L. Robertson, M. D. Staudinger, A. A. Rosenberg, E. Babijj, J. Brennan, G. W. Schuurman, and G. E. Hofmann. 2015. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conservation Letters: http://dx.doi.org/10.1111/conl.12190.

Bell, J. D., A. Ganachaud, P. C. Gehrke, S. P. Griffiths, A. J. Hobday, O. Hoegh-Guldberg, J. E. Johnson, R. L. Borgne, P. Lehodey, J. M. Lough, R. J. Matear, T. D. Pickering, M. S. Pratchett, A. S. Gupta, I. Senina, and M. Waycott. 2013. Mixed response of tropical Pacific fisheries and aquaculture to climate change. Nature Climate Change 3:591-599.

Bell, R. J., J. A. Hare, J. P., Manderson, and D. E. Richardson. 2014. Externally driven changes in the abundance of summer and winter flounder. ICES Journal of Marine Science 71:2416–2428.

Bellwood, D. R., T. P. Hughes, C. Folke, and M. Nystrom. 2004. Confronting the coral reef crisis. Nature 429:827-833.

Bellwood, D. R., A. S. Hoey, and J. H. Choat. 2003. Limited functional redundancy in high diversity systems: resilience and ecosystem function on coral reefs. Ecology Letters 6:281-285.

Berkeley, S. A., Chapman, C., and S. M. Sogard. 2004. Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes Melanops*. Ecology 85:1258-1264.

Boldt, J.L., R. Martone, J. Samhouri, R.I. Perry, S. Itoh, I.K. Chung, M. Takahashi, and N. Yoshie. 2014. Developing ecosystem indicators for responses to multiple stressors. *Oceanography* 27:116–133.

Brander, K. 2010. Impacts of climate change on fisheries. Journal of Marine Systems 79:389-402.

BREP (Bycatch Reduction Engineering Program). 2013. 2013 Bycatch Reduction Engineering Program Grant Awards By Region. Available: www.nmfs.noaa.gov/by_catch/docs/2013_brep_awards_abstracts_final1.pdf. (October 2015).

Brown, C. J., E. A. Fulton, H. P. Possingham, and A. J. Richardson. 2012. How long can fisheries management delay action in response to ecosystem and climate change? Ecological Applications 22:298-310.

Brown, C. J., D. S. Schoeman, W. J. Sydeman, K. Brander, L. B. Buckley, M. Burrows, C. M. Duarte, P. J. Moore, J. M. Pandolfi, E. Poloczanska, W. Venables, and A. J. Richardson. 2011. Quantitative approaches in climate change ecology. Global Change Biology 17:3697-3713.

Brunel, T. and G. J. Piet. 2013. Is age structure a relevant criterion for the health of fish stocks? ICES Journal of Marine Science 70:270-283.

Burkepile, D.E., and M. E. Hay. 2008. Herbivore species richness and feeding complementarity affect community structure and function on a coral reef. Proceedings of the National Academy of Sciences 105:16201-16206.

Campbell, C. 2013. Implications of changing ecosystems for fisheries managers. Pages 160-167 *in* Managing our Nations Fisheries 3: Advancing Sustainability. Proceedings of a Conference on Fisheries Management in the United States. Portland Oregon. Available: http://www.managingfisheries.org/2013_documents/Proceedings_session2.pdf. (October 2015).

CFMC (Caribbean Fisheries Management Council). 2011. Comprehensive Annual Catch Limit Amendment for the U.S. Caribbean. Available:http://sero.nmfs.noaa.gov/sustainable_fisheries/caribbean/2011_acl/documents/pdfs/2011_caribb_acl_amend_feis.pdf. (October 2015).

CFMC (Caribbean Fisheries Management Council). 2013. Regulatory Amendment four to the Fishery Management Plan for the Reef Fish Fishery of Puerto Rico and the U.S. Virgin Islands. Available: http://www.gpo.gov/fdsys/pkg/FR-2013-03-11/pdf/2013-05538.pdf. (October 2015).

Chassot, E., S. Bonhommeau, G. Reygondeau, K. Nieto, J. J. Polovina, M. Huret, N. K. Dulvy, and H. Demercq. 2011. Satellite remote sensing for an ecosystem approach to fisheries management. ICES Journal of Marine Science 68:651-666.

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

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S. 2013. Sea Level Change. Pages 1137-1216 *in* T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Cooley, S. R., and Doney, S. C. 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters 4:024007.

Daw, T., W. N. Adger, K. Brown, and M. Badjeck. 2009. Climate change and capture fisheries: potential impacts, adaptation and mitigation. Pages 107-150 *in* K. Cochrane, C. De Young, D. Soto and T. Bahri, editors. Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. *FAO Fisheries and Aquaculture Technical Paper.* No. 530. Rome, Italy.

De Oliveira, J. A. A. and D. S. Butterworth. 2005. Limits to the use of environmental indices to reduce risk and/or increase yield in the South African anchovy fishery. African Journal of Marine Science 27:191-203.

deReynier, Y. 2014. U.S. Fishery Management Councils as Ecosystem-Based Management Policy Takers and Policymakers. Coastal Management 42:512-530.

Dickey-Collas, M., M. R. Payne, B. M. Trenkel, and R. D. M. Nash. 2014. Hazard warning: model misuse ahead. ICES Journal of Marine Science 71:2300-2306.

Dunn, S., L. Rodwell, and G. Joseph. 2006. The Palau arrangement for the management of the western Pacific purse seine fishery – managmenet scheme (vessel day scheme). Sharing the Fish Conference, Perth Australia. Available: http://www.fishallocation.com/papers/pdf/papers/GlenJoseph.pdf. (October 2015).

Ekstrom, J. A., L. Suatoni, S. R. Cooley, L. H. Pendleton, G. C. Waldbusser, J. E. Cinner, J. Ritter, C. Langdon, R. van Hooidonk, D. Gledhill, K. Wellman, M. W. Beck, L. M. Brander, D. Rittschof, C. Doherty, P. E. T. Edwards, and R. Portela. 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. Nature Climate Change 5:207-214.

Field, J. C., and R. C. Francis. 2002. Cooperating with the Environment: Case studies of climate and fisheries in the Northern California current. Pages 245-260 *in* N. A. McGinn, editor. Fisheries in a changing climate. American Fisheries Society Symposium 32, Bethesda, Maryland.

Fogarty, M., L. Incze, K. Hayhoe, D. Mountain, and J. Manning. 2008. Potential climate change impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. Mitigation and Adaptation Strategies for Global Change 13:453-466.

Frusher, S. D., A. J. Hobday, S. M. Jennings, C. Creighton, D. D'Silva, M. Haward, N. J. Holbrook, M. Nursey-Bray, G. T. Pecl, and E. I. vanPutten. 2014. The short history of research in a marine climate change hotspot: from anecdote to adaptation in south-east Australia. Reviews in Fish Biology and Fisheries 24:593-611.

Fussel, H. M. 2007. Adaptation planning for climate change: concepts, assessment approaches and Key lessons. Sustainability Science 2:265-275.

Gilman, E. L., J. Ellison, N. C. Duke, and C. Field. 2008. Threats to mangroves from climate change and adaptation options. A review. Aquatic Botany 89:237-250.

Glass, C.W. 2000. Conservation of fish stocks through bycatch reduction: a review. Northeastern Naturalist 7:395-410.

Grafton, R.Q. 2010. Adaptation to climate change in marine capture fisheries. Marine Policy 34:606-615.

GMRI (Gulf of Maine Research Institute). 2016. Gulf of Maine Lobster Forecasting. Available: http://www.gmri.org/our-work/research/projects/gulf-maine-lobster-forecasting (February 2016).

Hare, J. A., M. A. Alexander, M. J. Fogarty, E. H. Williams, and J. D. Scott. 2010. Forecasting the dynamics of a coastal fishery species using a coupled climate-population model. Ecological Applications, 20:452–464.

Harley, C. D. G., A. R. Hughes, K. M. Hultgren, B. G. Miner, C. J. B. Sorte, C. S. Thornber, L. F. Rodriguez, L. Tomanek, and S. L. Williams. 2006. The impacts of climate change in coastal marine systems. Ecology Letters 9:228-241.

Haynie, A. C., and L. Pfiefer. 2013. Why economics matters for understanding the effects of climate change on fisheries. ICES Journal of Marine Science 70:1023-1037.

Heithaus, M. R., A. Frid, A. J. Wirsing, and B. Worm. 2008. Predicting ecological consequences of marine top predator declines. Trends in Ecology and Evolution 23:202-210.

Herrmann, M., J. Greenberg, C. Hamel, H. Geier. 2004. Extending federal crop insurance programs to commercial fisheries: the case of Bristol Bay, Alaska, sockeye salmon. North American Journal of Fisheries Management 24:352-366.

Hewitt, N., N. Klenk, A. L. Smith, D. R. Bazely, N. Yan, S. Wood, J. I. Maclellan, C. Lipsig-Mumme, I. Henriques. 2011. Taking stock of the assisted migration debate. Biological Conservation 144:2560-2572.

Hobday, A. J., J. R. Hartog, T. Timmiss, and J. Fielding. 2010. Dynamic spatial zoning to manage southern Bluefin tuna (*Thunnus maccoyii*) capture in a multi-species longline fishery. Fisheries Oceanography 19:243-253.

Hobday, A. J. 2011. Sliding baselines and shuffling species: implications of climate change for marine conservation. Marine Ecology 32:392-403.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D. B. Lindenmayer, C. Parmesan, H. P. Possingham, and C. D. Thomas. 2008. Assisted colonization and rapid climate change. Science 321:345-346.

Hoegh-Guldberg, O., and J. F. Bruno. 2010. The impact of climate change on the world's marine ecosystems. Science 328:1523-1528.

Holland, D. S. 2010. Management Strategy Evaluation and Management Procedures: Tools for Rebuilding and Sustaining Fisheries. OECD Food, Agriculture and Fisheries Working Papers, No. 25. OECD Publishing. Available: http://www.oecd.org/greengrowth/fisheries/45497984.pdf . (October 2015).

Holland, D. S., and J. E. Jannot. 2012. Bycatch risk pools for the U.S. West Coast Groundfish Fishery. Ecological Economics 78:132-147.

Hollowed, A. B., N. A. Bond, T. K. Wilderbuer, W. T. Stockhausen, Z. T. A'mar, R. J. Beamish, J. E. Overland, and M. J. Schirripa. 2009. A framework for modelling fish and shellfish responses to future climate change. ICES Journal of Marine Science 66:1584-1594.

Hollowed, A. B., S. J. Barbeaux, E. D. Cokelot, E. Farley, S. Kotwicki, P. H. Ressler, C. Spital, and C. D. Wilson. 2012. Effects of climate variations on pelagic ocean habitats and their role in structuring forage fish distributions in the Bering Sea. Deep-Sea Research II 675-70:230-250.

Hsieh, C., C. S. Reiss, R. P. Hewitt, and G. Sugihara. 2008. Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. Canadian Journal of Fisheries and Aquatic Sciences 65:947-961.

Ianelli, J. N., Hollowed, A. B., Haynie, A. C., Mueter, F. J., and Bond, N. A. 2011. Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. ICES Journal of Marine Science 68:1297–1304.

Jackson, J., M. Kirby, W. Berger, and K. Bjorndal. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science, 293:629-637.

Jensen, F., H. Frost, T. Thogersen, P. Andersen, and J. L. Anderson. 2015. Game theory and fish wars: The case of the Northeast Atlantic Mackerel Fishery. Fisheries Research 172:7-16.

Jenkins, L. D., and K. Garrison. 2013. Fishing gear substitutions to reduce bycatch and habitat impacts: An example of social-ecological research to inform policy. Marine Policy 38:293-303.

Jepson, M., and L. L. Colburn 2013. Development of Social Indicators of Fishing Community Vulnerability and Resilience in the U.S. Southeast and Northeast Regions. U.S. Department of Commerce, NOAA Tech. Memo NMFS-F/SPO-129. Available: http://spo.nmfs.noaa.gov/tm/. (October 2015).

Johnson, J. E., and D. J. Welch. 2010. Marine fisheries management in a changing climate: A review of vulnerability and future options. Reviews in Fisheries Science 18: 106-124.

Julius, S. H., J. M. West, D. Nover, R. Hauser, D. S. Schimel, A. C. Janetos, M. K. Walsh, and P. Backlund. 2013. Climate change and U.S. Natural Resources: Advancing the Nation's Capability to Adapt. Issues in Ecology 18:1-16. Available: http://www.esa.org/esa/wp-content/uploads/2013/12/Issue18.pdf. (October 2015).

Kasperski, S. and D. S. Holland. 2013. Income diversification and risk for fishermen. Proceedings of the National Academy of Sciences 110:2076-2081.

Kaplan, I. C., P. S. Levin, M. Burden, and E. A. Fulton. 2010. Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. Canadian Journal of Fisheries and Aquatic Sciences 67:1968-1982.

Kelly, R. P., M. M. Foley, W. S. Fischer, R. A. Feely, B. S. Halpern, G. G. Waldbusser, and M. R. Caldwell. 2011. Mitigating local causes of ocean acidification with existing laws. *Science* 332:1036-1037.

Klaer, N. L., R. N. O'Boyle, J. J. Deroba, S. E. Wayte, L. R. Little, L. A. Alade, and P. J. Rago. 2015. How much evidence is required for acceptance of productivity regime shifts in fish stock assessments: Are we letting managers off the hook? Fisheries Research 168:49-55.

Koehn, J. D., A. J. Hobday, M. S. Prtchett, and B. M. Gillanders. 2011. Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. Marine and Freshwater Research 62:1148-1164.

Kershner, J., J. F. Samhouri, C. A. James, P. S. Levin. 2011. Selecting indicator portfolios for marine species and food webs: a Pugent Sound case study. PLoSONE 6:e25248.

Keyl, F. and M. Wolff. 2008. Environmental variability and fisheries: what can models do? Reviews in Fish Biology and Fisheries 18:273-299.

Levin, P. S. 2013. Assessment and maintenance of ecosystem health in the face of a changing climate. Pages 168-174 *in* Managing our Nations Fisheries 3: Advancing Sustainability. Proceedings of a Conference on Fisheries Management in the United States. Portland Oregon. Available: http://www.managingfisheries.org/2013_documents/Proceedings_session2.pdf. (October 2015).

Lewison, R. L. , L.B. Crowder, and D. J. Shaver. 2003. The impact of turtle excluder devices and fisheries closures on loggerhead and Kemp's Ridley strandings in the Western Gulf of Mexico. Conservation Biology 17:1089-1097.

Lewison, R. , A. J. Hobday, S. Maxwell, E. Hazen, J. R. Hartog, D. C. Dunn, D. Briscoe, S. Fossette, C. E. O'Keefe, M. Barnes, M. Abecassis, S. Bograd, N.D. Bethoney, H. Bailey, D. Wiley, S. Andrews, L. Hazen, and L.B. Crowder. In Press. Dynamic ocean management: identifying the critical ingredients of dynamic approaches to ocean resource management. Bio Science.

Lim-Camacho, L., A. J. Hobday, R. H. Bustamante, A. Farmery, A. Fleming, S. Frusher, B. S. Green, A. Norman-Lopez, G. T. Pecl, E. E. Plaganyi, P. Schrobback, O. Thebaud, L. Thomas, and I. van PUtten. 2014. Facing the wave of change: stakeholder perspectives on climate adaptation for Australian seafood supply chains. Regional Environmental Change 15:595-606.

Lindergren, M. and D. M. Checkley, Jr. 2013. Temperature dependence of Pacific sardine (*Sardinops sagax*) recruitment in the California Current Ecosystem revisited and revised. Canadian Journal of Fisheries and Aquatic Sciences 70:245-252.

Lindholm, J., M. Gleason, D. Kline, L. Clary, S. Rienecke, A. Cramer, M. LosHuertos. 2015. Ecological effects of bottom trawling on the structural attributes of fish habitat in unconsolidated sediments along the central California outer continental shelf. Fishery Bulletin 113:82-96.

Link, J. S. 2010. Ecosystem-Based Fisheries Management: Confronting Tradeoffs. Cambridge University Press, Cambridge, UK.

Link, J. S., J. A. Nye, and J. A. Hare. 2011. Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish and Fisheries 12: 461-469.

Link, J. S., R. Griffis, and S. Busch (Editors). 2015. NOAA Fisheries Climate Science Strategy. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-F/SPO-155, 70p. Available:

https://www.st.nmfs.noaa.gov/Assets/ecosystems/climate/documents/NCSS_Final.pdf. (Febrary 2016).

Litzow, M. A. F. J. Mueter, and J. D. Urban. 2013. Rising catch variability preceded historical fisheries collapses in Alaska. Ecological Applications 23:1475-1487.

Lomeli, M. J. M., and W. W. Wakefield. 2013. A flexible sorting grid to reduce Pacific halibut (*Hippoglossus stenolepis*) bycatch in the U.S. west coast groundfish bottom trawl fishery. Fisheries Research 143:102-108.

Lorenzen, K., K. M. Leber, and H. L. Blankenship. 2010. Responsible approach to marine stock enhancement: an update. Reviews in Fisheries Science 18:189-210.

Lorenzen, K., A. Agnalt, H. L. Blankenship, A. H. Hines, K. M. Leber, N. R. Longeragan, M. D. Taylor. 2013. Evolving context and maturing science: aquaculture-based enhancement and restoration enter the marine fisheries management toolbox. Reviews in Fisheries Science 21:213-221.

Lynch, P. D., J. A. Nye, J. A. Hare, C. A. Stock, M. A. Alexander, J. D. Scott, K. L. Curti, and K. Drew. 2015. Projected ocean warming creates a conservation challenge for river herring populations. ICES Journal of Marine Science 72:374-387. doi:10.1093/icesjms/fsul134.

MacNeil, M. A., N. A. J. Graham, J. E. Cinner, N. K. Dulvy, P. A. Loring, S. Jennings, N. V. C. Polunin, A. T. Fisk, and T. R. McClanahan. 2010. Transitional states in marine fisheries: adapting to predicted global change. Philosophical Transactions of the Royal Society B 365:3753-3763.

Madin, E., M. P., N. C. Ban, Z. A. Doubleday, T. H. Holmes, G. T. Pecl, and F. Smith. 2012. Soci-economic and management implications of range-shifting species in marine systems. Global Environmental Change 22:137-146.

MAFMC (Mid Atlantic Fisheries Management Council). 2014. East coast climate change and fisheries governance workshop. March 19-21, Washington D.C. Available: http://www.mafmc.org/council-events/2014/east-coast-climate-change-and-fisheries-governance-workshop. (October 2015).

Mathis, J. T., S. R. Cooley, N. Lucey, S. colt, J. Ekstrom, T. Hurst, C. Hauri, W. Evans, J. N. Cross, R. A Feely. 2015. Ocean acidification risk assessment for Alaska's fishery sector. Progress in Oceanography 136:71-91.

Maunder, M. N. and G. M. Watters. 2003. A general framework for integrating environmental time series into stock assessment models: model description, simulation testing, and example. Fisheries bulletin 101:89-99.

McClanahan, T. R., S. D. Donner, J. A. Maynard, M. A. MacNeil, N. A. J. Graham, J. Maina, A. C. Baker, J. B. Alemu, M. Beger, S. J. Campbell, E. S. Darling, C. M. Eakin, S. F. Heron, S. D. Jupiter, C. J. Lundquist, E. McLeod, P. J. Mumby, M. J. Paddack, E. R. Selig, and R. van Woesik. 2012. Prioritizing key resilience indicators to support coral reef management in a changing climate. PlosOne 7:e42884.

Micheli, F. and B. S. Halpern. 2005. Low functional redundancy in coastal marine assemblages. Ecology Letters 8:391-400.

Miller, K. A., and G. R. Munro. 2004. Climate and Cooperation: A new perspective on the management of shared fish stocks. Marine Resource Economics 19:367-393.

Mills, K. E., A. J. Pershing, C. J. Brown, Y. Chen, F. S. Chiang, D. S. Holland, S. Lehuta, J. A. Nye, J. C. Sun, A. C. Thomas, and R. A. Wahle. 2013. Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic. Oceanography 26:60-64.

Mooney, H., A. Larigauderie, M. Cesario, T. Elmquist, O. Hoegh-Guldberg, S. Lavorel, G. Mace, M. Palmer, R. Scholes, and T. Yahara. 2009. Biodiversity, climate change, and ecosystem services. Current Opinion in Environmental Sustainability 1:46-54.

Moore, S. S., N. E. Seavy, and M. Gerhart. 2013. Scenario planning for climate change adaptation: A guidance for resource managers. Point Blue Conservation Science and California Coastal Conservancy. Available: http://www.prbo.org/refs/files/12263_Moore2013.pdf. (October 2015).

Moser, S. C., and J. A. Ekstrom. 2010. A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences 107:22026-22031.

Mumford, J. D., A. W. Leach, P. Levontin, and L. T. Kell. 2009. Insurance mechanisms to mediate economic risks in marine fisheries. ICES Journal of Marine Science 66:950-959.

Munguia-Vega, A., A. Saenz-Arroyo, A. P. Greenley, J. A. Espinoza-Montes, S. R. Palumbi, M. Rossetto, and F. Micheli. 2015. Marine reserves help preserve genetic diversity after impacts derived from climate variability: lessons from the pink abalone in Baja California. Global Ecology and Conservation 4:264-276.

Munro, G., A. VanHoutte, and R. Willman. 2004. The conservation and management of shared fish stocks: legal and economic aspects. FAO Fisheries Technical Paper 465. Rome, FAO. Available: ftp://ftp.fao.org/docrep/fao/007/y5438e/y5438e00.pdf. (October 2015).

NCSE (National Council for Science and the Environment). 2014. Managing marine fisheries in a changing climate. Session 10 at Building Climate Solutions. 14th National Conference and Global Forum on Science, Policy and the Environment. Available:

http://www.buildingclimatesolutions.org/topics/view/523383680cf2ea76e535e6f0/. (October 2015).

NEFSC (Northeast Fisheries Science Center). 2012. Southern New England Mid-Atlantic yellowtail flounder (*Limanda ferruginea*) stock assessment for 2012, updated through 2011. Available: http://www.nefsc.noaa.gov/publications/crd/crd1218/partb.pdf. (October 2015).

NEFSC (Northeast Fisheries Science Center). 2014. 58th Northeast Regional Stock Assessment Workshop (58th SAW) Assessment Summary Report. US Department of Commerce, Northeast Fish Science Center. Available: http://nefsc.noaa.gov/publications/crd/crd1403/crd1403.pdf. (October 2015).

NFWPCAP (National Fish, Wildlife and Plants Climate Adaptation Partnership). 2012. National Fish, Wildlife and Plants Climate Adaptation Strategy. Association of Fish and Wildlife Agencies, Council on Environmental Quality, Great Lakes Indian Fish and Wildlife Commission, National Oceanic and Atmospheric Administration, and U.S. Fish and Wildlife Service. Washington, DC. Available: http://www.wildlifeadaptationstrategy.gov/pdf/NFWPCAS-Final.pdf. (October 2015).

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., and Woodroffe, C.D. 2007. Coastal systems and low-lying areas. Pages 315-356 *in* M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, editors. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

NMFS (National Marine Fisheries Service). 2011. Bluefin tuna bycatch reduction in the Gulf of Mexico pelagic longline fishery. Available: http://www.gpo.gov/fdsys/pkg/FR-2011-04-05/pdf/2011-8052.pdf#page=1. (October 2015).

NMFS (National Marine Fisheries Service). 2015. Operational guidelines for the Magnuson-Stevens Fishery Conservation and Management Act fishery management process appendices. Available: http://www.nmfs.noaa.gov/sfa/management/councils/operational_guidelines/og_append.pdf. (October 2015).

NMFS (National Marine Fisheries Service). 2016. National Marine Fisheries Service Ecosystem Based Fishery Management Policy. Available: http://www.st.nmfs.noaa.gov/Assets/ecosystems/ebfm/Final-EBFM-Policy-PDS-Review-5.20.2016-final-for-PDS.pdf. (October 2016).

NRC (National Research Council), 1997. Striking a Balance: Improving Stewardship of Marine Areas. National Academy of Sciences, National Academies Press. Available:

http://www.nap.edu/catalog/5797/striking-a-balance-improving-stewardship-of-marine-areas. (October 2015).

Nye, J. A., J. S. Link, J. A. Hare, W. J. Overholtz. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series 393:111-129.

Nystrom, M. 2006. Redundancy and response diversity of functional groups: Implications for the resilience of coral reefs. Ambio 35:30-35.

O'Connor, M. I., J. F. Bruno, S. D. Gaines, B. S. Halpern, and S. E. Lester. 2007. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. Proceedings of the National Academy of Sciences 104:1266-1271.

Orphanides, C. D., and D. L. Palka. 2013. Analysis of harbor porpoise gillnet bycatch, compliance, and enforcement trends in the U.S. northwestern Atlantic, January 1999-May 2010. Endangered Species Research 20:251-269.

Ottersen, G., S. Kim, G. Huse, J. J. Polovina, and N. C. Stenseth. 2010. Major pathways by which climate may force marine fish populations. Journal of Marine Systems 79:343-360.

Pörtner, H. O., and M.A. Peck. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. Journal of Fish Biology 77:1745-1779.

PFMC (Pacific Fishery Management Council). 2013. Pacific Coast Fishery Ecosystem Plan for the U.S. Portion of the California Current Large Marine Ecosystem. Available: http://www.pcouncil.org/wp-content/uploads/FEP_FINAL.pdf. (October 2015).

PFMC (Pacific Fishery Management Council). 2014. Status of the Pacific Coast coastal pelagic species fishery and recommended acceptable biological catches. Stock Assessment and Fishery Evaluation for 2014. Appendix C: 2014 Pacific Sardine Stock Assessment. Available: http://www.pcouncil.org/wp-content/uploads/2014_CPS_SAFE_Text_FINAL.pdf. (October 2015).

Paine, R. T. 1995. A conversation on refining the concept of keystond species. Conservation Biology 9:962-964.

Palumbi, S. R. 2004. Why mothers matter. Nature 430:621-622.

Patrick, W. S., and J. S. Link 2015. Myths that continue to impede progress in ecosystem based fisheries management. Fisheries 40:155-160.

Pauls, S. U., C. Nowak, M. Balint, and M. Pfenninger. 2013. The impact of global climate change on genetic diversity within populations and species. Molecular Ecology 22:925-946.

Pecl, G., S. Frusher, C. Gardner, M. Haward, A. Hobday, S. Jennings, M. Nursey-Bray, A. Punt, H. Revill, and I. vanPutten. 2009. The east coast Tasmanian rock lobster fishery – vulnerability to climate change impacts and adaptation response options. Report to the Department of Climate Change, Australia. Available: http://www.environment.gov.au/system/files/resources/48b0b14e-9234-480f-9a6b-602274396991/files/rock-lobser-report.pdf. (October 2015).

Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. Science 308:1912-1915.

Pikitch, E. K., K. J. Rountos, T. E. Essington, C. Santora, D. Pauly, R. Watson, U. R. Sumaila, P. D. Boersma, I. L. Boyd, D. O. Conover, P. Cury, S. S. Heppell, E. D. Houde, M. Mangel, E. Plaganyi, K. Sainbury, R. S. Steneck, T. M.Geers, N. Gownaris, and S. B. Munch. 2014. The global contribution of forage fish to marine fisheries and ecosystems. Fish and Fisheries 15:43-64.

Pinsky, M., B. Worm, M. Fogarty, J. Sarmiento, and S. Levin. 2013. Marine taxa track local climate velocities. Science 341:1239-1242.

Pinksy, M. L., and M. Fogarty. 2012. Lagged social-ecological responses to climate and range shifts in fisheries. Climatic Change 115:883-891.

Pinsky, M. L. and N. J. Mantua. 2014. Emerging adaptation approaches for climate-ready fisheries management. Oceanography 27:17-29.

Plaganyi, E. E., J. D. Bell, R. H. Bustamante, J. M. Dambacher, D. M. Dennis, C. M. dichmont, L. X. C. Dutra, E. A. Fulton, A. J. Hobday, E. I. vanPutten, F. Smith, A. D. M. Smith, and S. Zhou. 2011a. Modelling climate-change effects on Australian and Pacific aquatic ecosystems: a review of analytical tools and management implications. Marine and Freshwater Research 62:1132-1147.

Plaganyi, E. E., S. J. Weeks, T. D. Skewes, M. T. Gibbs, E. S. Policzanska, A. Norman-Lopez, L. K. Blamey, M. Soares, and W. M. L. Robinson. 2011b. Assessing the adequacy of current fisheries management under changing climate: a southern synopsis. ICES Journal of Marine Science 68:1305-1317.

Plaganyi, E. E., T. D. Skewes, N. A. Dowling, M. Haddon. 2013. Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. Climate Change 119:181-197.

Plaganyi, E. E., I. vanPutten, O. Thebaud, A. J. Hobday, J. Innes, L. Lim-camacho, A. Norman-Lopez, R. H. Bustamante, A. Farmery, A. Fleming, S. Frusher, B. Green, E. Hoshino, S. Jennings, G. Pecl, S. Pascoe, P. Schrobback, L. Thomas. 2014. A quantitative metric to identify critical elements within seafood supply networks. PlosOne 9:e91833.

Planque, B., J. Fromentin, P. Cury, K. F. Drinkwater, S. Jennings, R. I. Perry, and S. Kifani. 2010. How does fishing alter marine populations and ecosystem sensitivity to climate? Journal of Marine Systems 79:403-417.

Punt, A. E. 2006. The FAO precautionary approach after almost 10 years: have we progressed toward implementing simulation-tested feedback-control management systems for fisheries management? Natural Resource Modeling 19:441-464.

Punt, A. E., T. A'mar, N. A. Bond, D. S. Butterworth, C. L. de Moor, J. A. A. De Oliveira, M. A. Haltuch, A. B. Hollowed, A. B., and C. Szuwalski. 2014. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science 71:2208-2220.

Punt, A. E., D. S. Butterworth, C. L. de Moor, J. A. A. De Oliveira, and M. Haddon. 2016. Management strategy evaluation: best practices. Fish and Fisheries 17:303-334.

Rhein, M., S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, G. C. Johnson, S. A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L. D. Talley and F. Wang. 2013. Observations: Ocean. Pages 255-315 *in* T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY. Available: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter03_FINAL.pdf. (October 2015).

Ramos, J. E., G. T. Pecl, N. A. Moltschaniwskyj, J. M. Strugnell, R. I. Leon, and J. M. Semmens. 2014. Body size, growth, and life span: Implications for the polewards range shift of Octopus tetricus in South-Eastern Australia. PlosOne 9:e103480.

Rouyer, T., G. Ottersen, J. M. Durant, M. Hildago, D. O. Hjermann, J. Persson, L. C. Stige, and N. C. Stenseth. 2011. Shifting dynamic forces in fish stock fluctuations triggered by age truncation? Global Change Biology 17:3046-3057.

Rouyer, T., A. Sadykov, J. Ohlberger and N. C. Stenseth. 2012. Does increasing mortality change the response of fish populations to environmental fluctuations? Ecology letters 15:658-665.

Tingley, M. W., E. S. Darling, and D. S. Wilcove. 2014. Fine- and course-filter conservation strategies in a time of climate change. Annals of the New York Academy of Sciences 1322:92-109.

Scheffer, M., S. Barrett, S. R. Carptenter, C. Folke, A. J. Green, M. Holmgren, T. P. Hughes, K. Kosten, I. A. vandeLeemput, D. C. Nepstad, E. H. vanNes, E. T. H. M. Peeters, and B. Walker. 2015. Creating a safe operating space for iconic ecosystems: Manage local stressors to promote resilience to global change. Science 347:1317-1319.

Schindler, D. E. and R. Hilborn. 2015. Prediction, precaution and policy under global change. Science 347:953-954.

Serafy, J. E., S. J. Cooke, G. A. Diaz, J. E. Graves, M. Hall, M. Shivji, and Y. Swimmer. 2012. Circle hooks in commercial, recreational, and artisanal fisheries: research status and needs for improved conservation and management. Bulletin of Marine Science 88:371-391.

Senko, J., E. R. White, S. S. Heppell, and L. R. Gerber. 2014. Comparing bycatch mitigation strategies for vulnerable marine megafauna. Animal Conservation 17:5-18.

Sethi, S. A., M. Dalton, and R. Hilborn. 2012. Managing harvest risk with catch-pooling cooperatives. ICES Journal of Marine Science 69:1038-1044.

Staudinger, M. D., S. L. Carter, M. S. Cross, N. S. Dubois, J. E. Duffy, C. Enquist, R. Griffis, J. J. Hellmann, J. J. Lawler, J. O'Leary, S. A. Morrison, L. Sneddon, B. A. Stein, L. M. Thompson, and W. Turner. 2013. Biodiversity in a changing climate: a synthesis of current and projected trends in the U.S. Frontiers in Ecology and the Environment 11:465-473.

Stein, B., A. Staudt, M. S. Cross, N. S. Dubois, C. Enquist, R. Griffis, L. J. Hansen, J. J. Hellmann, J. J. Lawler, E. J. Nelson, and A. Pairis. 2013. Preparing for and managing change: climate adaptation for biodiversity and ecosystems. Frontiers in Ecology and Environment 11:502-510.

Stein, B. A., P. Glick, N. Edelson, and A. Staudt, editors. 2014. Climate-smart conservation: putting adaptation principles into practice. National Wildlife Federation, Washington D.C. Available: http://www.nwf.org/pdf/Climate-Smart-Conservation/NWF-Climate-Smart-Conservation_5-08-14.pdf. (October 2015).

Stock, C. A., M. A. Alexander, N. A. Bond, K. M. Brander, W. W. L. Cheung, E. N. Curchitser, T. L. Delworth, J. P. Dunne, S. M. Griffies, M. A. Haltuch, J. A. Hare, A. B. Hollowed, P. Lehodey, S. A. Levin, J. S. Link, K. A. Rose, R. R. Rykaczewski, J. L. Sarmiento, R. J. Stouffer, F. B. Schwing, G. A. Vecchi, and F. E. Werner. 2011. On the use of IPCC-class models to assess the impact of climate on living marine resources. Progress in Oceanography 88:1-27.

Stoll, J. S., and M. C. Holliday. 2014. The Design and Use of Fishing Community and Regional Fishery Association Entities in Limited Access Privilege Programs. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-F/SPO-138. Available: http://www.nmfs.noaa.gov/op/docs/tm138_fishing_communities_guidance.pdf. (October 2015).

Sumaila, U. R., W. W. L. Cheung, V. W. Y.Lam, D. Pauly, and S. Herrick. 2011. Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change 1:449-456.

Szuwalski, C. S., K. A. Vert-Pre, A. E. Punt, T. A. Branch, and R. Hilborn. 2014. Examining common assumptions about recruitment: a meta-analysis of recruitment dynamics for worldwide marine fisheries. Fish and Fisheries 16:633-648. DOI: 10.1111/faf.12083.

Titus, J. G. 2011. Rolling easements. U.S. Environmental Protection Agency. Washington, D.C. Available: http://www2.epa.gov/sites/production/files/documents/rollingeasementsprimer.pdf. (October 2015).

Van Oppen, M. J. H., J. K. Oliver, H. M. Putnam, and R. D. Gates 2015. Building coral reef resilience through assisted evolution. Proceedings of the National Academy of Sciences 112:2307-2313.

Vert-pre, K. A., R. O. Amoroso, O. P. Jensen, and R. Hilborn. 2013. The frequency and intensity of productivity regime shifts in marine fish stocks. Proceedings of the National Academy of Science 110:1779–1784.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, Adaptability and Transformability in social-ecological systems. Ecology and Society 9:5.

Wallace, S., B. Turris, J. Driscoll, K. Bodtker, B. Mose and G. Munro. 2015. Canada's pacific groundfish trawl habitat agreement: A global first in an ecosystem approach to bottom trawl impacts. Marine Policy 60: 240-248.

Ward, T. J., D. Heinemann, and N. Evans. 2001. The Role of Marine Reserves as Fisheries Management Tools: a Review of Concepts, Evidence and International Experience. Bureau of Rural Sciences, Canberra, Australia.

Wayte, S. E. 2013. Management implications of including a climate-induced recruitment shift in the stock assessment for jackass morwong (*Nemadactylus macropterus*) in south-eastern Australia. Fisheries Research 142:47-55.

Wilson, S. K., S. C. Burgess, A. J. Cheal, M. Emslie, R. Fisher, I. Miller, N. V. C. Polunin, and H. P. A. Sweatman. 2008. Habitat utilization by coral reef fish: implications for specialists vs generalists in a changing environment. Journal of Animal Ecology 77:220-228.

WSBRP (Washington State Blue Ribbon Panel on Ocean Acidification). 2012. Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response. H. Adelsman and L. Whitely Binder, editors. Washington Department of Ecology Publication no. 12-01-015. Olympia, Washington. Available: https://fortress.wa.gov/ecy/publications/documents/1201015.pdf. (October 2015).

Table 1. Summary of management alternatives.

	Possible options					
Reactive management	Creating flexible, nimble management system	Adjusting reference points	Adjusting fisheries allocations	Adjusting fishing practices or gears		
Proactive Management to increase Resilience of stocks or species	Incorporating environmental parameters into stock assessments and management	Managing for uncertainty: scenario planning	Protecting age structure and/or old females	Decreasing existing stressors	Enhancing or translocating stocks	Managing to promote adaptive capacity
Proactive management to increase resilience of ecosystem	Protecting key habitats and species	Designing appropriate marine reserves	Applying ecosystem models to create robust management			
Pro-active Management to increase resilience of fishermen	Providing insurance for fishermen	Expanding flexibility in fisheries permitting	Improving flexibility in the supply chain			
Practices that Improve Management in a Changing Climate	Updating and clarifying management goals	Monitoring for climate change	Using regional planning to address local needs			