THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY
Oceanography

CITATION
Pinsky, M.L., and N.J. Mantua. 2014. Emerging adaptation approaches for climate-ready fisheries management. *Oceanography* 27(4):146–159, http://dx.doi.org/10.5670/oceanog.2014.93.

DOI
http://dx.doi.org/10.5670/oceanog.2014.93

COPYRIGHT
This article has been published in *Oceanography*, Volume 27, Number 4, a quarterly journal of The Oceanography Society. Copyright 2014 by The Oceanography Society. All rights reserved.

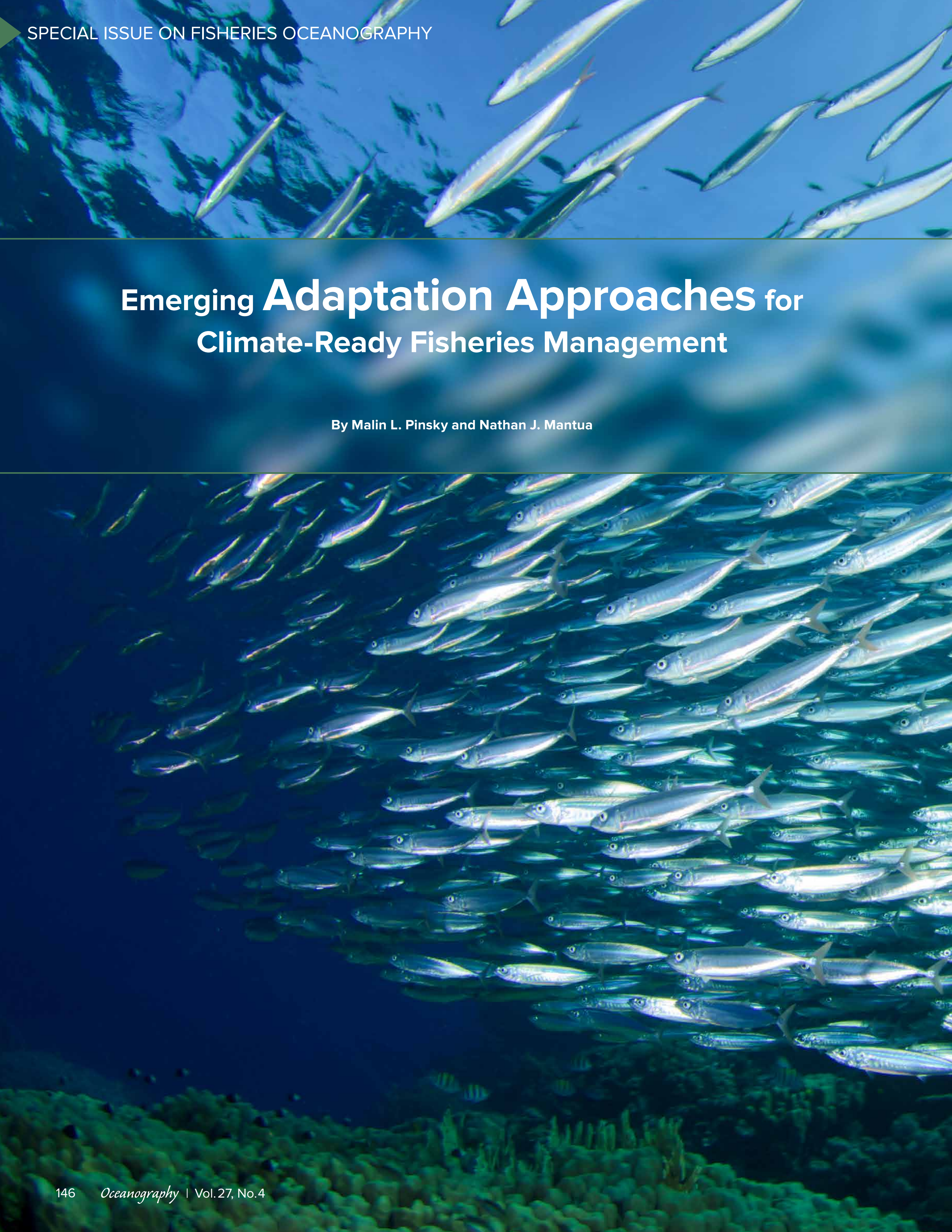
USAGE
Permission is granted to copy this article for use in teaching and research. Republication, systematic reproduction, or collective redistribution of any portion of this article by photocopy machine, reposting, or other means is permitted only with the approval of The Oceanography Society. Send all correspondence to: info@tos.org or The Oceanography Society, PO Box 1931, Rockville, MD 20849-1931, USA.

DOWNLOADED FROM HTTP://WWW.TOS.ORG/OCEANOGRAPHY

SPECIAL ISSUE ON FISHERIES OCEANOGRAPHY

Emerging Adaptation Approaches for Climate-Ready Fisheries Management

By Malin L. Pinsky and Nathan J. Mantua



ABSTRACT. By 2100, ocean waters are expected to be substantially warmer and more acidic than they are today, with profound effects on coupled social-ecological fisheries systems. Despite broad recognition of impacts from both anthropogenic climate change and natural climate variability, incorporating climate and acidification considerations into management approaches has been difficult. However, clear opportunities exist for fostering "climate-ready" fisheries management, as evidenced by emerging research and implementation experiences that we review here. Approaches now exist for integrating climate change and variability into monitoring, vulnerability assessments, stock assessments, spatial management, annual harvest limits, international agreements, and management of emerging fisheries. While uncertainty, limited understanding, and the increased complexity of these new considerations have delayed more widespread implementation to date, these factors do not change the reality of climate change impacts on living marine resources. We conclude that, despite ongoing research needs, fisheries management can substantially expand capacity to respond to a changing climate.

INTRODUCTION

Natural climate variations contribute to profound changes in living marine resources (Brander, 2007; Pinsky et al., 2013). Moreover, because of anthropogenic increases in greenhouse gas emissions, global temperatures are projected to be 2°–4°C warmer and ocean waters substantially more acidic at the end of this century than they are today, with dramatic effects on marine ecosystems and coupled social-ecological fisheries systems (Sumaila et al., 2011; McCay, 2012; Pinsky and Fogarty, 2012; Mills et al., 2013). At least some anthropogenic ocean change is inevitable, and together with the ocean's natural variability, society is challenged to consider not only how to mitigate future climate impacts, but also how to adapt fisheries management to a changing ocean. Deciding how to adapt is not straightforward given the complex feedbacks, lags, cumulative impacts, and potential for thresholds in the dynamics of coupled systems like fisheries (Liu et al., 2007). In addition, the ways in which humans adapt to a changing ocean is likely to have impacts on marine ecosystems as great as, if not greater than, the direct effects of climate change alone (Turner et al., 2010).

Considerations of long-term climate change do not appear prominently in the traditional fisheries science that guides management in North America, Europe, Australia, and elsewhere around the world (Hilborn and Walters, 1992; Walters and Martell, 2004; Keyl and Wolff, 2007). Instead, fisheries management is largely based around the concept of a stable relationship between abundance and population growth, which assumes that fishery yields can be maximized by controlling abundance. Climate variation is typically considered as "noise" around that pattern, and management approaches have been developed to be relatively robust to seasonal-to-interannual fluctuations (Walters and Parma, 1996; King and McFarlane, 2006). A fundamental challenge of considering multidecadal oscillations and anthropogenic climate change in fisheries management is that these forcings directly and indirectly affect ecosystems in many ways. They can manifest as threshold and/or transient responses, which have no historical analog, rather than varying within a long-term, stationary distribution seen in historical data. Rapid state shifts and more slowly evolving trends pose serious challenges to managers and conservation planners aiming to manage sustainable use of living marine resources, recover threatened and endangered species, or protect specific habitats or ecosystems.

Because the broad impacts of climate change and ocean acidification on fish and fisheries have been reviewed recently (Lehodey et al., 2006; Brander, 2007; Cochrane et al., 2009; Sumaila et al., 2011; Branch et al., 2012), our review here focuses specifically on management techniques, tools, and approaches that could allow coupled social-ecological fisheries systems to cope more adeptly with climate impacts across a broad spectrum of time scales. Our focus is primarily on industrialized fisheries in the developed world, though similar challenges face small-scale artisanal and subsistence fisheries globally (Cochrane et al., 2009). Such actions fit well within the concepts of ecosystem-based management (EBM) or an ecosystem approach to fisheries management (EAFM) (Arkema et al., 2006). As approaches to implementing marine EBM have developed, however, explicit considerations of natural and anthropogenic climate change have been largely absent, including within fisheries management (Arkema et al., 2006; McLeod and Leslie, 2009). This review starts by briefly highlighting a few key aspects of climate impacts on marine systems and reviewing past attempts to incorporate climate into fisheries management. The bulk of the review describes recent approaches that appear promising for adaptation of fisheries management to climate impacts going forward.

KEY CLIMATE IMPACTS ON FISH AND FISHERIES

Climate impacts marine ecosystems in a multitude of ways that include changes to temperature, net primary productivity and food webs, oxygen minimum zones, acidification, ocean circulation, sea level, the frequency and magnitude of extreme events, disease incidence, land-sea interactions, and the availability of habitat-forming species such as corals and kelps (Lehodey et al., 2006; Brander, 2007; Cochrane et al., 2009; Pörtner et al., 2014; Wong et al., 2014). Broadly, these impacts affect marine fish and invertebrates by changing spatial distributions, recruitment, abundance, phenology, and evolution (Brander, 2007; Cochrane et al., 2009), though specific impacts and mechanisms often depend on details of the ecosystem and the species.

Several broad characteristics of this complexity can help to guide adaptation strategies. First, there is substantial variability in climate impacts, not only among species but also through time and among regions. For example, although the global ocean has been warming rapidly, the California and Humboldt Current ecosystems largely cooled from 1980 to 2012 (Chavez et al., 2011; Trenberth and Fasullo, 2013), a time period of relevance to fisheries management and institutional knowledge in the region. Bathymetry and local factors can also alter the responses of marine species to climate changes, such as driving species deeper rather than poleward during a recent period of upper ocean warming in the Gulf of Mexico (Pinsky et al., 2013). There is growing awareness that acidification is highly heterogeneous as well, particularly near the coast where upwelling, bathymetry, photosynthesis, and runoff from land can all exacerbate or mitigate the anthropogenically caused acidification process (Kelly et al., 2011). This heterogeneity suggests that regionally specific adaptation approaches will be most effective.

Second, the impacts of climate change and acidification in the real world can rarely be understood outside of cumulative effects from multiple stressors, including directed fishing, bycatch, habitat destruction, and loss of prey (Pikitch et al., 2004). Fishing, for example, often truncates the age structure of exploited species, reduces their intra-specific diversity, and causes their geographic ranges to contract (Hilborn et al., 2003; Fisher and Frank, 2004; Brander, 2007). All of these factors reduce resilience to climate impacts and increase the magnitude of population fluctuations (Hilborn et al., 2003; Hsieh et al., 2006; Brander, 2007; Planque et al., 2010; Shelton and Mangel, 2011). The combined effect can be greater than the sum of each individual effect (Ainsworth et al., 2011).

Third, the impacts of climate on fisheries cannot be fully understood without accounting for the mediating effects of social, regulatory, and economic factors (McCay, 2012; Pinsky and Fogarty, 2012). For a fishery to shift poleward, for example, either individual fishers have to land fish in new ports or travel further from their current ports; high-latitude fishers have to catch more fish; or low-latitude fishers have to catch fewer fish. Regulations and economic considerations may directly limit which, if any, of these options are feasible, while social preferences may alter which options are most appealing or accessible (St. Martin et al., 2007; McCay et al., 2011).

Finally, climate impacts act at both slow and fast time scales, creating the strong potential for mismatches in scale between ecological and social systems. Extreme events can have dramatic impacts in a single year: the 2012 warm event in the Northwest Atlantic led to an early and large catch of lobsters that outstripped market demand, collapsed the price, and created economic hardship (Mills et al., 2013). In addition, while physical aspects of the environment are generally linear but noisy, biological measures are nonlinear and have the potential for dramatic responses to small changes in climate or other driving forces (Hsieh et al., 2005). Ecological shifts may therefore occur rapidly but sporadically in response to gradually evolving anthropogenic climate change (Harley and Paine, 2009). Other effects can appear slowly over many decades, such as gradual but noisy shifts in marine fish and invertebrate distributions (Perry et al., 2005; Pinsky et al., 2013). Without long-term records to set historical baselines for the ecosystem, neither abrupt nor gradual changes would be apparent.

Malin L. Pinsky (malin.pinsky@rutgers.edu) is Assistant Professor, Department of Ecology, Evolution, and Natural Resources, Rutgers University, New Brunswick, NJ, USA. **Nathan J. Mantua** is Landscape Ecology Team Leader, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Science Center, Santa Cruz, CA, USA.

PAST EXPERIENCE WITH ENVIRONMENTAL INDICATORS

Given the clear impacts that climate has on population dynamics, a goal of fisheries oceanography has long been to identify oceanographic indicators that can improve fisheries management and, particularly, to find indicators that predict annual recruitment (Kendall and Duker, 1998). The major challenge has been that most recruitment-environment correlations fail when retested with additional years of data, in part because a multitude of factors drive population dynamics in marine fishes (Myers, 1998). These challenges have, understandably, sharply limited the adoption of simple environmental indicators in management processes (see Box 1 for a counter example).

Ecosystem indicators are now re-emerging as critical tools for tracking and assessing ecosystem conditions and for providing early warning of climate impacts (see Real-Time Responses to Climate, below). Environmental indicators are more often correlated to population dynamics at species range edges (Myers, 1998), for example, and a new focus on linking climate indicators to species distributions rather than recruitment may also prove fruitful. Marine range limits generally conform to species' physiological thermal limits more closely than do terrestrial ranges, implying that climate impacts on species distributions may be more predictable in the ocean (Sunday et al., 2012).

APPROACHES FOR CLIMATE ADAPTATION

While traditional approaches to fisheries management focus strongly on the impacts of fishing, increased attention to climatic impacts has led to a new generation of management approaches and scientific tools. The approaches are diverse (Table 1), but together are beginning to provide a coherent set of tools, techniques, and considerations that can be applied individually or in combination, depending on the social and ecological context. We describe some of the major approaches in the following sections.

Addressing Cumulative Impacts

As described above, the impacts of changing climates are best viewed in the context of many influences and stressors on marine populations, and calls for an ecosystem approach to fisheries management have emphasized that fisheries can be more effectively managed by addressing this full range of stressors (McLeod and Leslie, 2009). One approach for adapting to different types of climate change is therefore to "address the basics" and reduce other stressors where possible, including overfishing, stock depletion, damage to habitat, reduced ecosystem productivity, loss of prey, and bycatch (Brander, 2007). Reducing stressors, however, can be difficult if they require cross-organization cooperation (e.g., the involvement of organizations beyond fisheries managers; McLeod and Leslie, 2009).

The specific approaches for reducing stressors will vary substantially among regions based on local needs, though comprehensive planning tools such as Ecological Risk Assessment and ecosystem-level Management Strategy Evaluation (Smith et al., 2007) may be broadly useful. For North Sea cod, for example, an evaluation of management strategies suggested that reduced fishing mortality is one of the most important steps toward rebuilding this overfished stock in both the short and long term, even under a changing climate (Kell et al., 2005). Approaches to reduce mortality could include quotas, effort and gear restrictions, and technical measures to reduce bycatch of juveniles in multispecies fisheries. A risk analysis for tropical Pacific fisheries revealed that ending overfishing as well as managing catchment vegetation to reduce runoff to nursery and coral reef habitats would be key adaptation options (Bell et al., 2013). Distributing fishing effort across substocks and age classes to maintain genetic, age, and spatial diversity within populations is also important for providing resilience to climate impacts (Planque et al., 2010), though knowledge and appreciation for such diversity in the first place is required. The broader message is that those populations facing the fewest nonclimate stressors will likely be best able to support robust fisheries in the face of climate change.

BOX 1

Ocean temperature has been explicitly written into the harvest rule for Pacific sardines (*Sardinops sagax*), one of the few species that has been managed with a climate indicator (Myers, 1998). Sardines in California appear to be more productive during temperatures near 17.5°C (Figure B1b), possibly because older fish from Mexico shift north with warmer temperatures (Jacobson and MacCall, 1995). Simulations suggest that the probability and duration of the drastic sardine collapse in the early 1950s could have been substantially reduced if harvest rates had been lower during that cold period (Lindegren et al., 2013).

Under the Pacific Fishery Management Council's harvest control rule, a larger fraction of the available stock can be harvested during warm years, though never more than 15% or less than 5% (Figure B1c). These limits are imposed to reduce variability for the fishing industry. An ultimately flawed re-analysis led the Pacific Fishery Management Council to drop the temperature rule in 2011 (Jacobson and McClatchie, 2013), though efforts were underway as of 2014 to reinstate it (PFMC, 2014). Despite the apparent validity of the temperature-based harvest control rule, conditions have not yet been cool enough to trigger it.

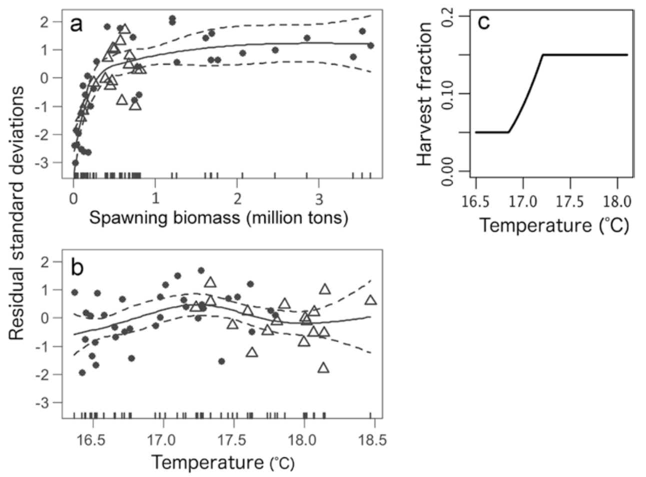


FIGURE B1. Sea surface temperature and the Pacific sardine fishery. A re-analysis by Jacobson and McClatchie (2013) confirmed that sardine recruitment is related to both (a) spawning biomass and (b) sea surface temperature. In both (a) and (b), the y-axis shows standardized residuals from a Generalized Additive Model. In (c), the harvest control rule for Pacific sardine specifies that a larger fraction of the harvestable stock can be fished in years with warmer sea surface temperatures. The fraction is limited to no more than 15% and no less then 5% to limit variability for the fishing industry. *Parts (a) and (b) © Canadian Science Publishing or its licensors*

TABLE 1. Management strategies and approaches for coping with climate impacts on fisheries.

Climate Forcing	Ecological Impact	Potential Responses	Potential Concerns	Examples
Seasonal, interannual, and multidecadal oscillations and directional anthropogenic climate change	Greater variability and uncertainty in productivity	Increase the precautionary buffer between maximum sustainable yield and total allowable catch limits	Reduced fishing opportunities	Proposed reduction in harvest rates for shared US/Canada salmon (McIlgorm et al., 2010)
		Integrate ecosystem monitoring into annual fisheries management decision making	Increased complexity of decision making	Changes to Bering Sea pollock quota by the North Pacific Fishery Management Council (Coyle et al., 2011; NOAA, 2012)
	Changes in species distribution	Implement spatially explicit stock assessments	Increased complexity of assessment models (Hart and Cadrin, 2004)	Spatial models for yellowtail flounder (Hart and Cadrin, 2004)
Multiyear to multidecadal oscillations and directional anthropogenic climate change	Wide range of potential impacts	Evaluate management approaches against climate scenarios	Can be time-consuming	Evaluation of management options for US West Coast groundfishes (Kaplan et al., 2010)
		Reduce subsidies and other incentives for overcapacity in fisheries	Can be politically and economically difficult	Proposals to reduce fishery subsidies generally (Sumaila et al., 2011)
	Change in population productivity	Mitigate nonclimate stressors to enhance resilience to climate impacts	May require coordination across multiple management organizations	Reduce fishing pressure on Atlantic cod (Kell et al., 2005), mitigate damage to coral reefs in the tropical Pacific (Bell et al., 2013)
		Manage for age, spatial, genetic, and temporal diversity within stocks (portfolio effects)	Relevant diversity may be cryptic or unknown	Balance harvest across multiple subpopulations in Bristol Bay (Hilborn et al., 2003)
		Use stock assessments with temporally variable productivity	Increased complexity of assessment models (Dorner et al., 2009)	Declining productivity in northern Alaska salmon (Collie et al., 2012)
Multidecadal oscillations and directional anthropogenic climate change	Wide range of potential impacts	Rapid assessment of stock vulnerability to climate change	Limited by expert knowledge and judgment (Chin et al., 2010)	Climate vulnerability of Australian sharks and rays (Chin et al., 2010)
		Develop regional climate change scenarios	Regional processes often poorly resolved in models, surprises will remain likely (Stock et al., 2011)	Atlantic croaker in the Northeast US (Hare et al., 2010), English sole in the California Current (Ainsworth et al., 2011)
	Change in population productivity	Restrict stock assessments to current environmental regime	Detecting regime shifts in real time is difficult, and short time series create uncertainty (Haltuch and Punt, 2011)	Detection of recruitment variation in Pacific groundfish (Haltuch and Punt, 2011)
		Re-evaluate rebuilding goals and timelines	May be constrained by regulatory requirements	Full rebuilding of southern cod stocks may not be possible (Mieszkowska et al., 2009)
	New species shifting into a region	Temporary moratorium on new fisheries	Reduces flexibility for fishing industry	Closure of US Arctic waters (Stram and Evans, 2009)
		Prioritize new species for research, including experimental fishing	New priorities compete for funding with existing needs	North Sea anchovy prioritized for research by ICES (Petitgas et al., 2012)
	Difficult social and economic transitions	Rapid assessment of social vulnerability to climate change	May require collection of new social data	Global economic vulnerability (Allison et al., 2009), the Northeast US community vulnerability (Jepson and Colburn, 2013)
		Co-management between government and fishing stakeholders	Can fail if fishing incentives do not foster sustainability (Miller et al., 2010)	Baja California cooperatives (McCay et al., 2011)
		Promote diversification across fisheries and livelihoods	Reduced short-term economic efficiency	New fisheries for southern species in the UK (Cheung et al., 2012)
		Climate adaptation fund	Rules for implementation not yet defined (Sumaila et al., 2011)	Proposed endowment fund (Sumaila et al., 2011)

Continued on next page…

TABLE 1. Continued...

Climate Forcing	Ecological Impact	Potential Responses	Potential Concerns	Examples
Directional anthropogenic climate change	Changes in species distributions	Re-evaluate and potentially move stock boundaries	Existing stock boundaries often based on limited data	Proposal to re-evaluate stock boundaries for a wide range of species (Link et al., 2011)
		Move closed area and other management boundaries	Location may be constrained by economic, social, or regulatory factors	Dynamic bycatch avoidance in Australia and Hawaii (Howell et al., 2008; Hobday et al., 2010), proposal to move the North Sea "Plaice Box" (van Keeken et al., 2007)
		Pre-agreements, side payments, or transferable quotes among nations	Lack of common understanding that distribution is changing, lack of existing mechanisms for side payments (Miller and Munro, 2004)	Norway/Russia examples from the Barents Sea (Miller and Munro, 2004)

Prepare for Emerging Fisheries

Long-term shifts in species distributions are expected to both close down traditional fisheries (Sumaila et al., 2011) and create new opportunities that may be critical for replacing lost fisheries. In the United Kingdom, for example, growth in populations of sea bass (*Dicentrarchus labra*), red mullet (*Mullus barbatus*), John dory (*Zeus faber*), anchovy (*Engraulis encrasicolus*), and squid associated with warming temperatures sparked new fisheries for these species (Cheung et al., 2012).

The challenge is that the knowledge and data needed for management of species in new regions may not be available. Ecosystem models that build from fundamental ecological processes may help to provide general guidance in such novel ecosystems, but they are only beginning to be tested (Barange et al., 2014). In addition, management agencies can prioritize research on newly emerging stocks, even though these "minor" fisheries may seem less important in the short term (Stram and Evans, 2009; Link et al., 2011). For example, the International Council for the Exploration of the Sea (ICES) coordinated research on a newly abundant anchovy stock in the North Sea and revealed that this stock was separate from a southern stock traditionally exploited by Spanish and French fishers (Cheung et al., 2012; Petitgas et al., 2012). An alternative, adaptive management solution to emerging fisheries would be to implement carefully monitored experimental fishing programs (Stram and Evans, 2009).

An important consideration is that emerging fisheries can reduce net population growth rates at the leading edge of species' ranges, which is precisely where changes to growth rates have the most impact on a species' ability to colonize new territory (Hastings et al., 2005). This consideration suggests that delaying the emergence of new fisheries will enable larger, more productive fisheries in the future. These minor fisheries, however, are often the least likely to be managed. Such a precautionary approach supports a population's ability to fully establish itself, though at the cost of limiting short-term economic returns. As one example, the North Pacific Fisheries Management Council closed US Arctic waters to fishing and froze the bottom trawl footprint in Alaska (Stram and Evans, 2009). In contrast, the northward movement of Humboldt squid (*Dosidicus gigas*) into Washington State in the United States led to the rapid opening of a new fishery for the species in 2009 (The Associated Press, 2009). The fishery has declined substantially since 2009, as Humboldt squid were largely absent from the area during the past few years.

Accounting for Climate Effects in Stock Assessments

While standard stock assessment methods often assume a fixed relationship between abundance and productivity, a recent meta-analysis suggests that environmental regime dynamics are detectable in nearly seven out of every 10 stocks (Vert-pre et al., 2013). Modern stock assessment guidelines now recommend the consideration of environmental factors when assessing stock abundance and productivity (Mace, 2001), but implementing such advice has been difficult, in part because we often lack a mechanistic understanding for which environmental indicators to include in a given situation (Methot and Wetzel, 2013).

One approach to identifying regime shifts is to use multiple environmental variables to determine when the environment has changed (Hare and Mantua, 2000), and then only use data from the recent climate regime in the stock assessment. If climate variability affects recruitment, managers have about one generation length to respond to regime shifts, so immediate detection is not critical for longer-lived species (King and McFarlane, 2006). However, using only recent data will often result in short time series, which are often insufficient for estimating fisheries management reference points reliably (Haltuch and Punt, 2011).

Another approach for dealing with both climate variability and long-term change is to model variation in stock productivity using an environmental indicator, rather than assuming that productivity is constant through time (Peterman et al., 2000; Keyl and Wolff, 2007; A'mar et al., 2009; Jiao, 2009). The correlation between a population dynamics process, such as recruitment, and an environmental indicator can be estimated as part of the stock assessment model and subjected to statistical hypothesis testing (Maunder and Watters, 2003; Deriso et al., 2008). For example, including the size of the Atlantic Warm Pool as a covariate for swordfish catchability substantially improved the fit of the stock assessment (ICCAT, 2013). Interestingly, the covariate model was not used for management advice in 2013 because the assessment team lacked time to fully evaluate it (ICCAT, 2013). In contrast, the relationship between sablefish (*Anoplopoma fimbria*) recruitment and a coastal sea surface height index has been repeatedly evaluated and supported in stock assessments, though stock assessment results have not been strongly sensitive to the inclusion of the environmental index (Stewart et al., 2011). Sea surface height, as a metric of upwelling intensity, is hypothesized to indicate the suitability of coastal conditions for larval sablefish survival (Schirripa and Colbert, 2005).

Where a clear environmental variable is not available, other methods may be helpful. In northern Alaska, declining productivity of salmon populations was detected with a Kalman filter approach, and managing for time-varying population levels (escapement) performed better than other methods (Figure 1; Collie et al., 2012). Similarly, an evaluation of management strategies for walleye pollock found that a stock assessment that allowed unfished biomass to vary through time had a lower probability of recommending fishing levels that would drive the population to low abundance, though the improvement was slight (A'mar et al., 2009). Model-free forecasting methods that account for nonlinear population dynamics and physical forcing from climate may also hold promise for short-term forecasts for one or a couple years ahead (Deyle et al., 2013). The additional sources of bias and uncertainty in more complex statistical methods appear to limit their practical utility at the moment (Dorner et al., 2009; Glaser et al., 2013).

Part of the challenge is to separate the effects of climate from those of fishing because both are often operating at the same time (Haltuch and Punt, 2011). A number of methods have been proposed to separate these effects, including long time series that capture multiple environmental cycles (Haltuch and Punt, 2011) and comparisons across many independent populations (Mueter et al., 2002). Analyzing data on species distributions may also be helpful because fishing tends to reduce the breadth of a population's distribution, while climate shifts a population's spatial distribution in one direction (Fisher and Frank, 2004; Perry et al., 2005), though the two can be confounded (Jensen and Miller, 2005). Similarly, changes in species composition are somewhat easier to attribute to climate than are single-species changes in abundance because warm-water and cold-water species are expected to increase and decrease (respectively) in response to climate warming, but both decline in response to fishing (Collie et al., 2008). Shifts in distribution can also complicate stock assessments if assessment boundaries are not properly defined (see below, Dynamic Spatial Boundaries), and spatially explicit assessment models may be needed (Link et al., 2011).

In addition, spatial shifts can alter how much of a stock is assessed by annual scientific surveys, affecting the utility of surveys as indices of abundance in stock assessments. If accurate models for a species' dynamic habitat are available, survey indices can be corrected for the amount of habitat surveyed before being included in stock assessments, as was done in 2014 for butterfish (*Peprilus triacanthus*) in the Northeast United States (NEFSC, 2014).

Finally, the potential impacts of both natural and anthropogenic climate change could be included in stock assessments as greater uncertainty around the recommended fisheries reference points, as has been proposed for the management of Pacific salmon (McIlgorm et al., 2010). This approach leaves a larger buffer zone

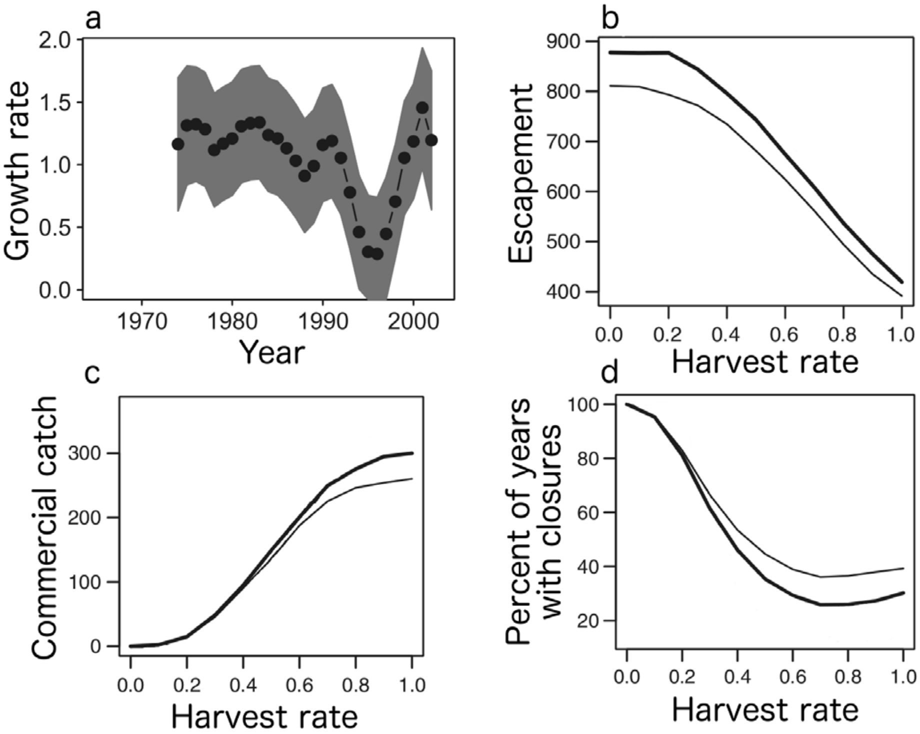


FIGURE 1. Incorporating climate impacts into stock assessments. (a) Kalman filter estimates of time-varying growth rates in the Yukon River fall chum population. Management that accounts for this variation in growth rates by adjusting annual population targets (thick line) outperforms time-invariant management approaches (thin line) across a range of measures and a range of harvest rates, including (b) average, after-catch population level, (c) average commercial catch, and (d) risk of having a year in which the commercial fishery never opens. *Modified from Collie et al. (2012). © Canadian Science Publishing or its licensors*

between the harvest rates that would support maximum sustainable yield and the implemented harvest rates, in order to reduce the probability of overfishing. One consequence, however, is a reduction in fishing opportunities.

Dynamic Spatial Boundaries

Long-term shifts in species distribution also have direct implications for spatial fisheries management. For example, offshore shifts in juvenile plaice (*Pleuronectes platessa*) in the North Sea have made a closed area (the "Plaice Box") less effective for reducing mortality of juveniles (its primary purpose), and these shifts appear to be tied to higher temperatures in inshore waters (van Keeken et al., 2007). More generally, shifts in distribution may cross stock boundaries and confound attempts to assess stocks accurately (Link et al., 2011).

As an adaptation measure, the spatial boundaries of some management areas can be moved to adjust to shifts in species distributions (Link et al., 2011). Deciding whether to move a boundary will depend on its objectives, and the case will often be strongest for those that are tied to a relatively narrow purpose, such as spatial protections for a particular species or life stage. For example, re-assessment will be critical for stock unit areas, as misspecification of the unit area will suggest reference points and management measures that are not appropriate (Link et al., 2011). However, the research required for re-evaluation of stock boundaries can be relatively time-consuming and prone to uncertainty.

On the other hand, moving boundaries will often be less important for management areas with broad objectives (e.g., the Marine Life Protection Act areas in California or Natura 2000 protected areas in Europe). Instead, it will be important to ensure in these cases that the function of the entire network of protected areas is robust to shifts in ocean conditions and species distribution.

Some spatial management measures have already been designed with dynamic boundaries that are updated in near-real time. Because endangered loggerhead sea turtles (*Caretta caretta*) are found primarily in waters cooler than 18.5°C and often appear as bycatch, the TurtleWatch program uses remotely sensed sea surface temperatures to publish daily maps of areas for longline fishing vessels to voluntarily avoid (Howell et al., 2008). In a related but mandatory program, the East Australian longline fishery is managed through a series of limited access spatial zones to avoid bluefin tuna (*Thunnus maccoyii*) bycatch. The zones are updated frequently based on known habitat preferences of bluefin tuna and the output from a near-real-time oceanographic model (Hobday et al., 2010).

Coordination Across Static Boundaries

Both short- and long-term shifts of species across national or fixed management boundaries raise complex issues of coordination and equity. If populations shift enough to straddle management boundaries, fishing in both regions can create a situation of "double jeopardy" with competitive harvesting that easily becomes unsustainable (Miller and Munro, 2004). For example, Iceland, the European Union, and other countries want to fish mackerel that have partially shifted into Icelandic waters, and the combined harvest threatens to overfish the stock (Figure 2; Cheung et al., 2012). Pacific salmon harvest in the United States and Canada has been a similarly difficult case of binational coordination (Miller and Munro, 2004).

In economic terms, shifting species can increase the discount rate for fishers and fisheries managers, creating incentives to severely overharvest a stock before it leaves a region (Reed and Heras, 1992). The increased use of limited access in management and the "creeping" enclosure of the commons may intensify this problem by reducing the flexibility of fishers (Murray et al., 2010; Olson, 2011), including their ability to exploit other species that become available as replacements. Future stakeholders on the receiving end of the shifting population would suffer the consequences of this overfishing. Alternatively, a stock may shift into international waters, where coordination among many nations and illegal fishing are substantially greater concerns.

Recognition of this problem has sparked research into potential solutions. Pre-agreements between organizations or nations, for example, can create a clear set of rules for how to adjust quotas and allocations based on indicators of changes in a stock (Miller and Munro, 2004). For stocks that are going to shift from being solely within one jurisdiction to straddling a jurisdictional boundary, projections of future stock distributions may be critical for showing the need for pre-agreements. In contrast, traditional sharing rules are often based on the concept of fixed distributions of a stock among organizations. The ability to trade fishing quotas among fishers across state, national, or other management boundaries could also reduce these incentives to overfish, though nearly all existing quota trading programs are within national boundaries (Costello et al., 2008).

Among nations, side payments have been proposed as an important mechanism to provide flexibility in negotiations and to help ensure that cooperation is worth more to the negotiating parties than competition (Miller and Munro, 2004). For example, swapping multispecies quotas and even cash among countries has been used to manage fluctuating and moving stocks in the Barents Sea and the Baltic Sea (Miller and Munro, 2004). Criteria for these systems to work include a common understanding of stock status (i.e., based on impartial scientific evidence), mechanisms for side payments and for discouraging cheating, and the recognition that unpredicted changes in each party's bargaining position may occur (Miller and Munro, 2004). The latter recognition, namely, that anthropogenic climate change will alter the relative distribution and abundance of shared stocks, is critical for ensuring that mechanisms for cooperation and side payments are developed ahead of time (Miller and Munro, 2004). Economic models also suggest that international cooperation becomes more difficult if the value of a fishery stock declines (Brandt and Kronbak, 2010).

Regional Anthropogenic Climate Change Projections

While the broad consequences of anthropogenic climate change on fishes are becoming increasingly apparent, the impacts in any particular place will depend on the species that are present, the impacts of other stressors, and the geography and oceanography of the region. There is, therefore, a need for region-specific scenarios of future climate and climate impacts. Scientifically, there has been an increasing focus on what is called climate "downscaling," or the translation of relatively coarse-resolution global climate model outputs to finer-resolution projections for a particular location (Stock et al., 2011). There are substantial scientific challenges to downscaling, particularly in nearshore waters, and current approaches range from coarse, first-order projections that can readily be developed from existing Intergovernmental Panel on Climate Change (IPCC)-class models (Hare et al., 2012) to dynamic oceanographic models that can project changes in upwelling, primary productivity, alkalinity, and other factors (Hermann et al., 2013). Making such projections more easily available could spark a wide range of uses, much as the US National Oceanic and Atmospheric Administration (NOAA) Climate Change Web Portal (http://www.esrl.noaa.gov/psd/ipcc) and the Climate Wizard (http://www.climatewizard.org) have begun to do.

Climate models can also be extended to project fish and ecosystem dynamics. The simplest approaches use expert judgment to identify the species most likely to be vulnerable to anthropogenic climate change or most in need of further study, building from first principles and natural history (Chin et al., 2010). More complex bioclimatic envelope models project population distribution from statistical relationships (Hare et al., 2012), while more advanced models include mechanistic dynamics for populations and ecosystems (Hare et al., 2010; Kaplan et al., 2010; Barange et al., 2014).

Long-term regional projections for future ocean conditions and ecosystem states could help inform difficult choices in fisheries management. Projections of species distributions, for example, might help to set long-term goals about which fisheries will be maintained, which closed, and which opened as species shift poleward. Long-term planning could also help to mitigate the impacts of these transitions on businesses and stakeholders. In the Northeast United States, for example, pollock and haddock appear likely to be substantially less available to fisheries by the end of the twenty-first century (Lenoir et al., 2011), but Atlantic croaker are projected to become more abundant (Hare et al., 2010). In the tropical Pacific, many coral reef species are likely to decline, but tuna appears to be an important substitute that may help meet food security needs in the region (Bell et al., 2013). Although climate change impact assessments have been carried out for some regional fish stocks, using future projections to inform real-world decisions remains a major challenge because of our limited understanding of many links in the anthropogenic climate change, regional responses, and ecosystem impacts chain (Snover et al., 2013).

Explicit consideration of future climate is important in the development and assessment of stock rebuilding plans because these plans have the long time

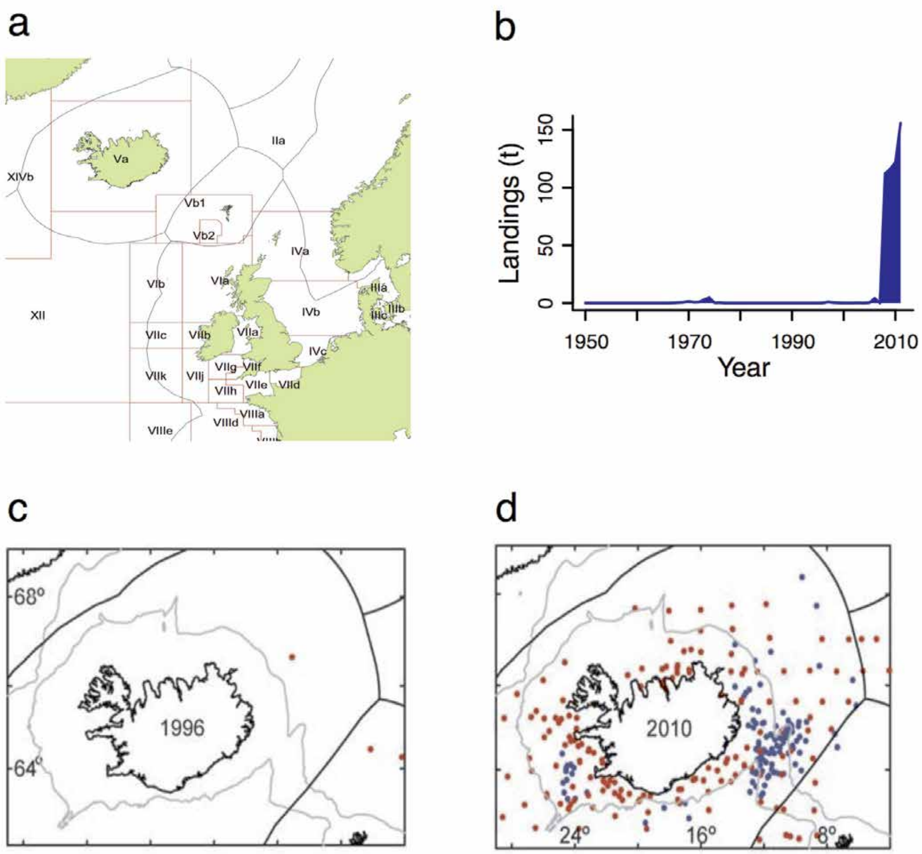


FIGURE 2. Shift of mackerel into Icelandic waters and impacts on the fishery. (a) Map of Exclusive Economic Zones (black) and fishery statistical zones (red) in northern Europe. *From ICES (2008).* (b) Icelandic landings of Atlantic mackerel, showing the rapid increase since 2006. *Data from FAO.* (c) and (d) Mackerel caught in scientific surveys (red) and by the Icelandic pelagic fishing fleet (blue) in 1996 and 2010. *From Astthorsson et al. (2012)*

horizons over which climate effects are likely to accumulate (MacCall, 2002). For example, even lower fishing rates than currently considered may be needed to achieve rebuilding goals for US West Coast rockfish if seasonal upwelling is delayed by climate change (Holt and Punt, 2009). Anthropogenic climate warming may also mean that rebuilding goals for cod stocks near the southern limit of the species' range will, at some future date, become unachievable (Mieszkowska et al., 2009). For other stocks, perhaps including Newfoundland cod, warming temperatures may actually help speed up recovery (Drinkwater, 2005).

Although detailed regional modeling systems that explicitly link future climate projections to changing ecosystems are available, it is imperative to note that uncertainty will remain high and there will always be a chance of unexpected transitions. Such uncertainty is not a reason for failing to consider climate: instead, it means that management approaches should be evaluated against a range of plausible future climate scenarios. Scenario-building and evaluation is now recommended as a routine part of climate adaptation in terrestrial conservation (Gillson et al., 2013). The preferred management approach may be the one that will do the best under a wide range of possible futures, or alternatively, the one that is least likely to do poorly (Kaplan et al., 2010). As one example, simulations suggested that individual transferable quotas would outperform status quo harvest management under a range of ocean acidification scenarios for US West Coast groundfishes (Kaplan et al., 2010).

Real-Time Responses to Climate

It seems likely that many climate change and ocean acidification impacts on fisheries and marine ecosystems will appear as surprises or extreme events over the annual time horizons of fisheries management. History is a cautionary guide here, and there is a long history of overfishing and subsequent stock collapse after a climate transition goes unrecognized, including the case of California sardines in the 1940s/50s and Greenland cod in the 1960s (Brander, 2007).

Comprehensive ecosystem monitoring programs are critically important for detecting ecosystem change, particularly because multiple lines of evidence are often necessary to detect climate-driven ecosystem shifts (Hare and Mantua, 2000). Efforts to greatly expand and broaden monitoring programs and to compile previously disparate programs into centralized, easily accessed databases are a useful step in this direction (e.g., the Global Ocean Observing System [http://www.ioc-goos.org] or the Integrated Ecosystem Assessment program [http://www.noaa.gov/iea]). Indicators can include temperature, primary productivity, upwelling, ocean currents, oxygen, carbonate chemistry, basin-scale climate indices, and the abundances, distributions, and recruitment of species across multiple trophic levels. However, maintaining funding for robust monitoring, integration, and evaluation programs has historically been challenging.

As an example, extensive monitoring of ocean conditions in the eastern Bering Sea revealed declining zooplankton prey, low pollock recruitment, and increased predator abundance from 2000–2005 (Coyle et al., 2011). Based on a mechanistic understanding that pollock recruitment and biomass would likely continue to decline in future years, the North Pacific Fishery Management Council cut the fishery quota by nearly 50% through 2010 (Ianelli et al., 2013). In 2011, new monitoring data suggested a shift back toward more favorable conditions, and the fishery quota was substantially increased (NOAA, 2012).

In some cases, robust monitoring data may detect impending ecosystem shifts before they occur (Scheffer et al., 2012). Substantial research still needs to be done, however, to apply these methods to real-world situations and open marine systems.

US efforts to inject monitoring data more effectively into management process discussions include the Ecosystem Considerations appendix prepared for the North Pacific Fisheries Management Council (Zador and Gaichas, 2010). However, pre-specification of management triggers or control rules is often critical for avoiding contentious and prolonged discussion about what do once a change in ocean conditions has been detected. In Southeast Australia, for example, real-time monitoring of southern bluefin tuna habitat guides in-season spatial closures that reduce bycatch of this vulnerable species (Hobday et al., 2010).

Promotion of Social-Ecological Resilience

Adapting fisheries to climate change and variability is not only about fisheries management; it also involves social and economic transitions for coastal towns and cities that rely on fishing for their culture, identity, and economy. Anthropogenic climate change is nearly certain to change the fishing opportunities available to communities (Sumaila et al., 2011). Progressive ecosystem changes will require adaptive responses, which may include increased travel to new fishing grounds, fishing new species, or transitioning out of fishing altogether (Coulthard, 2009; McCay, 2012; Pinsky and Fogarty, 2012). Each of these options presents both risks and opportunities for individuals and for fishing communities.

Highly specialized fisheries with low flexibility and mobility appear less likely to adapt smoothly to the challenges of climate change. Both fishing and processing capital can lack malleability, which impedes adaptation (McIlgorm et al., 2010). In Maine, for example, the lobster fishery has been proposed as a "gilded trap" that encourages over-specialization and over-investment (Steneck et al., 2011). Fishing communities that target a diversity of species, in contrast, are more likely to adapt smoothly to future changes (Bell et al., 2013). More generally, societies and communities adapted to climatic variability appear to have more flexibility to cope with longer-term climate change (whether natural or anthropogenic), while those used to targeting long-lived, stable species like cod may have fewer coping mechanisms (McCay et al., 2011). However, specialization can also be beneficial in some cases and lead to the accumulation of wealth and other resources (i.e., technology) that can aid adaptation (Sumaila et al., 2011). Efforts are underway to develop a broad suite of social indicators that would identify those coastal communities that are most reliant on fisheries and have high social vulnerability (Jepson and Colburn, 2013). Such communities would be a natural focus for targeted adaptation programs.

> “Maintaining these ecosystem services will require a range of adaptation measures that both sustain ecosystem productivity and support the social and economic systems that capture these services.”

In light of these coming societal transitions, actions that enhance the flexibility of the fishing industry will aid adaptation (Coulthard, 2009; McIlgorm et al., 2010). However, the societal trend in many cases has been in the opposite direction: limited access rights and other changes often make it difficult to enter a fishery (Murray et al., 2010). This situation creates a tension between sustainable fisheries management (for which limited access has been important) and the desire to foster long-term adaptive capacity. Co-management, or the sharing of regulatory decision making between the government and fishing stakeholders has been suggested as one mechanism for enhancing the ability of fishing communities to cope with change, as long as stakeholder incentives promote long-term planning (McCay et al., 2011). Transferable fishing quotas are another option for enhancing flexibility (Costello et al., 2008). Efforts to promote alternative, underdeveloped fisheries and livelihood diversification have been proposed as ways to foster adaptation, along with recommendations to reduce perverse incentives (including many subsidies) and to provide transitional funding sources to the fishing industry (McIlgorm et al., 2010; Sumaila et al., 2011).

CONCLUSIONS

In the face of stochastic recruitment and the often monthly to multi-annual time horizons for decision making in fisheries management, climate change can seem like a distant and abstract problem. However, the impacts of natural climate variations and anthropogenic climate change on marine ecosystems are becoming increasingly clear, and efforts are underway around the world to integrate climate adaptation into fisheries management. This review highlights a few of the promising approaches that have emerged to date. These can be summarized as eight adaptation approaches that together constitute a “toolbox” of strategies. Which approach or approaches listed below will be most useful in any given situation will depend on social and ecological context.

- Address cumulative impacts on marine ecosystems
- Prepare for sustainable management of emerging fisheries
- Adjust reference points as the environment changes
- Move targeted conservation areas when needed, but leave broad-purpose areas in place
- Prepare international agreements for shifts in species distributions
- Evaluate management against a range of regional scenarios for anthropogenic climate change impacts on ocean habitats and ecosystems
- Integrate monitoring and evaluation of climate and ecosystem states into the management cycle
- Reduce barriers to individual-level adaptation where possible

These strategies are not meant to be a complete set of all potential approaches, but they can provide guidance and a useful starting place for adaptation thinking. Considerable research, experimentation, and practice are also needed to implement these strategies. In addition, continued innovation, research, and experimentation will be required as fisheries managers grapple with the challenges posed by the changing ocean, particularly as the impacts of anthropogenic climate change become more severe. Adaptation in small-scale artisanal and subsistence fisheries and in developing country contexts may also require new approaches that were not carefully considered here.

Fisheries provide valuable ecosystem services, including a crucial source of protein for 60% of the world’s population and livelihood support for more than one in every 10 people alive today (FAO, 2012). Maintaining these ecosystem services will require a range of adaptation measures that both sustain ecosystem productivity and support the social and economic systems that capture these services. In the long term, the limits to adaptation remain uncertain, and efforts to mitigate and reduce anthropogenic climate change and ocean acidification should remain a critical part of the discussion.

ACKNOWLEDGMENTS. Many thanks to Mike Fogarty, Bonnie McCay, Roger Griffis, Olaf Jensen, Rebecca Goldburg, Kevin St. Martin, and Faith Kearns for conversations and comments on earlier drafts that helped inform our thinking on these questions. The Pew Charitable Trusts, the National Science Foundation (OCE-1426891 and OCE-1430218), and New Jersey Sea Grant (R/6410-0011) provided support for this project.

REFERENCES

Ainsworth, C.H., J.F. Samhouri, D.S. Busch, W.W.L. Cheung, J. Dunne, and T.A. Okey. 2011. Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES Journal of Marine Science* 68:1,217–1,229, http://dx.doi.org/10.1093/icesjms/fsr043.

Allison, E.H., A.L. Perry, M.-C. Badjeck, W.N. Adger, K. Brown, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries* 10:173–196, http://dx.doi.org/10.1111/j.1467-2979.2008.00310.x.

A'mar, Z.T., A.E. Punt, and M.W. Dorn. 2009. The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. *ICES Journal of Marine Science* 66:1,614–1,632, http://dx.doi.org/10.1093/icesjms/fsp044.

Arkema, K.K., S.C. Abramson, and B.M. Dewsbury. 2006. Marine ecosystem-based management: From characterization to implementation. *Frontiers in Ecology and the Environment* 4:525–532, http://dx.doi.org/10.1890/1540-9295(2006)4[525:MEMFCT]2.0.CO;2.

Astthorsson, O.S., H. Valdimarsson, A. Gudmundsdottir, and G.J. Oskarsson. 2012. Climate-related variations in the occurrence and distribution of mackerel (*Scomber scombrus*) in Icelandic waters. *ICES Journal of Marine Science* 69:1,289–1,297, http://dx.doi.org/10.1093/icesjms/fss084.

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, http://dx.doi.org/10.1038/nclimate2119.

Bell, J.D., A. Ganachaud, P.C. Gehrke, S.P. Griffiths, A.J. Hobday, O. Hoegh-Guldberg, J.E. Johnson, R. Le Borgne, P. Lehodey, J.M. Lough and others. 2013. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change* 3:591–599, http://dx.doi.org/10.1038/nclimate1838.

Branch, T.A., B.M. DeJoseph, L.J. Ray, and C.A. Wagner. 2012. Impacts of ocean acidification on marine seafood. *Trends in Ecology & Evolution* 28:178–186, http://dx.doi.org/10.1016/j.tree.2012.10.001.

Brander, K.M. 2007. Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America* 104:19,709–19,714, http://dx.doi.org/10.1073/pnas.0702059104.

Brandt, U.S., and L.G. Kronbak. 2010. On the stability of fishery agreements under exogenous change: An example of agreements under climate change. *Fisheries Research* 101:11–19, http://dx.doi.org/10.1016/j.fishres.2009.08.012.

Chavez, F.P., M. Messié, and J.T. Pennington. 2011. Marine primary production in relation to climate variability and change. *Annual Review of Marine Science* 3:227–260, http://dx.doi.org/10.1146/annurev.marine.010908.163917.

Cheung, W.W.L., J.K. Pinnegar, G. Merino, M.C. Jones, and M. Barange. 2012. Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 22(3):368–388, http://dx.doi.org/10.1002/aqc.2248.

Chin, A., P.M. Kyne, T.I. Walker, and R.B. McAuley. 2010. An integrated risk assessment for climate change: Analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Global Change Biology* 16:1,936–1,953, http://dx.doi.org/10.1111/j.1365-2486.2009.02128.x.

Cochrane, K., C. De Young, D. Soto, and T. Bahri. 2009. *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*. Fisheries and Aquaculture Technical Paper 530, Food and Agriculture Organization of the United Nations, Rome, 213 pp.

Collie, J.S., R.M. Peterman, and B.M. Zuehlke. 2012. A fisheries risk-assessment framework to evaluate trade-offs among management options in the presence of time-varying productivity. *Canadian Journal of Fisheries and Aquatic Sciences* 69:209–223, http://dx.doi.org/10.1139/F2011-148.

Collie, J.S., A.D. Wood, and H.P. Jeffries. 2008. Long-term shifts in the species composition of a coastal fish community. *Canadian Journal of Fisheries and Aquatic Sciences* 65:1,352–1,365, http://dx.doi.org/10.1139/F08-048.

Costello, C., S.D. Gaines, and J. Lynham. 2008. Can catch shares prevent fisheries collapse? *Science* 321:1,678–1,681, http://dx.doi.org/10.1126/science.1159478.

Coulthard, S. 2009. Adaptation and conflict within fisheries: Insights for living with climate change. Pp. 255–268 in *Adapting to Climate Change: Thresholds, Values, Governance*. W.N. Adger, I. Lorenzoni, and K.L. O'Brien, eds, Cambridge University Press, Cambridge, UK.

Coyle, K.O., L.B. Eisner, F.J. Mueter, A.I. Pinchuk, M.A. Janout, K.D. Cieciel, E.V. Farley, and A.G. Andrews. 2011. Climate change in the southeastern Bering Sea: Impacts on pollock stocks and implications for the oscillating control hypothesis. *Fisheries Oceanography* 20:139–156, http://dx.doi.org/10.1111/j.1365-2419.2011.00574.x.

Deriso, R.B., M.N. Maunder, and W.H. Pearson. 2008. Incorporating covariates into fisheries stock assessment models with application to Pacific herring. *Ecological Applications* 18:1,270–1,286, http://dx.doi.org/10.1890/07-0708.1.

Deyle, E.R., M.J. Fogarty, C.-h. Hsieh, L. Kaufman, A.D. MacCall, S.B. Munch, C.T. Perretti, H. Ye, and G. Sugihara. 2013. Predicting climate effects on Pacific sardine. *Proceedings of the National Academy of Sciences of the United States of America* 110:6,430–6,435, http://dx.doi.org/10.1073/pnas.1215506110.

Dorner, B., R.M. Peterman, and Z. Su. 2009. Evaluation of performance of alternative management models of Pacific salmon (*Oncorhynchus* spp.) in the presence of climatic change and outcome uncertainty using Monte Carlo simulations. *Canadian Journal of Fisheries and Aquatic Sciences* 66:2,199–2,221, http://dx.doi.org/10.1139/F09-144.

Drinkwater, K.F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. *ICES Journal of Marine Science* 62:1,327–1,337, http://dx.doi.org/10.1016/j.icesjms.2005.05.015.

FAO (Food and Agriculture Organization of the United Nations). 2012. *The State of World Fisheries and Aquaculture.* 2012. Food and Agriculture Organization of the United Nations, FAO Fisheries and Aquaculture Department, Rome, 230 pp.

Fisher, J.A.D., and K.T. Frank. 2004. Abundance-distribution relationships and conservation of exploited marine fishes. *Marine Ecology Progress Series* 279:201–213, http://dx.doi.org/10.3354/meps279201.

Gillson, L., T.P. Dawson, S. Jack, and M.A. McGeoch. 2013. Accommodating climate change contingencies in conservation strategy. *Trends in Ecology & Evolution* 28:135–142, http://dx.doi.org/10.1016/j.tree.2012.10.008.

Glaser, S.M., M.J. Fogarty, H. Liu, I. Altman, C.-h. Hsieh, L. Kaufman, A.D. MacCall, A.A. Rosenberg, H. Ye, and G. Sugihara. 2013. Complex dynamics may limit prediction in marine fisheries. *Fish and Fisheries*, http://dx.doi.org/10.1111/faf.12037.

Haltuch, M.A., and A.E. Punt. 2011. The promises and pitfalls of including decadal-scale climate forcing of recruitment in groundfish stock assessment. *Canadian Journal of Fisheries and Aquatic Sciences* 926:912–926, http://dx.doi.org/10.1139/F2011-030.

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, http://dx.doi.org/10.1890/08-1863.1.

Hare, J.A., J.P. Manderson, J.A. Nye, M.A. Alexander, P.J. Auster, D.L. Borggaard, A.M. Capotondi, K.B. Damon-Randall, E. Heupel, I. Mateo, and others. 2012. Cusk (*Brosme brosme*) and climate change: Assessing the threat to a candidate marine fish species under the US Endangered Species Act. *ICES Journal of Marine Science* 69:1,753–1,768, http://dx.doi.org/10.1093/icesjms/fss160.

Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47:103–145, http://dx.doi.org/10.1016/S0079-6611(00)00033-1.

Harley, C.D.G., and R.T. Paine. 2009. Contingencies and compounded rare perturbations dictate sudden distributional shifts during periods of gradual climate change. *Proceedings of the National Academy of Sciences of the United States of America* 106:11,172–11,176, http://dx.doi.org/10.1073/pnas.0904946106.

Hart, D.R., and S.X. Cadrin. 2004. Yellowtail flounder (*Limanda ferruginea*) off the northeastern United States: Implications of movement among stocks. Pp. 230–244 in *Species Conservation and Management: Case Studies.* H.R. Akçakaya, M.A. Burgman, O. Kindvall, C.C. Wood, P. Sjögren-Gulve, J.S. Hatfield, and M.A. McCarthy, eds, Oxford University Press, Oxford.

Hastings, A., K. Cuddington, K.F. Davies, C.J. Dugaw, S. Elmendorf, A.L. Freestone, S. Harrison, M.D. Holland, J. Lambrinos, U. Malvadkar, and others. 2005. The spatial spread of invasions: New developments in theory and evidence. *Ecology Letters* 8:91–101, http://dx.doi.org/10.1111/j.1461-0248.2004.00687.x.

Hermann, A.J., G.A. Gibson, N.A. Bond, E.N. Curchitser, K. Hedstrom, W. Cheng, M. Wang, P.J. Stabeno, L. Eisner, and K.D. Cieciel. 2013. A multivariate analysis of observed and modeled biophysical variability on the Bering Sea shelf: Multidecadal hindcasts (1970–2009) and forecasts (2010–2040). *Deep Sea Research Part II* 94:121–139, http://dx.doi.org/10.1016/j.dsr2.2013.04.007.

Hilborn, R.W., T.P. Quinn, D.E. Schindler, and D.E. Rogers. 2003. Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 100:6,564-6,568, http://dx.doi.org/10.1073/pnas.1037274100.

Hilborn, R., and C.J. Walters. 1992. *Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty*. Kluwer Academic Publishers, Boston, 570 pp.

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, http://dx.doi.org/10.1111/j.1365-2419.2010.00540.x.

Holt, C.A., and A.E. Punt. 2009. Incorporating climate information into rebuilding plans for overfished groundfish species of the US west coast. *Fisheries Research*, 100:57–67, http://dx.doi.org/10.1016/j.fishres.2009.03.002.

Howell, E.A., D.R. Kobayashi, D.M. Parker, G.H. Balazs, and J.J. Polovina. 2008. TurtleWatch: A tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. *Endangered Species Research* 5:267–278, http://dx.doi.org/10.3354/esr00096.

Hsieh, C.-h., S.M. Glaser, A.J. Lucas, and G. Sugihara. 2005. Distinguishing random environmental fluctuations from ecological catastrophes for the North Pacific Ocean. *Nature* 435:336–340, http://dx.doi.org/10.1038/nature03553.

Hsieh, C.-h., C.S. Reiss, J.R. Hunter, J.R. Beddington, R.M. May, and G. Sugihara. 2006. Fishing elevates variability in the abundance of exploited species. *Nature* 443:859–862, http://dx.doi.org/10.1038/nature05232.

Ianelli, J.N., T. Honkalehto, S. Barbeaux, S. Kotwicki, K. Aydin, and N. Williamson. 2013. Assessment of the walleye pollock stock in the Eastern Bering Sea. Pp. 53–152 in *NPFMC Bering Sea and Aleutian Islands SAFE*. The Plan Team for the Groundfish Fisheries of the Bering Sea and Aleutian Islands, ed., North Pacific Fishery Management Council, Anchorage, AK.

ICCAT (International Commission for the Conservation of Atlantic Tunas). 2013. *Report of the 2013 Atlantic Swordfish Stock Assessment Session*. Olhão, Portugal, September 2–10, 2013, Doc. No. SCI-036/2013, International Commission for the Conservation of Atlantic Tunas, Madrid, Spain, 123 pp.

ICES (International Council for the Exploration of the Sea). 2008. *Report of the Working Group on Widely Distributed Stocks (WGWIDE)*. 21-1 September 2008, ICES Headquarters Copenhagen, 67 pp, http://www.ices.dk/sites/pub/Publication Reports/Expert Group Report/acom/2008/WGWIDE/WGWIDE08.pdf.

Jacobson, L.D., and A.D. MacCall. 1995. Stock-recruitment models for Pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Sciences* 52:566–577, http://dx.doi.org/10.1139/f95-057.

Jacobson, L.D., and S. McClatchie. 2013. Comment on temperature-dependent stock–recruit modeling for Pacific sardine (*Sardinops sagax*) in Jacobson and MacCall (1995), McClatchie et al. (2010), and Lindgren and Checkley (2013). *Canadian Journal of Fisheries and Aquatic Sciences* 70:1,566–1,569, http://dx.doi.org/10.1139/cjfas-2013-0128.

Jensen, O.P., and T.J. Miller. 2005. Geostatistical analysis of the abundance and winter distribution patterns of the blue crab *Callinectes sapidus* in Chesapeake Bay. *Transactions of the American Fisheries Society* 134:1,582–1,598, http://dx.doi.org/10.1577/T04-218.1.

Jepson, M., and L.L. Colburn 2013. *Development of Social Indicators of Fishing Community Vulnerability and Resilience in the US Southeast and Northeast Regions*. NOAA Technical Memo NMFS-F/SPO-129, US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Regional Office, St. Petersburg, FL, 64 pp.

Jiao, Y. 2009. Regime shift in marine ecosystems and implications for fisheries management, a review. *Reviews in Fish Biology and Fisheries* 19:177–191, http://dx.doi.org/10.1007/s11160-008-9096-8.

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* 67:1,968–1,982, http://dx.doi.org/10.1139/F10-118.

Kell, L., G. Pilling, and C. O'Brien. 2005. Implications of climate change for the management of North Sea cod (*Gadus morhua*). *ICES Journal of Marine Science* 62:1,483–1,491, http://dx.doi.org/10.1016/j.icesjms.2005.05.006.

Kelly, R.P., M.M. Foley, W.S. Fisher, R.A. Feely, B.S. Halpern, G.G. Waldbusser, and M.R. Caldwell. 2011. Mitigating local causes of ocean acidification with existing laws. *Science* 332:1,036–1,037, http://dx.doi.org/10.1126/science.1203815.

Kendall, A.W., and J. Duker. 1998. The development of recruitment fisheries oceanography in the United States. *Fisheries Oceanography* 7:69–88, http://dx.doi.org/10.1046/j.1365-2419.1998.00056.x.

Keyl, F., and M. Wolff. 2007. Environmental variability and fisheries: What can models do? *Reviews in Fish Biology and Fisheries* 18:273–299, http://dx.doi.org/10.1007/s11160-007-9075-5.

King, J.R., G.A. McFarlane. 2006. A framework for incorporating climate regime shifts into the management of marine resources. *Fisheries Management and Ecology* 13:93–102, http://dx.doi.org/10.1111/j.1365-2400.2006.00480.x.

Lehodey, P., J. Alheit, M. Barange, T.R. Baumgartner, G. Beaugrand, K.F. Drinkwater, J.-M. Fromentin, S.R. Hare, G. Ottersen, R.I. Perry, and others. 2006. Climate variability, fish, and fisheries. *Journal of Climate* 19:5,009–5,030, http://dx.doi.org/10.1175/JCLI3898.1.

Lenoir, S., G. Beaugrand, and É. Lecuyer. 2011. Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. *Global Change Biology*, 17:115–129, http://dx.doi.org/10.1111/j.1365-2486.2010.02229.x.

Lindegren, M., D.M. Checkley, T. Rouyer, A.D. MacCall, N.C. Stenseth. 2013. Climate, fishing, and fluctuations of sardine and anchovy in the California Current. *Proceedings of the National Academy of Sciences of the United States of America* 110:13,672–13,677, http://dx.doi.org/10.1073/pnas.1305733110.

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, http://dx.doi.org/10.1111/j.1467-2979.2010.00398.x.

Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, E. Moran, A.N. Pell, P. Deadman, T. Kratz, J. Lubchenco, and others. 2007. Complexity of coupled human and natural systems. *Science* 317:1,513–1,516, http://dx.doi.org/10.1126/science.1144004.

MacCall, A.D. 2002. Fishery-management and stock-rebuilding prospects under conditions of low-frequency environmental variability and species interactions. *Bulletin of Marine Science* 70:613–628.

Mace, P.M. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries* 2:2–32, http://dx.doi.org/10.1046/j.1467-2979.2001.00033.x.

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. *Fishery Bulletin* 101:89–99, http://fishbull.noaa.gov/1011/08maunde.pdf.

McCay, B.J. 2012. Shifts in fishing grounds. *Nature Climate Change* 2:840–841, http://dx.doi.org/10.1038/nclimate1765.

McCay, B.J., W. Weisman, and C. Creed. 2011. Coping with environmental change: Systemic responses and the roles of property and community in three fisheries. Pp. 381–400 in *World Fisheries: A Socio-Ecological Analysis*. R.E. Ommer, R.I. Perry, K. Cochrane, and P. Cury, eds, Blackwell Publishing, West Sussex, UK.

McIlgorm, A., S. Hanna, G. Knapp, P. Le Floc'H, F. Millerd, and M. Pan. 2010. How will climate change alter fishery governance? Insights from seven international case studies. *Marine Policy* 34:170–177, http://dx.doi.org/10.1016/j.marpol.2009.06.004.

McLeod, K.L., and H.M. Leslie, eds. 2009. *Ecosystem-Based Management for the Oceans*. Island Press, Washington, DC, 392 pp.

Methot, R.D. Jr., and C.R. Wetzel. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research* 142:86–99, http://dx.doi.org/10.1016/j.fishres.2012.10.012.

Mieszkowska, N., M.J. Genner, S.J. Hawkins, and D.W. Sims. 2009. Effects of climate change and commercial fishing on Atlantic cod *Gadus morhua*. Pp. 213–273 in *Advances in Marine Biology*. D.W. Sims, ed., Elsevier, Boston, MA.

Miller, K., A. Charles, M. Barange, K. Brander, V.F. Gallucci, M.A. Gasalla, A. Khan, G. Munro, R. Murtugudde, R.E. Ommer, and others. 2010. Climate change, uncertainty, and resilient fisheries: Institutional responses through integrative science. *Progress in Oceanography* 87:338–346, http://dx.doi.org/10.1016/j.pocean.2010.09.014.

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., A.J. Pershing, C. Brown, Y. Chen, F.-S. Chiang, D.S. Holland, S. Lehuta, J.A. Nye, J. Sun, A. Thomas, and others. 2013. Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography* 26:191–195, http://dx.doi.org/10.5670/oceanog.2013.27.

Mueter, F.J., R.M. Peterman, and B.J. Pyper. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. *Canadian Journal of Fisheries and Aquatic Sciences* 463:456–463, http://dx.doi.org/10.1139/F02-020.

Murray, G., T.R. Johnson, B.J. McCay, K. St. Martin, and S. Takahashi. 2010. Cumulative effects, creeping enclosure, and the marine commons of New Jersey. *International Journal of the Commons* 4(1), http://www.thecommonsjournal.org/index.php/ijc/article/view/148.

Myers, R.A. 1998. When do environment-recruitment correlations work? *Reviews in Fish Biology and Fisheries* 8:285–305, http://dx.doi.org/10.1023/A:1008828730759.

NEFSC (Northeast Fisheries Science Center). 2014. *58th Northeast Regional Stock Assessment Workshop (SAW 58) Assessment Report*. Northeast Fisheries Science Center Reference Document 14-04, US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA, 784 pp, http://nefsc.noaa.gov/publications/crd/crd1404.

NOAA (National Oceanic and Atmospheric Administration). 2012. *Climate & Fish Sticks*, http://www.climate.gov/news-features/climate-and/climate-fish-sticks.

Olson, J. 2011. Understanding and contextualizing social impacts from the privatization of fisheries: An overview. *Ocean & Coastal Management* 54:353–363, http://dx.doi.org/10.1016/j.ocecoaman.2011.02.002.

Perry, A.L., P.J. Low, J.R. Ellis, and J.D. Reynolds. 2005. Climate change and distribution shifts in marine fishes. *Science* 308:1,912–1,915, http://dx.doi.org/10.1126/science.1111322.

Peterman, R.M., B.J. Pyper, and J.A. Grout. 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (*Oncorhynchus* spp.). *Canadian Journal of Fisheries and Aquatic Sciences* 57:181–191, http://dx.doi.org/10.1139/cjfas-57-1-181.

Petitgas, P., J. Alheit, M.A. Peck, K. Raab, X. Irigoien, M. Huret, J. van der Kooij, T. Pohlmann, C. Wagner, I. Zarraonaindia, and others. 2012. Anchovy population expansion in the North Sea. *Marine Ecology Progress Series* 444:1–13, http://dx.doi.org/10.3354/meps09451.

PFMC (Pacific Fishery Management Council). 2014. *Decision Summary Document: Pacific Fishery Management Council Meeting, March 8–13, 2014*. Pacific Fishery Management Council, Portland, OR, 6 pp.

Pikitch, E.K., C. Santora, E.A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, P.K. Dayton, P. Doukakis, D.L. Fluharty, B. Heneman, and others. 2004. Ecosystem-based fishery management. *Science* 305:346-347, http://dx.doi.org/10.1126/science.1098222.

Pinsky, M.L., and M. Fogarty. 2012. Lagged social-ecological responses to climate and range shifts in fisheries. *Climatic Change* 115:883–891, http://dx.doi.org/10.1007/s10584-012-0599-x.

Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin. 2013. Marine taxa track local climate velocities. *Science* 341:1,239–1,242, http://dx.doi.org/10.1126/science.1239352.

Planque, B., J.-M. Fromentin, P. Cury, K.F. Drinkwater, S. Jennings, R.I. Perry, and S. Kifani. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? *Journal of Marine Systems* 79:403–417, http://dx.doi.org/10.1016/j.jmarsys.2008.12.018.

Pörtner, H.O., D. Karl, P.W. Boyd, W. Cheung, S.E. Lluch-Cota, Y. Nojiri, D.N. Schmidt, and P. Zavialov. 2014. Ocean systems. Chapter 6 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, eds, Cambridge University Press, Cambridge, UK and New York, NY, USA, http://ipcc-wg2.gov/AR5/report.

Reed, W.J., and H E. Heras. 1992. The conservation and exploitation of vulnerable resources. *Bulletin of Mathematical Biology* 54:185–207, http://www.sciencedirect.com/science/article/pii/S0092824005800229.

Scheffer, M., S.R. Carpenter, T.M. Lenton, J. Bascompte, W.A. Brock, V. Dakos, J. van de Koppel, I.A. van de Leemput, S.A. Levin, E.H. van Nes, and others. 2012. Anticipating critical transitions. *Science* 338:344–348, http://dx.doi.org/10.1126/science.1225244.

Schirripa, M.J., and J.J. Colbert. 2005. *Status of the Sablefish Resource off the Continental US Pacific Coasts in 2005*. Pacific Fishery Management Council, Portland, OR, 161 pp.

Shelton, A.O. and M. Mangel. 2011. Fluctuations of fish populations and the magnifying effects of fishing. *Proceedings of the National Academy of Sciences of the United States of America* 108:7,075–7,080, http://dx.doi.org/10.1073/pnas.1100334108.

Smith, A.D.M., E.J. Fulton, A.J. Hobday, D.C. Smith, and P. Shoulder. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science* 64:633–639, http://dx.doi.org/10.1093/icesjms/fsm041.

Snover, A.K., N.J. Mantua, J.S. Littell, M.A. Alexander, M.M. McClure, and J. Nye. 2013. Choosing and using climate-change scenarios for ecological-impact assessments and conservation decisions. *Conservation Biology* 27:1,147-1,157, http://dx.doi.org/10.1111/cobi.12163.

St. Martin, K., B.J. McCay, G.D. Murray, T.R. Johnson, and B. Oles. 2007. Communities, knowledge and fisheries of the future. *International Journal of Global Environmental Issues* 7:221, http://dx.doi.org/10.1504/IJGENVI.2007.013575.

Steneck, R.S., T.P. Hughes, J.E. Cinner, W.N. Adger, S.N. Arnold, F. Berkes, S.A. Boudreau, K. Brown, C. Folke, L. Gunderson, and others. 2011. Creation of a gilded trap by the high economic value of the Maine lobster fishery. *Conservation Biology* 25:904–912, http://dx.doi.org/10.1111/j.1523-1739.2011.01717.x.

Stewart, I.J., J.T. Thorson, and C. Wetzel. 2011. *Status of the US Sablefish Resource in 2011*. Pacific Fishery Management Council, Portland, OR, 442 pp, http://www.pcouncil.org/wp-content/uploads/Sablefish_2011_Assessment.pdf.

Stock, C.A., M.A. Alexander, N.A. Bond, K. Brander, W.W.L. Cheung, E.N. Curchitser, T.L. Delworth, J.P. Dunne, S.M. Griffies, M.A. Haltuch, and others. 2011. On the use of IPCC-class models to assess the impact of climate on living marine resources. *Progress in Oceanography* 88:1–27, http://dx.doi.org/10.1016/j.pocean.2010.09.001.

Stram, D.L., and D.C.K. Evans. 2009. Fishery management responses to climate change in the North Pacific. *ICES Journal of Marine Science* 66:1,633–1,639, http://dx.doi.org/10.1093/icesjms/fsp138.

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, http://dx.doi.org/10.1038/nclimate1301.

Sunday, J.M., A.E. Bates, and N.K. Dulvy. 2012. Thermal tolerance and the global redistribution of animals. *Nature Climate Change* 2:686–690, http://dx.doi.org/10.1038/nclimate1539.

The Associated Press. 2009. WA state lets fishermen sell salmon-eating squid. In *The Seattle Times* September 13, 2009. The Seattle Times Company Seattle, WA, http://seattletimes.com/html/localnews/2009859494_apwahumboldtsquid1stldwritethru.html.

Trenberth, K.E., and J.T. Fasullo. 2013. An apparent hiatus in global warming? *Earth's Future* 1:19–32, http://dx.doi.org/10.1002/2013EF000165.

Turner, W.R., B.A. Bradley, L.D. Estes, D.G. Hole, M. Oppenheimer, and D.S. Wilcove. 2010. Climate change: Helping nature survive the human response. *Conservation Letters* 3:304–312, http://dx.doi.org/10.1111/j.1755-263X.2010.00128.x.

van Keeken, O.A., M. van Hoppe, R.E. Grift, and A.D. Rijnsdorp. 2007. Changes in the spatial distribution of North Sea plaice (*Pleuronectes platessa*) and implications for fisheries management. *Journal of Sea Research* 57:187–197, http://dx.doi.org/10.1016/j.seares.2006.09.002.

Vert-pre, K.A., R.O. Amoroso, O.P. Jensen, and R.W. Hilborn. 2013. Frequency and intensity of productivity regime shifts in marine fish stocks. *Proceedings of the National Academy of Sciences of the United States of America* 110:1,779–1,784, http://dx.doi.org/10.1073/pnas.1214879110.

Walters, C.J., and S.J.D. Martell. 2004. *Fisheries Ecology and Management*. Princeton University Press, Princeton, NJ, 448 pp.

Walters, C., and A.M. Parma. 1996. Fixed exploitation rate strategies for coping with effects of climate change. *Canadian Journal of Fisheries and Aquatic Sciences* 53:148–158.

Wong, P.P., I.J. Losada, J.P. Gattuso, J. Hinkel, A. Khattabi, K.L. McInnes, Y. Saito, and A. Sallenger. 2014. Coastal systems and low-lying areas. Chapter 5 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, eds, Cambridge University Press, Cambridge, UK, and New York, NY, USA, http://www.ipcc.ch/report/ar5/wg2.

Zador, S., and S. Gaichas 2010. Ecosystem considerations for 2011. Appendix C in *Bering Sea/Aleutian Islands and Gulf of Alaska Groundfish Stock Assessment and Fishery Evaluation*. North Pacific Fishery Management Council, Anchorage, AK, 242 pp.