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Contribution to the symposium: '*The effects of climate change on the world's oceans*'

Food for Thought

Towards climate resiliency in fisheries management

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It is increasingly evident that climate change is having significant impacts on marine ecosystems and dependent fisheries. Yet, translating climate science into management actions and policies is an ongoing challenge. In particular, four aspects have confounded implementation of climate-resilient management: (i) regional management tools may not be well-suited for managing the same systems under climate change, (ii) individual management policies and climate research studies are often implicitly focussed on spatio-temporal scales that are rarely aligned, (iii) management approaches seldom integrate across spatio-temporal scales and are, therefore, maladapted to unidirectional change and extreme events, and (iv) challenges to modelling socio-economic implications of climate change impede projections of cumulative costs to society, disguise adaptive limits, and ultimately impact climate risk and management trade-off assessments. We suggest that addressing environmental change favours adaptive and dynamic management approaches, while addressing shifting socio-economic and political conditions favours fixed long-term measures; considering both jointly requires a combination of dynamic-adaptive-fixed approaches. We outline a framework to integrate climate-responsive tools into a unified climate-resilient management approach using nested dynamic-adaptive-fixed management portfolios that improve management effectiveness and efficiency. This approach may help reduce future conflict between marine resource extractive and conservation goals through more explicit characterization of management trade-offs and identification of social and ecological tipping points.

Keywords: climate change, dynamic management, EBM, fisheries, marine, social-ecological systems

Introduction

Climate change poses an unprecedented risk to food and economic security for more than 3 billion people globally who depend on marine ecosystems (Barange *et al.*, 2010; Hollowed *et al.*, 2013; Poloczanska *et al.*, 2013; IPCC, 2014a; Gattuso *et al.*, 2015; Barange, 2018). Climate change risks increase with delays in implementation of adaptation measures (Melvin *et al.*, 2016) and include increased frequency and magnitude of extreme events and long-term warming trends (IPCC, 2014a; Allison and Bassett, 2015; Gattuso *et al.*, 2015). In the ocean, these risks are amplified by near and distant impacts on associated social-ecological systems (SES) as species populations more easily cross jurisdictional boundaries, confront physiological limits, or traverse ecological and management tipping points in response to changing ocean conditions (Hollowed *et al.*, 2013; Barange *et al.*, 2014; IPCC, 2014a; Pinsky and Mantua, 2014; Szuwalski and Hollowed, 2016;

Pinsky *et al.*, 2018). Despite uncertainty regarding the specific response *per se* of marine systems to climate change (Hollowed *et al.*, 2013; IPCC, 2014a; Punt *et al.*, 2014), it is clear that regional processes and pressures among three axes of internal and extrinsic influence—climate, socio-economic, and ecological—will together shape climate adaptation strategies (Hollowed *et al.*, 2013; Barange *et al.*, 2014; Ebi *et al.*, 2014; IPCC, 2014a, b; Pinsky and Mantua, 2014; Allison and Bassett, 2015; Brander, 2015; Link *et al.*, 2015; Busch *et al.*, 2016; Lubchenco *et al.*, 2016). Yet, while emerging scientific tools advance understanding of regional climate impacts and adaptive responses of marine social-ecological systems, development and coordination of tools has lagged behind terrestrial corollaries, increasing the likelihood of conflicting objectives, duplication of effort, and maladaptation (e.g. short-term gains at long-term costs) (Levin *et al.*, 2013; Noble *et al.*, 2014; Allison and Bassett, 2015). It is of paramount importance to actuate climate-resilient fisheries management (Pinsky and Mantua, 2014; Link *et al.*, 2015; Busch *et al.*, 2016), which we define as precautionary, efficient, and responsive policies that address climate uncertainty, explicitly consider feedbacks within coupled marine social-ecological systems (Liu *et al.*, 2007; Charles, 2012; Lubchenco *et al.*, 2016) and integrate tools and policies at multiple spatiotemporal scales (Lawler *et al.*, 2010; Charles, 2012; Noble *et al.*, 2014; Pinsky and Mantua, 2014; Allison and Bassett, 2015; Brander, 2015; Link *et al.*, 2015; Busch *et al.*, 2016; Costello *et al.*, 2016; Ojea *et al.*, 2016; Tommasi *et al.*, 2017a). Here, we propose a framework to integrate short- to long-term climate-responsive tools into a unified climate-resilient management portfolio for marine social-ecological systems.

Several recent reviews demonstrate that most ingredients for climate-resilient management already exist in the form of adaptive and precautionary ecosystem-based management (EBM) measures (Lawler *et al.*, 2010; Noble *et al.*, 2014; Pinsky and Mantua, 2014; Busch *et al.*, 2016; Costello *et al.*, 2016). Emerging strategic frameworks have also started to broadly identify a hierarchy of critical components to support climate readiness in marine systems (Noble *et al.*, 2014; Busch *et al.*, 2016; Ojea *et al.*, 2016). Although there is a clear need for implementation, and myriad management tools already exist (Pinsky and Mantua, 2014; Busch *et al.*, 2016; Ojea *et al.*, 2016), there remains a lack of organizational structure to translate strategic frameworks and criteria into on-the-ground climate-resilient marine management. Specifically, four aspects have confounded implementation of climate-resilient management policies and research efforts: (i) management systems that are built to adapt to a less dynamic environment may not be well suited for managing under climate change (Noble *et al.*, 2014; Pershing *et al.*, 2015; Costello *et al.*, 2016; Ojea *et al.*, 2016); (ii) individual management policies and climate research studies are seldom coordinated and often implicitly focussed on spatiotemporal scales that are rarely aligned or even explicitly stated, i.e. many climate studies and strategies are global to national and long-term (Barange *et al.*, 2010; Cheung *et al.*, 2015; Gattuso *et al.*, 2015), whereas management policies are often short-term and regional (Noble *et al.*, 2014; Allison and Bassett, 2015; Brander, 2015); (iii) management approaches seldom integrate across scales such that short-term management tools can effectively inform longer-term efforts, and vice versa, and are, therefore, maladapted to unidirectional change and extreme events; and (iv) challenges to modelling socio-economic implications of climate change (e.g. non-linearity, social hysteresis, and non-market valuations) impede projections of cumulative costs to society, disguise adaptive limits, and ultimately impact climate-risk and management trade-off assessments (Adger *et al.*, 2009; Levin *et al.*, 2013; Allison and Bassett, 2015; Haynie and Huntington, 2016; Lynham *et al.*, 2017).

Management and maladaptation under climate change: a need to move forward

"Flexible" marine management policies are increasingly advocated as an approach to address climate-change impacts by allowing management and fisheries to adapt to changing and extreme conditions as they arise (Noble *et al.*, 2014; Pinsky and Mantua, 2014; Gattuso *et al.*, 2015; Busch *et al.*, 2016; Barange *et al.*, 2018). In particular, local and rights-based approaches to fisheries management have emerged as a principle tool to enhance ecological and social resilience under climate change (Charles, 2012; Costello *et al.*, 2016; Ojea *et al.*, 2016). Yet, in some systems, rights-based management approaches may actually limit flexibility (Kasperski and Holland, 2013) and may be more effective when coupled with both dynamic and fixed management measures that address social and environmental variability and hysteresis (Levin *et al.*, 2013). The importance of an integrated approach is further underscored by potential erosion of confidence in management under climate-driven declines of marine species, even within well-managed systems (Mumby *et al.*, 2017).

Maladaptation is a critical consideration for climate-resilient marine management and has been defined as "actions, or inaction that may lead to increased risk of adverse climate-related outcomes" for the social-ecological system (IPCC, 2014b; Noble *et al.*, 2014). Importantly, recent reviews, including that by Thomsen *et al.* (2012), point out that management actions which consider internal variability and self-regulation of social-ecological systems may be less prone to maladaptation (Scheffer *et al.*, 2001; Lubchenco *et al.*, 2016), whereas actions that ignore or try to manipulate the influence of structuring physical and ecological processes "represent short-term strategies with uncertain consequences for resilience and increased risk of maladaptation" (Thomsen *et al.*, 2012; Levin *et al.*, 2013). Although Thomsen *et al.* (2012) focussed on self-regulation of ecological systems, the principles extend to social systems as well, with important implications for the design of climate-resilient marine management (Lubchenco *et al.*, 2016). In fisheries management, some examples of maladaptation include incentives that promote overcapitalization of fisheries that target range-shifting species, inadvertently reducing adaptive capacity of fisheries and fishing communities (Lubchenco *et al.*, 2016), and biased methods of engaging stakeholders that promote inertia in ecosystem states, preventing recovery and reducing flexibility (Lynham *et al.*, 2017). Failure to recognize variability and hysteresis in social systems and priorities and the intrinsic self-regulation of tightly coupled social-ecological systems (Cinner *et al.*, 2016) can similarly lead to selection of social-manipulative policies at increased risk of maladaptation (Levin *et al.*, 2013; Cinner *et al.*, 2016; Lubchenco *et al.*, 2016).

Noble *et al.* (2014) identified multiple considerations for selecting adaptive options that included "designed for an appropriate scope and time frame", "likely to avoid maladaptive traps", and "robust against a wide range of climate and social scenarios", yet for any given approach, these criteria may conflict with other criteria such as "flexible and responsive to feedback and learning" and "efficient (increase benefits and reduced costs)" (Noble *et al.*, 2014). Therefore, in practice, a combination of approaches is needed to reduce risk of maladaptation (Aplet and McKinley, 2017). Simulations demonstrate that underlying assumptions of stationarity in fixed and climate-naive management approaches can bias management advice under long-term change (Thomsen *et al.*, 2012). Other simulations favor dynamic or "climate-informed" adaptive strategies over fixed and climate-naive policies (Tommasi *et al.*, 2017a, b), yet such evaluations often contrast singular fixed and dynamic approaches in isolation of other approaches. The fixed-dynamic contrast represents a false dichotomy; in many areas, marine management is a patchwork of policies that cumulatively interact to influence realized patterns of resource utilization (Sigler *et al.*, 2016). These policies inherently span a range of temporal and spatial scales, rely on multiple sources of information, reflect a diversity of societal objectives, and increasingly incorporate a mix of dynamic and/or adaptive and fixed policies or approaches.

Avoiding maladaptation: climate-resilient management includes dynamic, adaptive, and fixed approaches

Most marine management policies fall within a spectrum of approaches that span fixed measures and adaptive policies and bourgeoning dynamic management approaches (Table 1). Fixed management measures (i.e. those revisited only periodically on decadal or longer scales, such as legislatively mandated policies, marine protected area boundaries, sector/gear specific fishing grounds, aggregate harvest limits, fishing moratoria, transboundary agreements) are, by design, difficult to modify in order to provide long-term protection and ensure persistence across shifting socio-economic pressures.

Once established, fixed measures can be practical in implementation, relatively less data- and resource-intensive than dynamic or adaptive management, and if implemented correctly, can support broad long-term societal goals in the face of rapidly shifting socio-economic priorities. However, fixed measures are often predicated on assumptions of stationarity in (or robustness to) environmental, ecological, and socio-economic conditions (Lewison *et al.*, 2015; Szuwalski and Hollowed, 2016) and can have significant unintended consequences (Abbott and Haynie, 2015). A global assessment of the performance of fixed and dynamic management revealed that dynamic management outperformed fixed management when the mechanisms underlying dynamic change were well known, while fixed measures performed better when mechanisms were less clear (Punt *et al.*, 2014; Fulton *et al.*, 2015). As such, fixed measures may provide some utility when climate-driven change to an ecosystem is uncertain or where novel system dynamics and whole ecosystem reorganization may arise as a result of multiple stressors (Scheffer *et al.*, 2001), including climate change [e.g. continued commercial fishing moratorium in the Arctic Ocean, given uncertainty about climate-driven changes to the ecosystem (Stram and Evans, 2009)].

Adaptive management approaches (e.g. annual or <5-year periodic updates to fixed boundaries, harvest quotas, or target biomasses) recognize the need to adjust management recommendations under varying conditions and, when ideally implemented using limits based on recent observations of species, fishery, and system productivity, can support long-term sustainability in fishery resources. Examples of adaptive management include quota-based fishery management, spatial allocation, rotating closure areas, and seasonal-area closures (e.g. Stram and Evans, 2009). Most adaptive management measures adjust for annual or multiyear variability in resources yet are also predicated on an assumption of long-term stationarity in environmental conditions and species productivity and rarely incorporate climate specific-approaches (Skern-Mauritzen *et al.*, 2016).

Dynamic management approaches (e.g. near-real-time bycatch closure areas, within-season adjustments to harvest periods or habitat access) grew out of a need for management tools that would increase effectiveness over climate-naïve adaptive measures for species whose distribution, abundance, or vulnerability to anthropogenic pressures was highly influenced by shifting conditions (Lewison *et al.*, 2015). Dynamic management utilizes environmental and ecological forecasts, nowcasts, or near-real-time information (e.g. within-year surveys) and input from participants to inform rapid interventions and to tailor management advice and limits to match shifting environmental or ecological conditions (Lewison *et al.*, 2015; Hazen *et al.*, 2018). Dynamic management, thereby, has the potential to reduce unintended management impacts on socio-economic and ecological systems (Hobday *et al.*, 2014, 2016b; Tommasi *et al.*, 2017a). Emerging dynamic management methods perform well in management simulations and applications (e.g. Hobday *et al.*, 2014, 2016b; Tommasi *et al.*, 2017b) and are, therefore, particularly appropriate for managing marine systems under a changing or variable climate (Lawler *et al.*, 2010).

Yet, often overlooked is the vulnerability of dynamic (and adaptive) management targets to manipulation under shifting socio-economic priorities. The regional expertise and oversight needed to execute and enforce dynamic and adaptive management approaches place a high degree of importance on regional priorities, stakeholder buy-in and compliance, and social and political support for consistent funding for high-resolution scientific tools and data essential for successful implementation. Changes in any of these supportive aspects have the potential to hinder the effectiveness of dynamic management in supporting long-term sustainability, increasing maladaptation risk (Noble *et al.*, 2014; Lubchenco *et al.*, 2016). Thus, it is important to consider potential changes in socio-economic priorities when designing scientific tools and data requirements to support flexible marine management approaches (Figure 1) (Levin *et al.*, 2013; Noble *et al.*, 2014; Allison and Bassett, 2015; Lubchenco *et al.*, 2016). Cost-effectiveness and cost-benefit analyses can be especially useful in highlighting the value of investment in personnel, monitoring, and data integration associated with dynamic management.

Building climate-resilient management across multiple scales

For many marine management issues, combinations of global and regional analyses and products are needed in order to identify management approaches that are vulnerable to maladaption under future climate conditions, and to identify measures that are flexible enough to adapt to a range of potential futures. For example, seasonal forecasts have increasing utility for short-term rapid intervention and dynamic management actions (Tommasi *et al.*, 2017a, b), whereas longer-term scenario projections may help evaluate the vulnerability of fixed policies to changing conditions (Figure 2). A combination of approaches can help clarify focal nodes for climate-change adaptation, identify dependent scientific needs, promote adaptation to variability and shocks,

Table 1. Selected examples of short-, medium-, and long-term climate-resilient management approaches.

Management measures	Example	Spatial scale	Frequency of update	"Climate-informed" methods
Short-term				
Rapid intervention	Harvest closures due to harmful algal blooms (HABs) and toxicological exposure	Subbasin	Daily	Risk assessment via climate nowcasts or forecasts; rapid response infrastructure; emergency funds.
Dynamic to seasonal measures	Bycatch reduction measures; endangered species protection; habitat impact reduction	Subbasin, subregional	Daily to annual	Predictive scenarios using projections of catch and bycatch.
Adaptive annual or biannual measures	Annual updates to harvest limits and targets; acceptable take limits	Basin, regional	Annual; biannual	Short-term projections to provide context for management decisions and/or environmentally based predictions of recruitment/ production (e.g. 1–2 years).
Medium-term				
Adaptive biological and ecological reference points	Climate- or multispecies based estimates of unfished biomass; annually varying natural mortality; aggregate maximum sustainable yield.	Basin, regional	1–10 years	Development of climate- and trophic-dependent BRPs based on mechanistic relationships among biological processes and environment.
Fishery stock management approaches	Rationalization programmes/catch-share programmes/essential fish habitat designations	Basin, regional	10–25 years	Projections of various alternative and *status quo* management measures under various climate and socioeconomic scenarios; climate and species projections for future stock share value.
Recovery and rebuilding plans	Overfished stock rebuilding plans; protected species recovery plans	Basin, regional	10–20 years	Projection of climate and environmental conditions; management scenario analyses evaluating species response to long-term climate drift and medium-term decadal variability in climate conditions.
Long-term				
Legislatively mandated conservation measures	Marine protected areas, critical species "take" protection; maximum groundfish harvest in the Eastern Bering Sea; eelgrass protection measures in Puget Sound.	Basin to regional	10–50 years depending on system and projected changes	Spatial analyses of climate-driven spatial shifts that may alter ecosystem productivity under future conditions.
Place-based conservation measures	Arctic commercial fishing moratorium area; California marine protected areas; Canadian marine parks.	Variable from subbasin to international.	10–50 years depending on system and projected changes	Projections of long-term changes in distribution; explorative evaluation of stock accessibility and productivity under future climate conditions.
International jurisdictions	International boundaries for harvest; international agreements for shared stocks	Regional, international	10–50 years depending on system and projected changes	Climate projection data to assess stock availability and access under future scenarios.

ensure consistency across shifting conditions, and provide guidance for long-term management directives. This, in turn, requires multimodel approaches (Hollowed *et al.*, 2013) as well as a plurality of perspectives through diverse stakeholder engagement (Lynham *et al.*, 2017) and multi-institutional and transnational coordination (Allison and Bassett, 2015).

Addressing extreme events and rapid change (<3 years)

Historically, disruptive events and extreme climate variability can cause rapid changes to marine ecosystems (Scheffer *et al.*, 2001) as species move to more favourable conditions, exhibit sudden behavioural and phenological responses to altered conditions, and experience changes in mortality from climate-mediated predation, fishery vulnerability, physiological stress, or toxicity (IPCC, 2014b; Deutsch *et al.*, 2015; Gattuso *et al.*, 2015). Rapid intervention and dynamic management approaches are effective in reducing impacts of episodic events on species and habitats and, when combined with adaptive and fixed measures, have been successful in allowing fisheries to operate efficiently and sustainably under seasonally variable conditions (Hobday *et al.*, 2014; Lewison *et al.*, 2015). For example, as part of the management of the Hawaiian longline swordfish (*Xiphias gladius*) fishery, thermal envelope models based on near-real-time satellite data inform dynamic management measures that reduce bycatch of loggerhead sea turtles (*Caretta caretta*) (Howell *et al.*, 2008, 2015; Lewison *et al.*, 2015). Similarly, near-real-time datastreams are used to reduce bycatch in the California drift gillnet fishery in the California current (Hazen *et al.*, 2018).

For dynamic management approaches that use within-season monitoring, short-term (weekly to seasonal) environmental and biological forecasts could help reduce the risk of crossing ecological and management tipping points (Figure 2) (Scheffer, 2010;

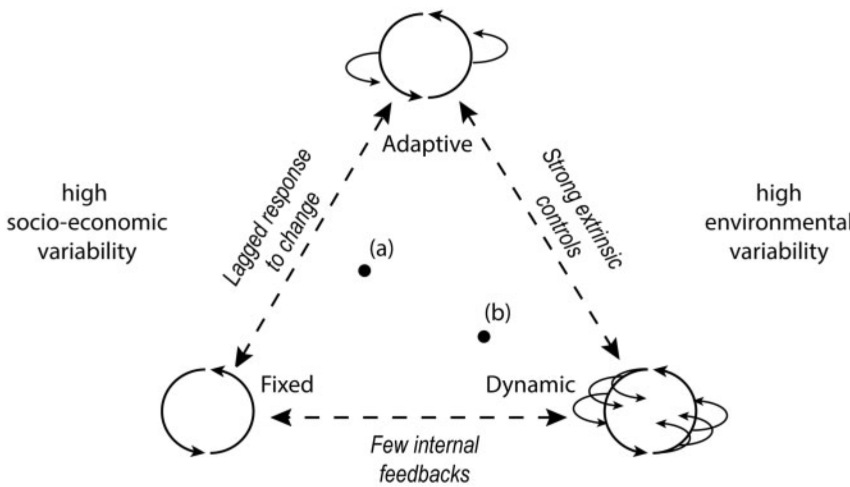

Figure 1. Management portfolio trade-offs. Shifting optimal portfolios for climate-ready management approaches depend on the relative strength of environmental vs. socio-economic variability. (a) When socio-economic conditions are variable, optimal climate-resilient management might include a larger suite of fixed management measures; (b) when socio-economic stability allows for more investment and greater management compliance, optimal management may include more dynamic management approaches.

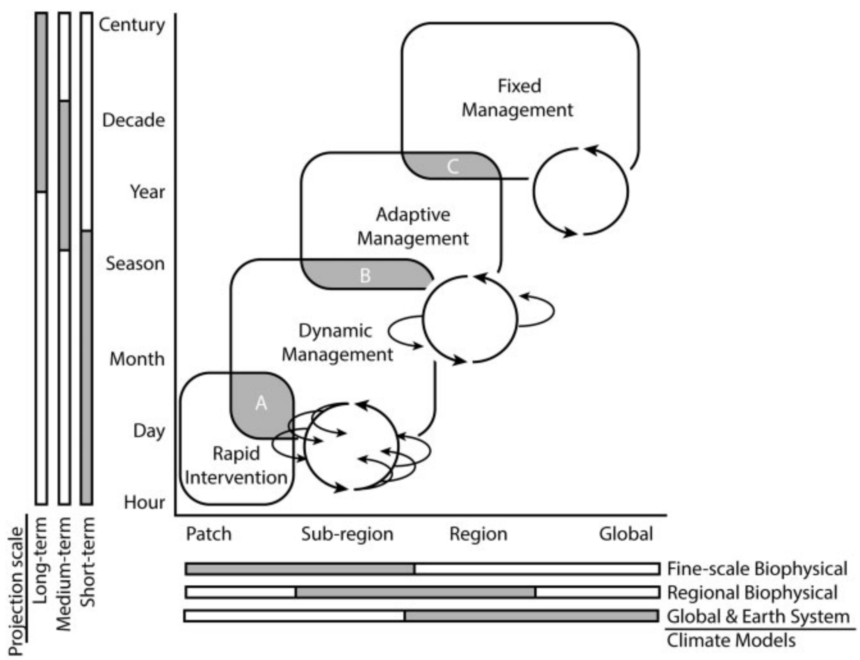

Figure 2. Spatio-temporal scales of marine management and research under climate change. Areas of overlap represent critical nodes of integration for climate-resilient management ("A", between rapid intervention and dynamic management, "B" between dynamic and adaptive management, and "C", between adaptive and fixed management). Horizontal bars (shaded) represent optimal model spatial extent to inform corresponding management (above); fine-scale statistical or mechanistic biophysical models (BPM); regional statistical or mechanistic BPM; global climate and earth system models. Vertical bars (shaded) represent forecast or projection management scenarios to inform corresponding management (right); predictive forecasts (0–3 years); medium- to long-term explorative projections; and medium- to long-term management strategy evaluations. At low spatiotemporal scales, predictive scenarios and risk profiles are optimal for informing climate-resilient management, while as spatiotemporal scales increase, explorative sensitivity scenarios can be used to scope biological response or management strategy evaluations can be used for "stress-tests" of alternative management approaches (note: arrows are graphical representations of the frequency of scientific updates and related management responses).

Kelly *et al.*, 2014, 2015; Lynham *et al.*, 2017) and may help avoid precautionary triggers that rapidly move the extraction–resource relationship into a zone of conservation (e.g. fishery-wide closure due to localized bycatch). Integrating short-term dynamic models with adaptive management triggers would ensure that management adjusts to climate-induced changes in marine taxa distribution and abundance (Lawler *et al.*, 2010; Szuwalski and Hollowed, 2016); such is the case in the Eastern Australian longline fishery where bluefin tuna (*Thunnus maccoyii*) bycatch discard rates have decreased following implementation of pre-fishing bioclimatic forecasting of tuna distributions (Lewison *et al.*, 2015; Hobday *et al.*, 2016b). Scientific advice to support dynamic climate-resilient management might include short-term predictive and ecological forecasts of conditions (Tommasi *et al.*, 2017b) (e.g. inclusion of sea surface temperature forecasts in harvest guidelines increased probability of meeting ecological and socio-economic objectives), distribution, and risk associated with climate variability and change or episodic events (Pinsky *et al.*, 2013; Lewison *et al.*, 2015) (e.g. spatial risk of fisheries bycatch, harmful algal blooms, or shifts in centroids of fish abundance) (Figure 2).

Addressing medium-term change (3–20 years) and decadal-scale variability

Medium-term alterations to marine systems may include decadal-scale climate variability superimposed on long-term trends in climate conditions, a tendency for conditions to drift towards historical bounds, and increased frequency of extreme events that may or may not drive sudden shifts into novel persistent climate regimes (Tommasi *et al.*, 2017a). At the same time, few projection models have sufficient skill at the decadal scale to precisely anticipate the timing of such changes, although they likely have the skill to anticipate the magnitude of change, frequency of events, and potential responses (Tommasi *et al.*, 2017a; Bonan and Doney, 2018). To address this challenge, medium-term adaptive management measures may need to include climate-dependent adaptive EBM strategies and tactical measures (e.g. gear modifications, electronic vessel monitoring devices, and seasonal–area closure measures to decrease habitat loss or reduce incidental harvest of novel or expanding bycatch species) that confer multiple advantages (Allison and Bassett, 2015) and can be adjusted to account for climate-driven shifts in productivity, trophic amplification, and ecological drift (Pinsky and Mantua, 2014; Lewison *et al.*, 2015; Link *et al.*, 2015; Busch *et al.*, 2016) (Table 1). Adaptive management measures, such as annually adjusted catch limits, have proven successful for managing groundfish resources in the Alaskan Bering Sea, which fluctuate substantially with variability in productivity driven by sea ice (Stram and Evans, 2009; Lawler *et al.*, 2010; Lewison *et al.*, 2015).

As with shorter-term approaches, climate-specific management triggers and limits could help prevent unintentional outcomes of interacting regional pressures and climate-driven changes (Link *et al.*, 2015; Busch *et al.*, 2016). For example, overfishing of Northwest Atlantic cod (*Gadus morhua*) may have persisted undetected for years despite the fishery operating within prescribed limits because quotas did not account for climate-driven declines in productivity (Pershing *et al.*, 2015). Latent overfishing that compounded climate impacts on cod productivity might have been avoided if management approaches included climate-specific mortality rates and lower effective population estimates for cod during warm years (Pershing *et al.*, 2015). Management strategy evaluations based on medium- to long-term projections can help screen potential climate-induced pitfalls in existing management and are useful for evaluating the performance of novel climate-specific reference points and alternative strategies (Brander, 2015; Pershing *et al.*, 2015). Such projections would be further strengthened by research that improves understanding of mechanistic linkages between global and regional drivers of change in physical conditions, human communities, ecosystem dynamics, and both individual- and population-level responses of marine species (Brander, 2015; Link *et al.*, 2015; Busch *et al.*, 2016) (e.g. growth, thermal preferences, migratory response, phenology).

Addressing long-term (20+ years) climate change and ecosystem drift

Species may respond to long-term changes in marine conditions by moving into or out of both fishing and marine protected areas, thus impacting assumptions of conservation and vulnerability that underlie existing management boundaries. Similarly, as species cross jurisdictional boundaries or differentially respond to climate conditions, new agreements may be needed to adjust allocations to prevent conflicts and avoid unintended management outcomes (Table 1) (Pinsky *et al.*, 2018). This is the case recently with Atlantic summer flounder (*Paralichthys dentatus*) whose biomass distribution has shifted northward, but whose fishery remains focussed in the southern region (Pinsky and Fogarty, 2012). In that case, because state allocations are fixed and centred around shore-based processors, fish captured in the north must be offloaded and processed at southern locations at a significant increase in fuel cost to southern fleets. The collective behaviour of individuals within social-ecological systems both influences, and is influenced by, local actions that accumulate gradually to inform broad beliefs, cultural values, and sense of risk on longer timescales (Levin *et al.*, 2013). These behaviours can be difficult to forecast, though some evidence would suggest they can be highly adaptive and mitigative (Levin *et al.*, 2013; Haynie and Huntington, 2016).

Thus, while fixed management policies are often essential to meet broad social objectives (e.g. long-term resource conservation), they represent some of the least "climate-resilient" management measures (Lewison *et al.*, 2015). To help reduce cascading economic and social impacts of climate change, fixed management structures should be explicitly integrated with adaptive or dynamic strategies that can adjust management targets and recommendations incrementally—and promote social adaptation that keeps pace with global climate and socio-economic change (Figures 1,2). Where this has arisen in an *ad hoc* manner, such nodes of integration between fixed and adaptive approaches should be identified and preserved, and scientific advice should be used to help delineate climate thresholds. Additionally, periodic evaluation of long-term fixed structures will likely be needed to ensure their continued performance under climate change. Long-term (i.e. 20+ year) projections of the distribution and abundance of marine taxa and habitats, explorative scenarios of socio-economic and biological response, and management strategy evaluations can provide foresight to guide the frequency of such evaluations (Levin *et al.*, 2013; Punt *et al.*, 2014; Brander, 2015). Research could also inform performance and bolster integration with finer-scale adaptive management triggers. For example, research that supports multiyear measures (e.g. market development or new fisheries management plans for novel or expanding species) could be initiated when projections indicate increasingly favourable conditions for climate-tolerant species (Cheung *et al.*, 2015). Altering federal policy and fixed management structures requires a high degree of scientific consensus and stakeholder support that can take years to manifest (Levin *et al.*, 2013; Freestone *et al.*, 2014); using medium to long-term projections and tools to initiate evaluations preemptively can help expedite vetting and garner diverse stakeholder input and support.

Toward a framework for climate-resilient management

Emerging climate-change science strategies and integrated ecosystem-based directives are opportune for coordinating climate-related marine activities in the US (Levin *et al.*, 2014; Link *et al.*, 2015; Busch *et al.*, 2016; Sigler *et al.*, 2016) and with an organized blueprint for development are being used to build climate-resilient management portfolios. Here, we define "climate-resilient" management as an optimal mix of dynamic, adaptive, and fixed approaches that balance regional trade-offs between heterogeneity, redundancy, and modularity in management policies (Levin *et al.*, 2013) (Figure 1) and reflect a plurality of perspectives on social and economic climate impacts (Allison and Bassett, 2015). Building on previous advice (Charles, 2012; Noble *et al.*, 2014; Allison and Bassett, 2015; Busch *et al.*, 2016; Ojea *et al.*, 2016), we propose an element-wise approach to evaluate if management is climate-resilient (Figure 3), which includes considering existing science and management approaches along near- to long-term horizons of management at the appropriate spatial scale(s). This approach resolves the four aspects of many existing management systems mentioned above that can hinder them from being precautionary, efficient, responsive, and integrative under climate change. Case studies involving the US Bering Sea fisheries and the Eastern Australian Southern Bluefin tuna fishery which address several of the following elements are provided in the Supplementary Material.

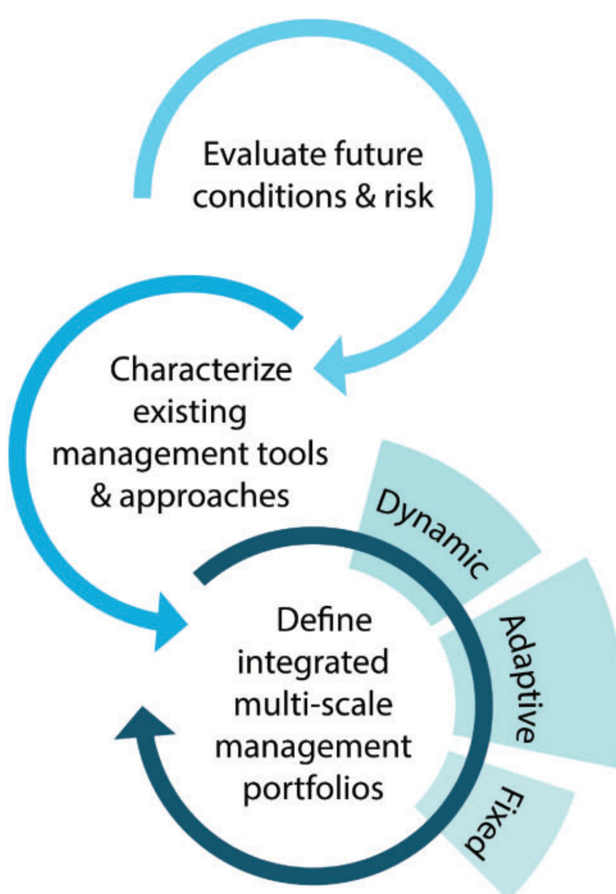

Figure 3. A stepwise approach to preparing fisheries management for climate change: (i) evaluate future condition and risk of the social-ecological system; (ii) characterize existing management on the spectrum of dynamic to adaptive to fixed approaches, identify nodes of integration between approaches and tools, and highlight gaps and uncertainty that may increase vulnerability to maladaptation or manipulation under changing social and climate conditions; (iii) define a portfolio of approaches to facilitate adaptation and resilience to climate-driven change that include a mix of short-term dynamic, medium-term adaptive, and long-term fixed management tools and targets. Use a combination of near-term forecasts and long-term projections to evaluate risk and performance of the integrated management portfolio(s) under climate change.

Element 1: consider future condition and risk of the social-ecological system

Using ecosystem-risk assessment methods that have been reviewed elsewhere (IPCC, 2014b; Levin *et al.*, 2014; Noble *et al.*, 2014; Busch *et al.*, 2016; Colburn *et al.*, 2016; Hare *et al.*, 2016; Himes-Cornell *et al.*, 2016; Holsman *et al.*, 2017) including workshops, expert opinion, and quantitative evaluations, assess the risk and vulnerability of species, habitats, management approaches, and human communities to climate-induced changes. A key component of this evaluation is an assessment of the frequency and magnitude of extreme events over time (e.g. Hobday *et al.*, 2016a) and longer-term historical trends in conditions, exposure, and responses to climate variability and change (Hare *et al.*, 2016). Vulnerable species and management policies, unidirectional "drift" in conditions, and potential ecological and socio-economic tipping points should be advanced as focal nodes for research and targets of climate-resilient management policies.

Element 2: characterize existing management, improve coordination, and identify gaps

Second, through iterative dialogue among scientists, regional managers, and stakeholders, existing regional management approaches should be evaluated and defined along a spectrum of fixed to dynamic approaches and near- to long-term objectives. In this element, it is important to maintain an ecosystem perspective and consider methods across multiple spatial and temporal scales that may interact to influence resource use and associated dynamics (Cochrane *et al.*, 2009). In the United States, fisheries ecosystem plans (Marshall *et al.*, 2017), regional comanagement and tribal councils, Integrated Ecosystems Assessments (Levin *et al.*, 2014), marine spatial planning teams (such as regional planning bodies), and state and county plans can facilitate implementation of this element. Evaluation of existing approaches could include identification of supportive data and scientific tools, availability of both over time, and assessment of future feasibility, given institutional capabilities, jurisdictional relationships, and interactions, and variability in socio-economic support (e.g. funding, willingness, and ability to pay for different scales of data collection and scientific tools). To increase management efficiency, this should include consideration of redundancy across policies and potential reciprocal nodes of integration where fine-scale advice can inform or include long-term projections, and vice versa. This is particular relevant for highly migratory species where data collection and management is (or may become) transboundary and multi-institutional.

Element 3: define optimal portfolio of approaches to facilitate adaptation and resilience

Finally, alternative portfolios of dynamic and fixed management policies should be regularly evaluated in terms of ecosystem and socio-economic resilience criteria, such as those outlined in recent reviews (Noble *et al.*, 2014; Lubchenco *et al.*, 2016; Ojea *et al.*, 2016). The optimal portfolio of fixed, adaptive, and dynamic management measures may be developed from evaluation of environmental, biological, and economic variability, regional oceanography, and management stability as well as the social context (Allison and Bassett, 2015) (e.g. hysteresis in cultural identity, community cohesion, sense of place, economics). This consideration is best met through an operational approach and institutionalized support for regional climate assessments and periodic re-evaluations (e.g. through fishery ecosystem plans like that in development for the Bering Sea, AK; www.npfmc.org/bsfep) (Marshall *et al.*, 2017). Criteria for evaluation may reflect multiple, potentially conflicting, socio-ecological objectives (Levin *et al.*, 2013; Lynham *et al.*, 2017) and consideration of climate justice for communities that are highly dependent on marine ecosystems and most exposed to climate-driven changes (e.g. indigenous and local or small-scale shore-based fishing communities) (Allison and Bassett, 2015). Long-term fixed policies may help protect these communities through conservation of subsistence fishing in nearshore areas for example, but only if climate change does not disrupt local productivity. Sensitivity simulations, ensemble modelling, and management strategy evaluations (Punt *et al.*, 2016) can inform the mix of nested dynamic-adaptive-fixed management approaches needed to balance heterogeneity, redundancy, and modularity and buffer social-ecological systems to short-term variation in regional environmental conditions and socio-economic priorities, yet also build capacity to adapt to long-term change (Levin *et al.*, 2013; Allison and Bassett, 2015) (Figure 2).

Considerations for "climate-informed" scientific advice

The following considerations should frame research and scientific advice to support short-, medium-, and long-term climate-resilient management measures. First, climate research and scientific advice to support management policies should align with the spatio-temporal scales of societal pressure and ecosystem response to climate change and should consider non-stationarity (and potential unidirectional change) in environmental conditions and socio-economic priorities. Second, a balanced portfolio of fixed-adaptive-dynamic management measures should be identified that (i) increases compliance, (ii) improves management coordination and avoids conflicting actions, (iii) spreads climate risk across adaptive measures in order to increase the ability of the coupled socio-ecological marine system to respond and adapt to climate change, and (iv) accounts for potential social and ecological hysteresis in response to changes to climate drivers and management actions (Lubchenco *et al.*, 2016; Lynham *et al.*, 2017). Third, portfolios of dynamic-adaptive-fixed management approaches (Figure 1) that improve management effectiveness and efficiency may help reduce future conflict between marine resource extractive and conservation goals through more explicit identification of management trade-offs and avoidance of social and ecological tipping points (Scheffer *et al.*, 2001; Scheffer, 2010; Kelly *et al.*, 2015). Integrated multiscale management portfolios, therefore, represent the consummate model to steer development of regional climate-resilient policies and foster strong science–management–stakeholder dialogue. Where this integration is tested through short-term climate advice to support dynamic management, extension to longer-term climate-resilient policies is promising (Hobday *et al.*, 2016b); where it is lacking, long-term climate resilience through ecosystem-based marine management is less certain (Skern-Mauritzen *et al.*, 2016). Finally, one of the most important, but often overlooked, considerations when designing and evaluating the performance of marine management under climate change is the hysteresis and variability of the socio-economic system coupled to the marine ecosystem of interest. Thus, it is critical to establish an integrative, multiscale portfolio approach to climate-resilient management that considers both environmental and socio-economic variability over time.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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