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Quo Vadimus

Proposed business rules to incorporate climate-induced changes in fisheries management

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Changing oceanic conditions are having impacts on living marine resources (LMRs) and their management, often in ways beyond what we have ever seen before. This is largely manifested as changes in production or location of these LMRs. The challenge has been not only to disentangle the possible causes of these changes to LMR stocks, but then even if clear changes are detected, it has been unclear what we can actually do about them. Here, we propose a set of recommended actions or "business rules" to better address climate-induced changes to LMR production and location. These emphasize a series of diagnostics which can be used to demarcate significance of whether action is necessary, and then if action is deemed necessary, we propose a set of insertion points or "on-ramps" to address the nuances of locational or production changes at every step in the science to management process. These proposed "business rules" for dealing with climate-induced changes to fisheries can always be debated, can always be updated with new information, and can always be adjusted under a given set of circumstances. But, we also assert that it would be wise to start acting on them, as a proposed set of options, given the urgency and exigency of the situation.

Keywords: business rules, climate change, distribution shifts, living marine resources, on-ramps, productivity, science to management process.

Introduction

"A little less conversation a little more action please…"

– Elvis Presley, 1968

The world's oceans have been altered in response to global climate change (IPCC, 2019). These dynamics are well-documented, too numerous to list here, and in many cases represent shifts beyond the range of observations for a whole host of oceanic processes (Hoegh-Guldberg *et al.*, 2014; IPCC, 2019). These changes are often unidirectional and irreversible (in a systemic, hysteresis sense; Solomon *et al.*, 2009; Abram *et al.*, 2019), and can represent fundamental changes to, or extremely increased variability of, major oceanic features (Belkin, 2009; IPCC, 2019). These changing oceanic conditions are having impacts on living marine resources (LMRs) and the management thereof (e.g. Poloczanska *et al.*, 2013, 2016; Barange *et al.*, 2014, 2018; Pershing *et al.*, 2018; Bindoff *et al.*, 2019; Free *et al.*, 2019; Karp *et al.*, 2019).

There are many possible impacts, but the two most obvious instances of climate-induced oceanic changes on LMRs are changes in the location (either distribution or range) of these marine taxa (Nye *et al.*, 2009; Cheung *et al.*, 2010; Lenoir *et al.*, 2011; Sunday *et al.*, 2012; Pinsky *et al.*, 2013; Poloczanska *et al.*, 2016) and changes to their productivity (Hare *et al.*, 2010; Blanchard *et al.*, 2012; Hollowed *et al.*, 2013; Wayte, 2013; Free *et al.*, 2019). Marine species distribution shifts are well-documented, having been observed and conclusively documented now for nearly 15 years (Fogarty *et al.*, 2008; Mueter and Litzow, 2008; Nye *et al.*, 2009; Pinsky *et al.*, 2013; Poloczanska *et al.*, 2016), with observations expanded to include multiple regions, multiple taxa across multiple trophic levels (Cheung *et al.*, 2013; Poloczanska *et al.*, 2013, 2016; Kleisner *et al.*, 2016), and future projections of such shifting distributions emerging as

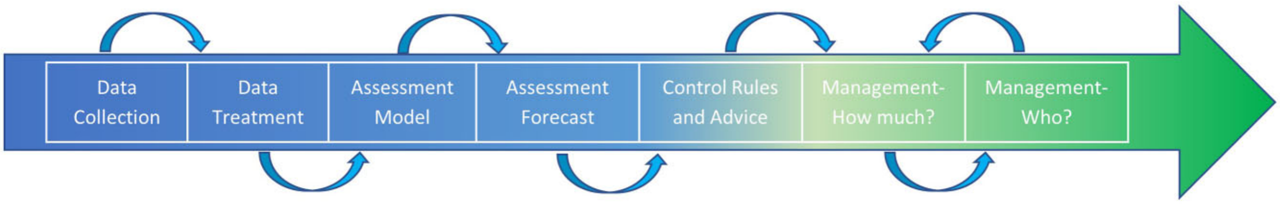

Figure 1. Generic science to management process (linked to column headings of Table 3). Although presented in a linear fashion, it is understood that the process iterates over the period of management cycles.

quite useful and attention-getting (Cheung *et al.*, 2015; Morley *et al.*, 2018). The general "gestalt" of these observations and predictions is either a poleward shift or a movement of taxa into deeper waters, both reflective of cooler waters in those locations. Additionally, as species shift their location, the extent of their location is also changing. We see evidence for range expansions for those taxa with broader thermal habitats (Perry *et al.*, 2005; Dulvy *et al.*, 2008; Bates *et al.*, 2014) and range contractions, again often into deeper, cooler waters, for those taxa more negatively impacted by water temperature warming in a given ecosystem (Perry *et al.*, 2005; Nye *et al.*, 2009; Pinsky *et al.*, 2013; Bates *et al.*, 2014). There are many mechanisms hypothesized to cause these shifts which we do not fully treat here, other than to note that generally speaking taxa are moving to inhabit waters closer to their thermal preference, or at least not outside of their thermal tolerance. Studies tracking the trajectory and velocity of these marine species distributions reinforce the patterns of unidirectional responses seen in the underlying oceanography. Additionally, these shifts in the center of marine species distribution are occurring at a rate six times faster than on land (Burrows *et al.*, 2011; Poloczanska *et al.*, 2013; Lenoir *et al.*, 2020), such that some major, iconic taxa may leave their current jurisdictions within a decade, with all the attendant ramifications that that would imply.

Perhaps less straightforward but no less pervasive are shifts in marine species productivity. Though there have not been as many of the meta-analysis summaries for LMR production changes in the literature that there have been for LMR distribution shifts (but see Poloczanska *et al.*, 2016), there is evidence and it is clear to those of us working in operational LMR contexts that there have been these shifts in production for at least the past decade. Numerous indicators of LMR production (size, maturity, recruitment, and so on; Froese, 2004; Ottersen *et al.*, 2004; Link *et al.*, 2020) have all exhibited changes, either increasing or decreasing depending upon the particular traits of a given taxa (Hare *et al.*, 2010; Poloczanska *et al.*, 2013). One would expect from first principles that persistent changes in temperature would notably affect poikilothermic organisms (i.e. animals whose internal temperature varies considerably in concert with thermal environmental conditions), and we see evidence that this is now occurring across a wide range of LMR taxa in a wide range of marine ecosystems (Mueter *et al.*, 2011; Poloczanska *et al.*, 2016). Again, there are many hypothesized mechanisms causing these changes, and we do not fully treat those here, other than to note that oceanic changes are impacting LMR taxa both directly (*via* physiological effects; Young *et al.*, 2006; Portner and Knust, 2007; Pörtner and Peck, 2010; Horodysky *et al.*, 2015, 2016) and indirectly (*via* changes in timing of thermal events, altered phenologies, trickle-through food web effects, and so on; Edwards and Richardson, 2004; Pörtner and Peck, 2010; Stock *et al.*, 2017; Dahlke *et al.*, 2020; Friedland *et al.*, 2020). We particularly acknowledge that these also include changes to the underlying, basal ecosystem (primary) productivity that drives the production of LMRs (Ryther, 1969; Chassot *et al.*, 2010; Conti and Scardi, 2010); this basal productivity ultimately constrains the energy available and hence potential for LMR production (Ryther, 1969; Friedland *et al.*, 2012; Stock *et al.*, 2017). Studies tracking basal, primary productivity show global shifts in production consistent with projected shifts in the underlying oceanography (Polovina *et al.*, 2008; Blanchard *et al.*, 2012; Kwiatkowski *et al.*, 2017), with continued implications for the productivity of LMRs (Cheung *et al.*, 2010; Poloczanska *et al.*, 2016), particularly the decline in production of some significant taxa.

It is one thing to know that there are shifts in distribution and changes to productivity of LMRs, that these changes are predicted to continue if not even accelerate (Burrows *et al.*, 2011; Lenoir *et al.*, 2020; Pinsky *et al.*, 2020), and that there will be foreseeable (or more actually, continued) implications from them. But the question begs: what can we do about it? How do we best consider these known changes—in productivity and location—in the sustainable use and management of these LMRs?

Before proceeding on to possible solutions to deal with changing distributions and productivities, it seems wise to ascertain if there are current "on-ramps" (i.e. a step where climate information can be included or considered in the fishery science and management decision-making process) in extant LMR management jurisdictions, as well as management authorities, that allow for the possible range of options we might propose to even be considered to adapt to climate impacts on LMRs. The vast majority of LMR management processes entail some form of data collection, then data treatment, then assessment model, then assessment forecast, then control rules and management advice (i.e. usually some form of fishing or biological limits), then management decisions of how much to catch/remove, and then management decisions of who is involved (allocation, with who has the jurisdiction assumed, etc.). A schematic (Figure 1; adapted from Karp *et al.*, 2018, 2019) shows this general science to management process. Our observation in the various regional jurisdictions in the U.S., as well as comparable LMR jurisdictions in other countries, fisheries management organizations, and consortia (Rudd *et al.*, 2018; Link *et al.*, 2019) is that there are certainly nuances to the schematic in these different locales, but generally this process is how science-based LMR management decisions are made (http://www.fisherycouncils.org/). We also note that even in instances of more urgent need to address depleted populations, such as stock rebuilding or species endangerment, though the terminology is distinct and some of the control rules, limits or range of actions are different, this general science to management process persists. Our other observation is that among the many various mandates and authorities (e.g. Rudd *et al.*, 2018; Link *et al.*, 2019; c.f. Supplemental Materials), across a range of LMR taxa and legislation, we are certainly allowed to consider these climate change effects now. Perhaps more clarity in terms of what is required to address climate considerations when managing LMRs could be beneficial. But in fact, a clear reading of these mandates in the context of climate change *vis-à-vis* "prevailing environmental conditions" implies that we need to do so already. The salient point is that currently climate change is considered in an *ad hoc* manner, if even at all, with no systematic approach as to how it is considered or addressed.

In this context, there have been calls to "alter fisheries management" or otherwise rather generic suggestions that changes need to be made in the science advice and management protocols that account for, or at least accommodate, these factors (e.g. Busch *et al.*, 2016; Pinsky *et al.*, 2018, 2020; Free *et al.*, 2020; Bahri *et al.*, 2021, etc.). We agree, yet few have provided the specificity that results in any actionable recommendations in actual management contexts. A former fisheries manager once asked, *"How do I know if a stock is moving out of my area, how do I attribute it to that and not fishing, and what do I do about it in a management arena? That is, what specific actions (i.e. options, I need options) can I choose if you're telling me it hasn't been included in the data or assessments?"* (J. Bullard, pers. comm.). That question sums up the situation rather nicely. Certainly, there have been nascent attempts to propose some workable options that address these issues (Link *et al.*, 2011, 2015, 2020; Lynch *et al.*, 2015; Morrison and Termini, 2019; Karp *et al.*, 2019; Bell *et al.*, 2020, etc.) and some of those may have promise that can be built upon. But the relatively limited amount of action taken, at least to date, to address changes in location and productivity can be at least partly attributed to the lack of clear operational guidance on when action is necessary, what that action would entail, and providing any guidance thereon cognizant of the usual (and even increased) uncertainty of making these decisions. We aim to explore this challenge, proposing recommended actions or "business rules" on when and how it is germane to insert climate-related information into the LMR management process.

Diagnosing changes and determining whether to take action

When the realized abundance of an LMR in a given ecosystem notably changes, whether that is a decline in a stock or an increase in a population, often a response is notably requested (e.g. allow more catch) or even mandated (e.g. stop overfishing and start rebuilding). This call for a management response has been a recurring theme in the fisheries discipline throughout its history (Graham, 1943; Smith, 1994). The challenge throughout the history of LMR management (Hjort, 1914; Punt *et al.*, 2014; Thompson–Burkenroad as described in Skud, 1975; Smith, 1994; Rose, 2000), but heightened in the current situation, is to delineate when and why changes in the realized abundance of an LMR are occurring. In the simplest terms, these changes are often expressed as just increases or decreases in the amount of fish in a given area. But, this reflects some degree of increases or decreases in productivity, a population shifting its distribution into or out of an area, an expansion or contraction of its range, a shift in physiology, a change in mortality, and/or even a change in fishing pressure, or a combination thereof. Identifying these changes, in terms of type (productivity, location, and fishing), direction (e.g. increase, decrease, and expansion), and magnitude is key, as each warrants a different set of approaches, actions and urgency to address the change.

This leads to two main questions; how do we best disentangle the effects of climate, the environment, and fishing pressure on productivity, distribution shifts, and range shifts (*sensu* Bell *et al.*, 2015; Link *et al.*, 2020)?; and how do we know if an observed shift in location (distribution or range) or a change in production is significant enough to warrant making adjustments to data, assessments, forecasts, and/or management actions? There is a growing body of literature that attempts to diagnose *when* and *why* a change is occurring (Link *et al.*, 2011, 2020; Bates *et al.*, 2015; Bell *et al.*, 2015), and some general criteria have been proposed for when to take action (DFO, 2013; Klaer *et al.*, 2015; ICES, 2021a). In this section, we synthesize information on key indicators of changes in distribution and productivity, as coupled with first principles, to point to instances when a change is diagnosable as significant and warrants action. Additionally, we propose tangible guidelines on approaches to take to determine when change warrants action. This need for triage has become heightened, and we assert that to do so uses routinely collected and available information.

Indicators of changes in fish productivity

Disentangling the signal of a change in productivity due to changing environmental conditions from changes in productivity due to fishing pressure can be quite challenging. This is largely because the effects of fishing and environment on productivity can be confounded (ter Hofstede and Rijnsdorp, 2011; Gaichas *et al.*, 2012; Bell *et al.*, 2015), let alone also considering the degree of density dependence for a given stock. Distinguishing among these causalities therefore requires looking across a suite of indicators falling under three categories—population indicators, community indicators, and environmental indicators. Changes that coincide across these three types of indicators lend strong support that an environmentally induced change in productivity has occurred.

At the individual stock or population level, key indicators to track are related to fish growth (e.g. size-at-age, weight-at-age, and age-at-maturity; Froese, 2004; Rochet *et al.*, 2005; Froese *et al.*, 2008; Enberg *et al.*, 2012), reproduction (e.g. recruitment and fecundity; Sadovy, 2001; Froese, 2004; Pankhurst and Munday, 2011), and health and survival (e.g. natural mortality and condition factor; Lambert and Dutil, 1997; Tyrrell *et al.*, 2011; Enberg *et al.*, 2012). These vital rates delineate some of the major facets of fish production (Ottersen *et al.*, 2004; Poloczanska *et al.*, 2016). Measures of size (e.g. weight, length, and so on) certainly can infer growth. Measures of fecundity, maturity, and sex ratio can infer reproductive productivity besides what can be inferred from larval and young-of-year measurements to ascertain population-level growth. Measures of condition factor, liver weight, hepto-somatic index, and so on can also infer how much production is included in individual growth, indicative of shifts in condition of fish stocks. Several of these indicators are routinely measured from samples collected as part of standard fishery-independent and some fishery-dependent surveys (Link *et al.*, 2020). For instance, maximum and mean length can be determined from length frequency data collected from surveys, and recruitment can be estimated from larval and juvenile abundance data collected from targeted larval and juvenile surveys. Other indicators, such as size/weight-at-age, age-at-maturity, and fecundity are less routinely collected due to the data and time intensive process of ageing fish from otoliths and determining maturity from ovaries. Trophic data are also potentially useful; this includes not only diet composition but also how much food is consumed, often reported as a percentage of body weight, which can infer the growth

Table 1. Diagnostics of changes in LMR production. ↗ = increase, ↘ = decrease, ↗ ↘ = both possible, and N/A = not applicable.

Indicator	Expected direction Increasing production	Decreasing production
Population level		
Growth performance	↗	↘
Max length (Lmax)	↗	↘
Mean length	↗ ↘	↘
Weight-at-age	↗	↘
Length-at-age	↗	↘
Size-at-maturity (length or weight)	↗	↘
Age-at-maturity	↘	↗ ↘
Reproduction	↗	↘
Fecundity	↗	↘
Recruitment	↗	↘
Health and survival	↗	↘
Condition factor	↗	↘
Liver weight/HIS	↗	↘
Natural mortality (M)	↘	↗
Community/ecosystem level		
Phytoplankton abundance	↗	↘
Zooplankton biomass/abundance	↗	↘
Community composition	N/A	N/A

potential for a fish population. Monitoring simple ratios of commonly measured variables, such as the condition factor or %BW consumed, can also provide indications of major changes to productivity.

From recent empirical studies and ecological theory of the impact of changing environmental conditions on fish dynamics, we can assign expected direction of changes in these indicators associated with either an increase or decrease in fish productivity (Table 1; Ottersen *et al.*, 2004; Poloczanska *et al.*, 2016). However, it is important not to rely on only one indicator, but instead look across multiple indicators, as changes in some indicators can be misleading when evaluated alone. For instance, a decrease in mean length can be an indication of declining growth or survival, but can also be a result of increasing recruitment and a higher abundance of young and small fish in the population (Froese, 2004; Froese *et al.*, 2008). Similarly, a decline in age-at-maturity can lead to a decline in fecundity and productivity, particularly when a decline in size-at-maturity and max length is also occurring, but when combined with an increase in size-at-maturity and max length, is indicative of good growth conditions and increasing productivity. It is also feasible that these mechanisms may exhibit changes at different times or in different sequences. Therefore, when possible, indicators should be evaluated across fish growth, recruitment, and health/survival to provide a more complete picture of the changes in the population dynamics of the fish stock.

As noted before, fishing pressure can also induce similar changes in these fish life-history traits (Swain, 2011; Link *et al.*, 2020); mean length for instance is a commonly used indicator of fishing pressure to manage data-limited fisheries. Therefore, it is important to look across a suite of indicators, beyond changes in population dynamics to more fully determine causes for observed changes. This brings us to the suite of community and environmental indicators. Key indicators to track at the community level include the phytoplankton abundance/biomass, timing of peak in zooplankton blooms, zooplankton biomass, zooplankton size and species composition, guild biomass of major fished taxa groups, and the overall composition of species in the community. Changes in these indicators provide evidence for changes in system or community level productivity, which in turn can affect the productivity of a target fish stock (e.g. Friedland *et al.*, 2012). For instance, zooplankton are a key prey item of early life history stages of many fish species, and increases in zooplankton abundance has been linked to increasing fish recruitment success through increases in larval growth and survival (e.g. Perretti *et al.*, 2017; stage-duration hypothesis, Houde, 1987; McFarlane and Beamish, 1992; Buckley and Durbin, 2006). In addition to the population and community indicators, it is also important to track changes in the underlying climatic and oceanographic conditions. This could include regularly tracking sea surface temperature (SST), salinity, dissolved oxygen, as well as broad-scale climatic indices such as Atlantic Multidecadal Oscillation (AMO), El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), or North Atlantic Oscillation (NAO). Changes in these indicators coinciding with changes in the above population or community level indicators not only provide additional evidence for changes in productivity, but also provide potential mechanisms behind those changes.

Additionally, changes in productivity can occur alongside changes in distribution. In fact, declines in individual growth rate, condition, reproductive potential, and population recruitment and increasing mortality at the trailing edge of a stock's range, can be early signs of an impending range contraction or distribution shift (Bates *et al.*, 2014). Similarly, increases in these same demographic and vital rates at the leading edge can be signs of potential for range expansion or distribution shift. Therefore, indicators for changes in distribution should also be monitored and evaluated when a change in productivity is identified, and we discuss the key indicators of distribution shifts in the following section.

Indicators of shifts in distribution and range

Fished taxa moving into or out of an area is a major consideration for the effects of climate change on fisheries (Karp *et al.*, 2019; Pinsky *et al.*, 2020; Melbourne-Thomas *et al.*, 2021). Similarly, and often confounded, is the contraction or expansion of the range of these species (Link *et al.*, 2011). Here, we distinguish between them as the latter (range of a species) being the total area over which it is found and the distribution of a species as a measure of its density across its range. We note that the distinction between distribution and range shifts functionally is that the former being the movement of the population, *en masse*, to a new location and the latter being a change in the amount of total area (or volume) of the ocean being occupied. What are the clear diagnostics to delineate that these fishes have experienced significant shifts in their distribution or range? And how does one delineate between those two, as well possible changes due to shifts in production, overfishing, or other sources (Bell *et al.*, 2015; Link *et al.*, 2020)?

Often, the first indication of potential shift in distribution or range expansion is the observation of a species outside of its historical range. However, the appearance of a species in a new area can be signs of either a distribution shift in that direction, or a range expansion. Distinguishing between these two possibilities is important as they have slightly different implications for management.

Key measures of a range expansion include increases in the area occupied, distance between the min/max latitude and longitude of the stock, or in the 95th (or related) percentile of the geographic range of observed/survey biomass (Table 2; Fogarty *et al.*, 2008; Mueter and Litzow, 2008; Nye *et al.*, 2009; Pinsky *et al.*, 2013; Poloczanska *et al.*, 2016). A range expansion is also indicated by increases in productivity or abundance at the leading edge (one end) of the range, with no change or potentially an increase at the other end of its range, at the trailing edge (Perry *et al.*, 2005; Dulvy *et al.*, 2008; Bates *et al.*, 2014). In addition to a range expansion, species may also exhibit range contractions in response to climate change. The key diagnostics to indicate a range contraction would be the opposite of an expansion; that is, a shrinking of the total area covered by the taxa, a decline in the distance between the min/max latitude and longitude of the stock, a decline in the 95th (or related) percentile of the geographic range of observed/survey biomass (Table 2; Perry *et al.*, 2005; Pinsky *et al.*, 2013; Bates *et al.*, 2014), and a decrease in productivity or abundance at the trailing edge with no increase in abundance at the leading edge of the stock's range.

A shift in the distribution on the other hand is indicated if there has been a notable change in the latitude and longitude for the centroid of surveyed biomass, a directional shift in the area occupied by the taxa, or a change in the distance from a fixed point for centroid of biomass for a species; but no observed change in the measures of the range size or area occupied by the stock (Table 2, Fogarty *et al.*, 2008; Mueter and Litzow, 2008; Nye *et al.*, 2009; Pinsky *et al.*, 2013; Poloczanska *et al.*, 2016). A distribution shift is also indicated by increases in productivity or abundance at the leading edge (i.e. where the population is at the limits of its detection) of the range, and a decrease in productivity or abundance at the trailing edge. If the species is moving into a jurisdiction, these diagnostic parameters would be clearly seen (and perhaps mistaken for fishing pressure (F) of the incoming taxa), or at least increasing in their direction, magnitude and nature, whereas if the species is shifting out of an area they would be clearly exiting or decreasing in their direction, magnitude and nature (Table 2) (Here we use F not as the formal and specific fishing mortality rate, though it could include that, but more as shorthand for general fishing pressure.).

The challenge will be when conditions show evidence of climate-induced shifts in stock location and productivity along with evidence for overfishing (Bell *et al.*, 2014, 2015; Link *et al.* 2020). Relying solely on catch-per-unit-effort and associated measures is a challenge, as stocks can disperse, be less densely concentrated, be harder to reach, or be less productive and, hence, less abundant in any of these scenarios. For example, in stocks that congregate, declines in productivity and abundance may be masked as catch per unit effort in prime habitats remains constant, leading to a disconnect between what fishermen see and what scientists are measuring (J. Hare, pers. comm.). In those instances where multiple indicators suggest multiple possible impacts to a stock or fish community, as similar to other evaluations (*sensu* Link *et al.*, 2011, 2020), we propose that certainly overfishing considerations be addressed, but that positional considerations be addressed first so as to not falsely treat perceived stock status that may have moved.

Changes in species location linked to known thermal preferences, life-history traits, and related species-specific information would verify the veracity of changes in climate and environmental conditions being a major factor in observed stock position and dynamics (Cheung *et al.*, 2010; Pinsky *et al.*, 2013). Additionally, changes in a stock's centroid which is correlated with climate velocity (i.e. movement of an area of preferred temperature (or isotherm) though time is referred to as climate velocity; Loarie *et al.*, 2009), that is moving in the same direction and magnitude, also provide strong evidence of a climate-induced shift as opposed to fishing (Pinsky *et al.*, 2013).

Determining significance of any change or shift and when to consider accounting for such changes

The next, and arguably most crucial question, after observing a change in an indicator described above, is when do we have evidence suggesting that it's due to the environment and not fishing, and when is the change large enough that action is warranted (Haltuch and Punt, 2011; Klaer *et al.*, 2015)? To help answer that question, in addition to looking for persistent change in an indicator, other lines of evidence include: the change coincides with consistent evidence of environmental change, changes are observed across multiple stocks (or indicators), and stock size or location is not responsive to changes in fishing pressure (*sensu* Klaer *et al.*, 2015).

If the indicators described in the previous sections have been tracked over a long period of time (e.g. $>$ 20–30 years; Haltuch and Punt, 2011; Kraberg *et al.*, 2011), then there are standard statistical techniques that can be applied to time-series data of these indicators to test for statistically significant changes in trends, identify the points in time when they occurred (e.g. change-point and regime shift analysis), and test for correlations or alignment across multiple indicators. Obviously, the longer the time period of data the higher the power to correctly detect environmental forcing on the indicator (Haltuch and Punt, 2011).

Standard trend analysis can be applied to time-series of particular indicators, such as center of gravity or weight-at-age noted above, to test for significant positive or negative trends in that indicator through time. A commonly used change-point analysis method (i.e. STARS; Rodionov, 2004; Rodionov and Overland, 2005), which uses sequential t-tests, can be used to identify locations of abrupt changes in the mean level of the dataset. This method provides both the timing of the shifts in the mean as well as the mean values of the different periods.

Linear and non-linear regression and correlation methods can also be used to not only test for significant trends in time-series data, but to also relate those changes to underlying environmental drivers or community indicators (Kraberg *et al.*, 2011). Non-parametric equivalents exist to similarly detect trends for instances of non-normal data (Daniel, 1990). Comparable methods can be used to distinguish not only timing of events, but apportionment of probable causality (Peterman *et al.*, 2000; Collie *et al.*, 2012; Bell *et al.*, 2014). Significant changes in population level indicators of productivity over the time-series correlated with environmental covariates (e.g. temperature) or food web or community level indicators (e.g. zooplankton biomass), lends support to the key driver of changes in productivity being environmental and not fishing.

Another type of change-point detection method, chronological clustering, identifies discontinuities in a temporal dataset by partitioning the time-series into temporal groups (e.g. regimes) chosen to minimize the sum of squares within the groups (Legendre and Legendre, 2012; Perretti *et al.*, 2017), which can be used to identify regime shifts in multispecies datasets using information on all stocks simultaneously to delineate regime change points. Looking at changes in indicator time-series across multiple species can increase the ability to detect changes and provide stronger support for environmental, not fishing, induced changes in abundance (Perretti *et al.*, 2017).

Table 2. Diagnostics of changes in LMR location. ↗ = increase, ↘ = decrease, ↘↗ both possible, N/A = not applicable.

	Associated response of indicator			
Indicator	**Shift in**	**Shift out**	**Expansion**	**Contraction**
Lat/lon of centroid of biomass	Getting closer	Moving farther away	Either or no change	Either
Distance of centroid from fixed point in jurisdiction	↘	↗	↘↗	↘
Area occupied	N/A	N/A	↗	↘
Distance between min/max longitude or latitude	N/A	N/A	↗	↘
Abundance at leading edge	↗	↗	↗	
Abundance at trailing edge	↘	↘		↘
90th percentile geographic range	N/A	N/A	↗	↘
Climate velocity	Moving in same direction and magnitude as centroid			N/A

Change points, or regimes, identified for a key indicator can also be compared to change-points in other indicators (e.g. regimes in recruitment and copepod biomass, Perretti *et al.*, 2017), and coincidence in regime timing across key indicators of productivity provides strong evidence for environmentally induced productivity changes. Furthermore, stronger evidence of climate-induced changes in location or productivity is provided by looking across multiple stocks in the ecosystem. Coincidence in locational changes (even with opposite directions) provides strong evidence for broad-scale factors impacting distribution and range of fish communities. If a meta-analysis for all stocks in a given region (e.g. Nye *et al.*, 2009) were conducted, resulting in more than just one stock exhibiting shifts in its location, along with tracking major environmental signals as noted above, it would lend further credence to these shifts in stock location being environmentally driven.

Another statistical approach to detecting coincidental changes or patterns in multivariate data sets would involve using Dynamic Factor Analysis (DFA) or Principal Component Analysis (PCA). DFA is a multivariate dimension reduction technique designed to detect common patterns across a set of time-series data and relationships in these time-series and a set of explanatory variables (Zuur *et al.*, 2003). The common patterns can be common trends, common seasonal patterns, or common cycles which appear across the datasets. PCA is another frequently used technique to identify the presence of ecosystem regime shifts and identify the primary abiotic and biotic factors driving the change. Hare and Mantua (2000) used PCA to identify ecosystem regime shifts in the North Pacific using 31 climate and 69 biological time series.

As mentioned previously, the above statistical tests rely on having a long time-series of data; however, not having such time-series data should not preclude one from being able to assess changes and take necessary action. Here, we propose some rules of thumb thresholds for the amount of change that if exceeded, might indicate that action should be considered, even if statistical tests as described above cannot be performed. We fully acknowledge that there may be different levels of cutoff for action under different conditions, but wanted the following to propose as a starting point, noting that these have had some basis in the literature (Fulton *et al.*, 2005; Link, 2005; Blanchard *et al.*, 2010; Samhouri *et al.*, 2010, 2017; Shin *et al.*, 2010; Martone *et al.*, 2017; IUCN 2019). Additionally, as with the statistical tests, stronger evidence for the change being climate, and not fishing, induced is provided if a change is observed across multiple stocks in the ecosystem, and coincides with changes in environmental conditions (Klaer *et al.*, 2015).

Once the probable significance of any detected change or shift has been examined, or it is strongly suspected for situations with shorter time-series, it is important to explore when to consider accounting for such changes in the science to management process. Thus, we propose the following as rules of thumb to delineate major changes in stock production:

- Population size, reproduction, growth, and survival measures have declined (or increased; if not all of them, at least the majority of evidence from many of these metrics) over 10 years, or three generation times of fish (whichever is shorter) by:
    - 40% (or ∼0.5 *SD*)—need to seriously consider,
    - 66% (∼1 *SD*)—likely probable a change is occurring, or
    - ∼100% (95%; ∼2 *SD*)—then almost certain that it has occurred.

We propose the following as rules of thumb to delineate major positional changes in stock distribution:

- Stock centroid measures have shifted and persisted over 10 years or three generation times of fish (whichever is shorter) by:
    - 40% (or ∼0.5 *SD*)—need to seriously consider,
    - 66% (∼1 *SD*)—likely probable a change is occurring, or
    - ∼100% (95%; ∼2 *SD*)—then almost certain that it has occurred.
- Else centroid has shifted greater than 50 km or equivalent movement that has persisted over the time period noted (for either shifting in or out);

We propose the following as rules of thumb to delineate major positional changes in stock range:

- Stock area or distance measures have shifted and persisted over 10 years or three generation times of fish (whichever is shorter) by:
    - 40% (or ∼0.5 *SD*)—need to seriously consider,
    - 66% (∼1 *SD*)—likely probable a change is occurring, or
    - ∼100% (95%, ∼2 *SD*)—then almost certain that it has occurred.
- Else area has increased greater than 1000 km^2 (or ∼ 1 *SD* of total area) or equivalent that has persisted (for expansion)
    - or area declined by 100 km^2 or equivalent (or ∼0.5 *SD*) that has persisted (for contraction).

- Else distance has increased greater than 50 km or equivalent that has persisted (for expansion)
    - or distance has decreased by 25 km or equivalent that has persisted (for contraction).

The logic for these proposed rules of thumb includes recognition that 40, 65, and 95% of all observations lie within 0.5, 1, and 2 (1.96) *SD* of the mean (Zar, 1984; van Belle, 2002; Gotelli and Ellison, 2004). Further, most statistical measures of significance for inference of change rely on probabilities of detection set at around 5% (i.e. loosely corresponding to 95% of the distribution of observations; Zar, 1984); known instances when changes have occurred in these amounts, magnitudes, or percentiles have resulted in major shifts in stock or ecosystem dynamics (Samhouri *et al.*, 2017; Tam *et al.*, 2017). For the distance or areal measures, these amounts of change loosely correspond to the distance shifted (i.e. in terms of coordinates for centroid measures) in approximately one decade for average climate velocities of observed LMR movement (Burrows *et al.*, 2011; Pinsky *et al.*, 2013; Poloczanska *et al.*, 2013; Lenoir *et al.*, 2020). Additionally and using independent methods, retrospective studies, tipping point analyses, and congruence with the emerging literature on the topic all similarly point to these approximate cutoffs (e.g. Klaer and Polacheck, 1995; Blanchard *et al.*, 2010; Samhouri *et al.*, 2010, 2017; Shin *et al.*, 2010; Martone *et al.*, 2017; ICES, 2021a). Plus, a Delphic elicitation of approximate levels from several colleagues collectively representing hundreds of years of experience all generally coalesce around these proposed rules of thumb such that if biomass of a population has been altered by at around one half, if not two-thirds or even double, typically that is statistically significant (Zar, 1984; van Belle, 2002; Gotelli and Ellison, 2004) and corresponds to major dynamics occurring (Klaer and Polacheck, 1995; Restrepo *et al.*, 1998; Hilborn *et al.*, 2015; Rindorf *et al.*, 2017).

Proposed actions for specific scenarios

Once the type of change has been identified and that it is significant enough to warrant attention, it is reasonable and necessary to ask, "How and when do we appropriately address that change throughout the science-to-management process?" The answer to that question will of course differ depending on what type of change has been identified. There are several insertion points within the science-to-management process where climate information can enter. Here, we discuss actions that can be taken for both changes in productivity and changes in species distribution or ranges, and how these "on-ramps" can be best considered. These are presented largely in the U.S. federal fisheries management context (Supplemental Materials) but despite perhaps what might be specific terminology, these should be applicable globally. We propose these "business rules" not as having perfected them, but as a means to advance the way we address this challenge facing us.

Addressing productivity changes

There are several potential places in the science-to-management process to account for an identified change in productivity, whether it be an increase or a decrease.

Accounting for the change in productivity in data collection and treatment

Data on population vital rates form the basis for all subsequent somatic and reproductive production estimates. Thus, as a first step (Table 3, column 3—Productivity), to determine changes in productivity it is important to maintain, or increase, key data collection programs to continue obtaining information on population vital rates and features which, as discussed above, can serve as key indicators to track changes in productivity. In addition to observational field data and measuring those over time to obtain *in situ* estimates of rates, laboratory studies are also beneficial to obtain more refined measures of these important rates. If diet analysis is not already a routine part of data collection, then efforts should be taken to increase the collection and analysis of diet data. From a bioenergetics perspective, these data form the basis for all subsequent somatic and reproductive production. These diet data also help to explore trophic interactions, primarily to understand potential drivers of observed changes in stock productivity as caused by increases or decreases in prey resources, prey quality, amount of food consumed, and so on. These measures can also rule out major changes to natural mortality as compared to changes in production. For instance, the Alaskan, Northeast US, and some European regions routinely collect food habits and use that information to track mortality and production changes over time (Daan and Sissenwine, 1991; Smith and Link, 2010; Livingston *et al.*, 2017).

There may also be a need to take the change in productivity into account in the treatment of data (Table 3, column 4—Productivity). If changes in growth, such as length, or size- or weight-at-age have occurred then this may necessitate revisions to the estimates of key size and catch (at-age) inputs, maturity ogives, or L–W curves before these data are used in stock assessments. It may also be wise to explore statistical relationships among these factors and environmental covariates to see if different covariates (e.g. temperature) might be usefully included in stock assessment models as covariates (Keyl and Wolff, 2008), or if inputs into the models warrant being changed (step functions, split time-series, and so on). For instance, many species of groundfish in New England have had to have splits in their inputted time series used in subsequent modelling to deal with a range of problems (Legault, 2009).

Accounting for the change in productivity in stock assessments and forecasts

If the mechanism behind the change in productivity is strongly suspected and data exists to incorporate the environmental driver into the assessment model (Table 3, column 5—Productivity), then an advisable approach is to explicitly include that environmental driver into the stock assessment used to provide management advice (e.g. Keyl and Wolff, 2008). Certainly there remains differing opinions and evidence about the utility of incorporating environmental drivers into assessment models (e.g. De Oliveira and Butterworth, 2005; Punt *et al.* 2014), but there is increasing evidence that including these factors improves model fits and decreases uncertainty (Wayte, 2013; Miller *et al.*, 2016); a reasonable rule of thumb is that environmental indices that explain more than 50% of the variation in recruitment tend to result in management benefits (De Oliveira and Butterworth, 2005). Environmental drivers are most commonly explored and routinely included in the stock–recruitment relationship as this is the aspect of population dynamics most susceptible to changing environmental conditions and

Table 3. Proposed actions to address climate change in fisheries management, with suggested options for each stage of the science to management process. These can serve as potential "business rules" for incorporating climate considerations into fisheries management across a range of data availabilities, modelling capacities, and governance structures. L–W = length–weight, r = population growth rate, R = recruitment, g = individual growth (rate), F = fishing (rate, or more generally pressure), BRP = biological reference point, HCR = harvest control role, ESP = ecosystem socioeconomic profile, ESR = ecosystem status report, SA = stock assessment, MSE = management strategy evaluation, ID = identification, $p*$ = probability of overfishing, ID = identification, SDM = species distribution model, and B = biomass.

Type of change	Direction of change	Insertion points						
		Data		Assessment		Advice	Management	
		Data collection	Data treatment	Assessment model	Assessment forecast	Control rules and advice	Management options— how much	Management— who
Productivity	Increase	Continue collecting data on population vital rates Laboratory studies to estimate key parameters Analyse/collect diet data to explore trophic interactions	Revise estimates of key size and catch (at-age) inputs, maturity ogives, L–W curves Monitor condition factor Explore links to environmental covariates Evaluate evidence for major ecosystem changes	Modify parameters in model (r, R, g, or F) Consider environmental covariates in model Restrict data to recent environmental regime Incorporate non-stationarity and allow for time-varying parameters	Use standard SA model with new/updated input data or parameters Incorporate climate projections into development and assessment of stock rebuilding plans	Use new BRPs from updated stock assessment Include environmental covariate in HCR Conduct an MSE to evaluate HCRs that are most robust to time-varying productivity Adjust $p*$ (reduce buffer if increase, increase buffer if a decrease for allowable catch)	Consider information on environmental impacts on stock in management decision-making (e.g. SA reports, ESPs, or ESRs) Phase-in increases in F	Negotiate surplus and investment
	Decrease						Consider information on environmental impacts on stock in management decision-making Decrease in F	Negotiate declining production allocations
Distribution	In	Expand or establish monitoring program Model/map distributions Coordinate monitoring and data sharing across jurisdictions Conduct genetic and stock ID analysis to evaluate genetic diversity and stock ID Incorporate available tagging and movement data Incorporate relevant socioeconomic data	Revise stock ID and stock area Calibrate assessment input data with environmental covariates Correct survey indices for amount of species habitat surveyed (abundance index, age/length composition, and life-history info)	Explore use of spatially explicit model Include or adjust stock assessment model with time-varying catchability Use assessment model with new or updated input data Consider multispecies/whole of ecosystem models	Use SDMs to forecast future changes in distribution Projections from assessment model using updated input data Consider multi/ensemble modelling approaches to address different climate scenarios	Use new BRPs from updated stock assessment Adjust harvest control rule with location of biomass cutoff Increase $p*$ (reduce buffer on allowable catch)	Consider pause in fishing to allow establishment of stock Phase-in increase in F Re-evaluate/adjust closed areas	Negotiate new management authority Develop new or revise management plan Negotiate new allocations
	Out					Adjust down realized B and F Adjust harvest control rule with location of biomass cutoff Use new BRPs from updated stock assessment Decrease $p*$ (increase buffer on allowable catch)	Reduce F Adjust landings/permit requirements Consider fishery closures and re-evaluate/adjust closed areas	Adjust permits, landings requirements

Table 3. Continued

Type of change	Direction of change	Insertion points						
		Data		Assessment		Advice	Management	
		Data collection	Data treatment	Assessment model	Assessment forecast	Control rules and advice	Management options— how much	Management— who
Range	Expansion	Coordinate monitoring and data sharing across jurisdictions Conduct genetic and stock ID analysis Examine change in spatial age-structure	Correct survey indices for amount of species habitat surveyed Redo stock unit area and revise stock ID	Explore use of spatially explicit model Include or adjust stock assessment model with time-varying catchability Use assessment model with new or updated input data	Use SDMs to forecast future changes in distribution Projections from assessment model using updated input data and new stock ID	Use new BRPs from updated stock assessment Adjust $p*$ (reduce (if expand) or increase (if contract) buffer for allowable catch)	Consider pause in fishing to allow establishment of stock in new expanded area Phase-in increases in F in coordination with all jurisdictions within species' new expanded range Re-evaluate/adjust closed areas	Negotiate new management authority Develop new or revise management plan Negotiate new allocations
	Contraction		Redo stock unit area and revise stock ID	Consider multispecies/whole of ecosystem models			Decrease F Consider fishery closures	

typically how the size of the cohort is most directly determined (Tanaka, 2019; Tanaka *et al.*, 2019; Bell *et al.*, 2020), but other functional relationships may also usefully include these covariates. That is, environmental drivers can also be linked to other parameters in the assessment such as growth, mortality, or fecundity. Modifying these common stock assessment model parameters provides a means to explore, in a hypothesis-testing mode, the range of probable impacts of changing productivity. For instance, the west coast sablefish has had its parameter set examined in response to changing environmental conditions (Schirripa *et al.*, 2009; Hanselman *et al.*, 2017).

As is often the case, there may be a limited understanding of the underlying mechanisms of the productivity change and, therefore, the change might not be best accounted for through the direct inclusion of environmental covariates. This does not, however, prevent the ability to account for the change in productivity in the assessment (and subsequent management advice) as there are several approaches to accounting for the change that do not require knowledge of the exact mechanisms responsible. One approach is to adjust the historical time-period that informs assumptions in stock modelling and forecasts to best reflect the current productivity situation. This approach relies on there being strong evidence indicating that the change in productivity is associated with a particular time period (e.g. a regime shift), and then restricting data to the time period associated with the change in productivity. For example, Southern New England yellowtail flounder has used different "recruitment regimes" in its stock assessment to account for declines in productivity (NEFSC, 2012; Miller *et al.*, 2016). This approach is also employed in the North Pacific for all groundfish assessments, where there was clear evidence of regime shifts in response to the PDO (Hare and Mantua, 2000) leading to the use of different time-periods of data to reflect the current productivity regime. However, truncating the time series used in the assessment and forecast has its own issues (ICES, 2021a) and, therefore, should only be done when there is clear evidence that the stock will not return to the previous productivity regime before the next benchmark (i.e. major update) assessment. Another approach to account for changes in productivity when the underlying mechanisms are not understood is to allow for time-varying parameters and non-stationarity in the assessment model (Wilberg *et al.*, 2010; Johnson *et al.*, 2015; Szuwalski and Hollowed, 2016). State–space formulations are quite useful for implementing time-varying parameters, particularly when there are insufficient data for incorporating an environmental driver (Gudmundsson, 1994; Aanes *et al.*, 2007; Nielsen and Berg, 2014; Cadigan, 2016; Miller *et al.*, 2016; Aeberhard *et al.*, 2018). Time-varying parameters most often associated with changing productivity include growth, reproduction, and natural mortality. The use of time-varying productivity parameters results in time-varying reference points that inherently account for changes in underlying productivity (O'Leary *et al.*, 2020).

The stock assessment forecast could then be made using the time-varying model (Table 3, column 6—Productivity), the model with the new parameters coupled with environmental covariates, or by using the parameters associated with an appropriate time period. Additionally, climate projections can be incorporated as inputs into these facets just noted in an assessment forecast, when possible, particularly for the assessment of stock rebuilding forecasts (e.g. Hare *et al.*, 2010; Hollowed *et al.*, 2011, 2013; Tanaka, 2019). Simulating forecasts under assumptions of an environmental influence on productivity compared to fishing pressure influences on productivity, plus management responses (i.e. updated status determination criteria) is recommended as it can provide information on the risks of making a wrong decision (see discussion of Type-1 and Type-2 errors below). Certainly, forecasts of (climate-induced) environmental conditions may pose some limitations, but there are copious, ongoing efforts to increase the delivery of such products (e.g. Chen *et al.*, 2021; Drenkard *et al.* 2021). More so, increasing examples are demonstrating that including environmental covariates in various population dynamics models actually decreases uncertainty (Wayte, 2013; Miller *et al.*, 2016).

Accounting for the change in productivity in harvest control rules, risk policy, and catch advice

Another place to account for a change in productivity is in the control rule and catch advice (Table 3, column 7—Productivity). Specifics on how to account for the change depend on whether the stock is experiencing an increase or decrease in productivity, and if the change has already been accounted for in the data and/or stock assessment steps as described above. If the change has been accounted for in the data, stock assessment model and/or forecasts, then managers may simply use the updated biological reference points (BRPs) and uncertainty estimates from those updated estimates when setting catch advice. However, it is important when using these updated BRPs to keep in mind that there are potential risks of having committed a Type-I (assume a productivity shift when there is none) and Type-II (fail to detect a productivity shift when there is one) errors (Haltuch and Punt, 2011). Type-I errors are particularly risky for declining or depleted stocks, where the decline is falsely credited to a decrease in productivity and not fishing. Lowering reference points in this case could trap the stock at low abundance and prevent stock rebuilding (ICES, 2021a). Therefore, caution should be exercised when reference points are lowered as a result of a decreasing stock productivity, especially if in doing so an overfished stock is no longer considered as such, and therefore, a higher catch is recommended. It is thus more precautionary that in these situations, any increases in catch quotas be phased-in (see Holland *et al.*, 2020 for guidance on phase-in of catch quota changes) to give managers an opportunity to evaluate and adjust management actions in response to how the fishery responds to the change in catch quota.

If a change in productivity has not been accounted for in the previous steps (data collection to forecasts), there are several approaches to account for the change in the harvest control rule (HCR) and management actions. One approach is to explore the use of dynamic or adaptive HCRs that either adjust fishing pressure in response to changes in stock abundance or to changes in environmental conditions and, therefore, implicitly and directly account for changing productivity, which may increase successful management of a stock impacted by environmental forcing (Kvamsdal *et al.*, 2016; Tommasi *et al.*, 2017). Often these HCRs are tested and established using a management strategy evaluation (MSE; Punt *et al.*, 2016) process. An example of such a dynamic HCR is is seen the management of Pacific sardine. Here, the HCR is linked to SST in such a way that harvest declines when SST becomes sub-optimum for sardine productivity and increases when SST is optimum for sardine productivity (Kvamsdal *et al.*, 2016; PFMC, 2017). Similarly, single species F_{MSY} and associated quotas for cod and whiting in the Irish Sea were adjusted based on SST (ICES, 2020a; Howell *et al.*, 2021). Additionally, other ecosystem indicators can also be used to adjust quotas to account for changing conditions. For example, herring F and quotas were adjusted according to empirical estimates of zooplankton abundance (ICES, 2020a). This adjustment allows the ecosystem and climate understanding to be incorporated within the existing single-stock management framework. These adaptive HCRs are particularly useful in situations where the stock productivity fluctuates in response to climate conditions instead of exhibiting a unidirectional response, as they allow for a quick management reaction when conditions change.

If the change has not been accounted for in the models, forecasts or HCR, and the stock is experiencing a decrease in productivity, then we propose that it be accounted for by increasing the precautionary buffer between the overfishing limit (OFL) and the acceptable (or allowable) biological catch (ABC; e.g. lower risk tolerance; i.e. decrease $p*$, the probability of overfishing; Prager *et al.*, 2003; Shertzer *et al.*, 2008; Prager and Shertzer, 2010), and therefore, decreasing the allowable catch. That is, any limit to what can be caught is often adjusted with some form of a precautionary buffer to become what is actually recommended, based on a range of factors (FAO, 1995). Managers can use information about the stock and ecosystem from ecosystem status reports (Slater *et al.*, 2017) and stock assessment reports to help inform the decision about catch reductions (e.g. Shotwell *et al.*, 2018; Dorn and Zador, 2020) For example, the Eastern Bering Sea Pollock has had its management advice altered using a suite of risk tables informed by these broader ecosystem contexts, resulting in an increased buffer between its ABC and annual catch limits (ACL; e.g. Dorn and Zador, 2020). If, however, the stock is experiencing an increase in productivity, which has not already been accounted for in the models, forecasts and BRPs, then managers may consider decreasing the buffer between the OFL and the ABC (Prager *et al.*, 2003; Shertzer *et al.*, 2008; Prager and Shertzer, 2010), and, therefore, provide for an increase in allowable catch. It is important to keep in mind other sources of uncertainty, which may require the precautionary buffer to remain the same. Additionally, managers may consider phased-in increases in F, following the NS1 Technical Guidelines on the approach (Holland *et al.*, 2020). This is similar to the precautionary approach adopted in the European Union which adjusts buffers accordingly (ICES, 2021b).

We also recognize that it is often quite difficult to determine the most appropriate and robust management strategy to enact when faced with a changing climate. MSEs (Punt *et al.*, 2016) are a useful tool in these situations to analyse trade-offs between various management actions (e.g. time-area closures, size limits, as well as the aforementioned development of HCRs and risk policies) under different assumptions of stock productivity to determine the most robust choice given the uncertainty in observed changes. Executing MSEs is not a replacement for climate-informed decisions, but certainly helps to better elucidate them and their possible outcomes more clearly (Punt *et al.*, 2016; Holsman *et al.*, 2019; Hollowed *et al.*, 2020).

Accounting for the change in productivity through other management actions

There are also actions LMR managers can take to account for the change in productivity outside of the data, stock assessment and catch advice steps (Table 3, column 8 & 9—Productivity). For example, if a decrease in productivity is observed, depending on how great a decrease has occurred, managers may take steps to protect against collapse by considering fishery closures, effort controls and other measures, such as size limits, to protect and manage for age (and genetic) diversity in the stock to enhance stock resilience. The aim is to use the information in a broad range of stock-oriented context reports (e.g. Shotwell *et al.*, 2018; Dorn and Zador, 2020) and broader ecosystem report contexts (e.g. Slater *et al.*, 2017) and related materials to inform overall management decisions, such that if a decline in productivity is noted, then ultimately actions such as the ones mentioned here could be taken that effectively would result in a decline in fishing rates to preserve stock biomass for future, albeit limited, production.

Conversely, if there is an increase in production observed that has not been accounted for in prior steps, a phased-in increase in F might be considered. Managers may also wish to explore ways to develop other fisheries in the area for stocks which may be "winners" of climate change and experiencing increases in productivity to release pressure on declining stocks (Hare *et al.*, 2010, 2016; Gaichas *et al.*, 2014).

Addressing locational changes

There are several potential places in the science-to-management process to account for an identified change in location, whether it be a shift in or out of an ecosystem, or an expansion or contraction.

Accounting for the change in location in data collection and treatment

As a first step, again it is important to maintain key data collection programs to continue collecting information on population distribution and range (Table 3, columns 3 and 4—Distribution and range). If the distribution of a fish is suspected of shifting into a region, or its range is expanding, it is sensible to either expand or establish a monitoring program for that taxa (e.g. additional sampling in the Northern Bering Sea was executed in response to observed northward expansion of several groundfish species; Stevenson and Lauth, 2019), or explicitly include it in existing monitoring (https://www.fisheries.noaa.gov/feature-story/2019-southeastern-bering-sea-shelf-bottom-trawl-survey-gets-underway).
A simple, but often overlooked way to address species locational changes is to routinely map distributions from these surveys (Pittman *et al.*, 2007; Nye *et al.*, 2009; Link *et al.*, 2011; Grüss *et al.*, 2018); having maps plotted over time, with associated geostatistics, is an effective means to communicate location changes. Tracking locational metrics (c.f. Table 2) are often how changes in location are detected, and monitoring these measures for rates of locational change is insightful for modelling and predicting distribution and range shifts (see below). An important aspect of addressing locational changes in stocks is to ensure that there is adequate coordination among monitoring and data sharing efforts across the relevant jurisdictions (Melbourne-Thomas *et al.*, 2021). These can be addressed in how data are treated, with survey indices adjusted for amount of habitat surveyed or environmental covariates used to calibrate data inputs (Table 3, column 4—Distribution and range).

As shifts in location persist, the need to revisit how data are treated with respect to stock identification (stock ID) arises. Conducting genetic analysis, incorporating available tagging, and evaluating movement data are useful to evaluate stock ID, and if necessary, revising stock ID and stock unit areas may be an essential consideration to treat data before further use in the following analytical steps (Begg *et al.*, 1999; Cadrin *et al.*, 2013; Spies *et al.*, 2019). For example, Atlantic cod in the North Sea have exhibited environmentally-driven locational variability (Engelhard *et al.*, 2014; Nicolas *et al.*, 2014), which has resulted in heightened debates, and the need to re-evaluate the stock structure for this species (Jorde *et al.*, 2018; ICES, 2020b). Examining change in spatial age-structure, diet, or growth rates may be warranted, and insightful, as well. Survey indices and standard inputs (e.g. abundance index, age/length composition, life-history info, and so on) used in stock assessment models may also need to be corrected for geographic variation across a change in range or distribution regarding the amount of species habitat that is surveyed when there is clear evidence of locational changes. For example, black sea bass has had a well-documented range expansion, with recent studies finding evidence of significant differences in size, diet, condition, and maturity for sea bass in the expanded range compared with the southern historic range; differences which may need to be explored in the stock delineation and assessments (McMahan *et al.*, 2020).

Examining and incorporating relevant socioeconomic data can also help inform locational changes, as indicated by distance from port, where catches are landed, etc. and also inform subsequent management considerations. Obtaining that information also provides a means to track the impacts of species locational changes. All the data elements noted here are generally applicable ways to collect and treat data for both range expansions and contractions, as well as distribution shifts.

Accounting for the change in location in stock assessments and forecasts

Accounting for change in location is feasible in many of the analytical contexts (Table 3, column 5—Distribution and range) used in the science to management continuum (Figure 1). Exploring the use of spatially explicit models (Goethel *et al.*, 2011; Shelton *et al.*, 2014; Thorson, 2019) is both increasingly feasible as well advisable to directly handle shifts in the location of a stock. For example, spatially explicit stock assessment models have been considered for Atlantic highly migratory species which have yielded insights that would have been missed without the spatial structure, and are actually used to track local depletions (Carruthers *et al.*, 2011). Another option is to include time-varying catchability (for surveys and fisheries) in stock assessment models to account for the amount of habitat occupied by stock and that is available to the survey and/or fleet (Thorson and Berkson, 2010; Wilberg *et al.*, 2010; Thorson, 2011). For example, Yellowfin sole has had time-varying q to respond to the metabolic aspect of herding or distribution which can vary annually with bottom water temperature (Wilderbuer *et al.*, 2011). Of course, if several of the data treatment methods are utilized, especially regarding novel stock ID or use of information from expanded survey coverage, one can simply use an assessment model with this new or updated input data. Although not intuitive at first, the consideration of multispecies or whole-of-ecosystem models might also shed insights into population dynamics impacted by locational shifts due to the interactions with other taxa and the consideration of spatial dynamics in many of those models. The other reasons to use multispecies or ecosystem models is that most often, when a stock is shifting out of an area, there is a stock similarly shifting into that same region, and accounting for the multispecies trade-offs and options is wise (Hollowed *et al.*, 2000; c.f. Scheld and Anderson, 2017; Townsend *et al.*, 2019; Link *et al.*, 2020).

Using species distribution models (SDMs) to forecast future changes in distribution is a growing need, and such tools exist and can be usefully applied to project locational changes, which can then be incorporated into forecasts (Cheung *et al.*, 2015; Morley *et al.*, 2018; Moriarty *et al.*, 2020; Pinsky *et al.*, 2020; Stock *et al.*, 2020; Table 3, column 6—Distribution and range). For example, such models have forecast major changes in the locations for various species of Pacific tuna, with a wide array of implications for tuna catches (Dell *et al.*, 2015; Lehodey *et al.*, 2015; Hazen *et al.*, 2018; Venagas *et al.*, 2018). Projections from assessment models using novel or updated input data as noted above are also options for projections of future population dynamics and catches. Considering multiple or ensemble modelling approaches to address different climate scenarios is also an option, as is directly coupled downscaled climate-ocean-SDM-catch models (Ianelli *et al.*, 2016; Hollowed *et al.*, 2020; Jardim *et al.*, 2021), though the latter tend to be quite intensive efforts.

Again, all the approaches noted here are generally applicable ways to assess and forecast stock dynamics and catches for both range expansions and contractions, as well as distribution shifts.

Accounting for the change in location in HCRs, council risk policy, and catch advice

Another place to account for a change in location is in the control rule and catch advice (Table 3, column 7—Distribution). If a stock is shifting its distribution, and that has been accounted for in the stock assessment model, then managers can use the new BRPs from the updated stock assessment model and forecasts. If not, there are a few options. One would be to adjust HCRs with location of biomass cutoffs. For example, if more than ∼66% of the biomass has shifted out of an area (see diagnostics above), then the fishing rate would need to be adjusted proportionally (e.g. Link *et al.*, 2011, 2020; Tommasi *et al.*, 2017; Kritzer *et al.*, 2019; Lam *et al.*, 2019; Bell *et al.*, 2020; *sensu* Houk *et al.*, 2018). For instance, differing perspectives on changes to Pacific herring, and subsequent harvest rules, were reconciled by using a biomass cutoff (Lam *et al.*, 2019). Or, managers can adjust buffers on catch limits (e.g. increase $p*$, or reduce buffer on allowable catch if a stock shifts into an area; the opposite if a stock shifts out of an area; Prager *et al.*, 2003; Shertzer *et al.*, 2008; Prager and Shertzer, 2010) to account for this uncertainty of not knowing how much impact that shift in location will be. That is, if a stock is shifting out of an area, it seems prudent to adjust downward estimates of realized biomass and hence expectations for F (Link *et al.*, 2011).

For a range expansion or contraction, the same approaches apply of using new BRPs from the updated stock assessments (Table 3, column 7—Range). Or if the data to do so are not available or that change has not been included, then managers can adjust the buffer (reduce (if expand) or increase (if contract)) for allowable catch (Prager *et al.*, 2003; Shertzer *et al.*, 2008; Prager and Shertzer, 2010).

Accounting for the change in location through other management actions

Depending on how great a change in location it is, managers may also consider other options for the stock (Table 3, column 8—Distribution and range). For instance, if a stock has shifted into an area, there could then be a phased-in increase in F for the new stock, provided there is sufficient coordination with the jurisdiction it is shifting from. Limiting fishing on a stock as it shifts or expands into a new area could allow for better establishment of the stock in the new area. If the stock was previously managed via some form of area closure, a re-evaluation or adjustment of the closure might also be considered. Static time–area closures are notoriously flawed when distributions are changing, but area closures that rotate location or timing might prove moderately useful, especially for more site-oriented taxa (Hilborn *et al.*, 2004; Hobday *et al.*, 2010; Hazen *et al.*, 2018). If a stock is shifting out of an area, then managers will likely need to adjust landings/permit requirements. The effect of this shift in distribution change is functionally the equivalent of a stock being depleted. As such, "catching them all" before they leave would be the functional equivalent of stock overfishing and is not advisable, and likely also not legal in most jurisdictions. Genetic diversity of a population can be high at the trailing edge (Pauls *et al.*, 2013) and, thus, protection of these individuals may be necessary for protecting the building blocks for future adaptations. Thus, the usual approaches to minimize fishing pressure (i.e. implement appropriate effort controls, fishery closures, limit bycatch, and so on) would be advisable, but with the option to negotiate access for their constituents in the jurisdiction into which the stock is shifting. An expansion in the stock's range or its contraction would be treated similarly as if the stock were shifting into or out of an area, respectively, with the caveat that a contraction would be more severe and with less options than a shifting out of a region. As in the case with a species shifting into a jurisdiction, a species with an expanded range might warrant a phased-in increase in F, albeit in coordination with all jurisdictions involved. For example, the blueline tilefish shifted from the south Atlantic region north into the mid-Atlantic region and sparked an unregulated fishery, which was operating for at least a decade before fisheries managers were able to enact emergency rulemaking in the mid-Atlantic to address the fishing pressures experienced by tilefish there (Smith, 2013; S. Gaichas pers. comm.).

As alluded to in some of the options for accounting for locational shifts noted here, who is involved is an important consideration (Table 3, column 9—Distribution and range). If a stock is shifting into a region, there will likely be the need to adjust or negotiate new management authority, develop a new or at least revise an existing management plan, and consider if updates to allocations need to be negotiated (especially if the jurisdictions are international). All the associated adjustments to permits, landing requirements, etc. would also need to be considered, and all of this done in consultation with the jurisdiction from which the species is shifting. The converse is true for a species shifting out of an area. In essence, the jurisdictions may be relatively geographically fixed, but the taxa within them may not be, and coordination across jurisdictions to negotiate these changes is warranted. Similarly, range contractions or expansions may or may not cross jurisdictional boundaries. If they do, the approaches noted here apply with respect to cross-jurisdictional coordination; if they do not, the cross-jurisdictional approaches noted here might or might not apply, but certainly the revision of management plans and allocations would. For example, as noted above the blueline tilefish shifted its distribution northward along the Atlantic US coast, such that this species historically managed by the U.S. South Atlantic Fishery Management Council, started being landed within the jurisdiction of the Mid-Atlantic Fishery Management Council to the north. Coordination across the two councils was needed to ensure appropriate management of the species in the new jurisdiction. Ultimately, blueline tilefish management measures were added to a management plan from the Mid-Atlantic Council and the catch is allocated between the two councils to ensure the stock is not being overfished; the change in management plan, working with both the South Atlantic fisheries management council (FMC) to the Mid Atlantic FMC, needed to be negotiated and discussed (Smith, 2013; S. Gaichas pers. comm.). Again, the important point is to consider that most ecological niches are filled (Soberón, 2007; Chase and Myers, 2011), and if a taxa is contracting its range, most often another taxa is filling that niche space, and therein lies opportunities if a management organization considers the entire suite of fish movement and the collective losses and gains by *all* species to a region.

Discussion

The evidence that ocean conditions are changing due to climate change, and that these changes are impacting LMRs, is incontrovertible. There is clear evidence that fish stocks have altered their productivity (Hare *et al.*, 2010; Mueter *et al.*, 2011; Blanchard *et al.*, 2012; Hollowed *et al.*, 2013; Poloczanska *et al.*, 2013, 2016; Free *et al.*, 2019), shifted their distributions (Perry *et al.*, 2005; Dulvy *et al.*, 2008; Fogarty *et al.*, 2008; Mueter and Litzow, 2008; Nye *et al.*, 2009; Cheung *et al.*, 2010; Lenoir *et al.*, 2011; Sunday *et al.*, 2012; Pinsky *et al.*, 2013), and expanded or contracted their ranges (Dulvy *et al.*, 2008; Nye *et al.*, 2009; Bates *et al.*, 2014; Spies *et al.*, 2019). Although widely accepted with ever-growing evidence, the challenge has been for these situations, what do we do about it? What we propose here is a suite of pragmatic, tractable actions to address these challenges.

Here, we provide a proposed process for determining when change warrants action, and a list of options to address these changes that are manifested in LMR stocks. These potential "business rules" can be employed at various points as "on-ramps" in the operational science to management process (Figure 1), and represent tangible, actionable steps to address these situations beyond the generic statements that something "needs to be done" in fisheries management. We provide them at multiple steps in the science to management process to ensure that data or analytical or governance limitations are not the single choke-point precluding necessary action. It seems risk averse and wise to at least have such "on-ramp" redundancies built into the process of managing LMRs under changing climate conditions given the amount of uncertainty that such changes can induce (Miller *et al.*, 2010). Ensuring that no signals of change are lost and that no need for action is missed seems prudent.

We also do not assert that the proposed actions are perfect, are at the right cut-offs for action, nor are they entirely exhaustive. In fact, we highly suspect that they can be modified or adapted in a given situation, and would recommend that any particular application adopt those that make the most sense for that particular suite of risk policies, protocols, observed responses, and so on in a given jurisdiction. But, we posit that at least these proposed options could form the basis for potential action to be considered. Debating why a set of proposed actions may or may not work is a significant shift of the debate from how one can even begin to take action, let alone shifting the debate from whether or not action is warranted at all.

One of the challenges noted herein is disentangling the probable causes of the effects due to changes in location, productivity, fishing, or other factors. The solution we propose is to monitor a range of diagnostics simultaneously and as a combined suite of information. As noted in similar, previous attempts to distinguish among possible causes of changes to stock dynamics (Bates *et al.*, 2015; Bell *et al.*, 2015; Link *et al.*, 2020), often signals of change can blend together. But, systematically evaluating a broad range of what we hope become standardly monitored metrics can help identify those key, distinguishing factors to elucidate the major effects that are occurring. Many of these diagnostics are routinely collected or are readily estimable, but they are simply not evaluated as a composite suite given the context we propose here. We trust that mild to moderate adjustments to current monitoring and reporting efforts (e.g. ecosystem status reports, Slater *et al.*, 2017; Dorn and Zador, 2020; 2-page ecosystem–socioeconomic profile stock cards, Shotwell *et al.*, 2018 and so on) can assist in tracking down major impacts to fisheries that heretofore we have not routinely considered.

Another challenge is that if a change in stock location or productivity is detected or even suspected, when should action be taken? That poses the issue of how robust the diagnostics are, how frequently they are examined, and how likely the impact of detecting change would be after it has already been well under way. These nuances aside, what the issue of timing suggests is that there needs to be consistent and frequent monitoring of these diagnostics, and that if evidence of change were detected, and if done so early enough, a graded response could occur. For example, if evidence started to emerge of a distribution shift out of an area, the magnitude and rate of that change would indicate how much a buffer in catch rates could be considered before exploring higher buffers or changes to stock ID. The point being that the range of possible options to act on these changes can be proportional to the magnitude of the detected stock dynamics in location or productivity.

An important point to consider in all these LMR management contexts in the face of climate change is that managers have important choices to make. The default management response is often to resist change and try to retain historical conditions. However, there are other options to consider, including accepting the change that is coming or directing change towards an ecosystem that better meets stakeholder values and needs; thus, the issues often turn into how much to resist, accept, or direct (Thompson *et al.*, 2021)? That is, what is the level of mitigation that we can reasonably expect to effectively execute vs. how much of the change that we see is inevitable such that we need to learn to live with it and adapt *via* different strategies and approaches? The proposed actions we note herein admittedly contain a bit of both, but likely lean towards the adaptation set of approaches. The salient consideration is that many of the Earth-system changes we observe, and hence climate-induced changes to the ocean, are beyond the scope of what can be addressed in a LMR management forum. Certainly, the impacts to LMR are real and need to be addressed in those LMR fora, but some of the changes that are impacting these LMR stocks are well underway. Thus, instead of frustrating attempts to stop broad, global scale changes, or fatalistically accepting them as something that is just going to happen, we propose at the least attempting to adapt to these changing conditions via an intentional and systematic approach to take these changes into consideration.

An important means to address climate-induced changes to LMRs is to manage them as a system. Certainly, some stocks will have lower productivity, shrink their range, or shift their distribution out of a jurisdiction. But ecological niches are constantly being filled (Soberón, 2007; Chase and Myers, 2011), and by extension other fishes will have increased productivity, range expansions, or shift into a jurisdiction. By shifting the emphasis from one stock at a time to managing an entire "portfolio" of fisheries in a given region, the focus moves from just those stocks that are "losers" to also include opportunities and options from novel taxa or newly abundant taxa (Hare *et al.*, 2010; Link, 2018). There is actually a long history of utilizing new species in a given region, even to the point that "ugly fish" can become quite marketable (Link, 2007). This may require a shift in protocols and processes in a jurisdiction to account for all taxa at once, but there are approaches that can accommodate this thinking (Gaichas *et al.*, 2014; Link, 2018; Hollowed *et al.*, 2020). Additionally, higher catch diversity within fishing fleets and ability to move as fish move may buffer fishing communities from the negative effects of climate change (Young *et al.*, 2019). There are certainly socio-economic trade-offs as well to consider in this context. These portfolio approaches may necessitate some flexibility in management plans and regulations, but those possibilities are feasible and none of those are outside of current management guidelines or mandates (Link, 2018).

We conclude by noting that the proposed "business rules" for addressing climate-induced changes in fisheries management can always be debated, can always be updated with new information, and can always be adjusted under a given set of circumstances. But, we also assert that it would be wise to start acting on them, as a proposed set of options, given the urgency and exigency of the situation (IPCC, 2019). Our fear is that constant debate over minutia, analytical precision, the right metrics to consider, and so on is obfuscating not only the choices of possible action, but the need to act at all. We trust that this work at least spurs disciplinary thinking to move into tangible, actionable options before we miss too many opportunities, and thereby head off the social and economic challenges that we have already begun to observe (Allison *et al.*, 2009; Young *et al.*, 2019).

Supplementary data

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

Data availability statement

The data underlying this work are available in the article and in its online supplementary material; no new data were developed, but rather were synthesized for this work.

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