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# Incorporating Climate Change Impacts Within Harvest Strategies: An Overview of Approaches

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## ABSTRACT

Ensuring that harvest strategies are robust to climate change is a top priority for many fisheries jurisdictions globally. This is because climate change is altering ecosystem structure and the productivity of marine species. We outline a range of approaches for incorporating climate change impacts within harvest strategies, including how a harvest strategy is specified and changes to monitoring requirements. Approaches evaluated include the use of extended stock assessments, multi-species and ecosystem models, revised management reference points, implementing regime shifts in model parameters, the provision of climate-sensitive catch advice, projections under alternative climate change scenarios and expanded use of management strategy evaluation. We evaluate the utility of these approaches against cost, data needs and uncertainty criteria; highlight key learnings from a range of global jurisdictions and demonstrate the broad array of options available outside of direct incorporation of climate variables within stock assessments. We identify approaches that have been successfully implemented and show that the most complex responses are not always the most successful. While there is no one-size-fits-all way to incorporate climate change within harvest strategies, we outline the need for flexible management arrangements. We also provide examples of approaches that have been successfully implemented, demonstrating that many of the most data-intensive responses will only be applicable in a few cases, necessitating the application of cheaper, less data-intensive approaches that are associated with greater uncertainty.

## 1 | Introduction

Climate change is demonstrably affecting oceans and marine ecosystems, with significant implications for fisheries resources (Tittensor et al. 2021). Considerable research is being undertaken to assess climate change impacts on species, ecosystems and fisheries (e.g., Pinsky and Mantua 2014; IPCC 2022; Rovellini et al. 2024; Table 1). However, responding to climate change impacts on fisheries requires changes to how management decisions are made, as the expected changes in species distributions and productivity will violate the key assumptions of most stock assessments and harvest strategies. This requires changes to our science and management *modus operandi* (Duplisea et al. 2021; Roux et al. 2022).

Formal harvest strategies are a key component of modern fisheries management. They have been adopted in various forms in, for example, Australia, the United States, the European Union (EU), New Zealand, Iceland, Norway, Canada, South Africa and by some Regional Fisheries Management Organisations and also by the Marine Stewardship Council for sustainability evaluations (Sloan et al. 2014; Dichmont et al. 2016). Formal harvest strategies, sometimes referred to as management procedures, comprise a set of rules for making management decisions, including specifications for (i) a monitoring programme, (ii) indicators to be calculated from the monitoring data (often using a stock assessment) and (iii) the use of those indicators and their associated reference points in management decision-making, through application of decision (or harvest control) rules (Smith et al. 2013; Dowling et al. 2015).

There is a long history of investigating the impact of changing environmental conditions on stock assessment and harvest strategy performance (e.g., Walters 1975; Beddington and May 1977; Parma 1990; Walters and Parma 1996). Most of these studies have focused on investigating the impacts of variation without trend in environmental conditions through time. In contrast, climate change is resulting in directional change and/or increased variability in productivity and other variables of interest (IPCC 2022), necessitating a broader range of approaches than has been explored in the past.

Globally, various approaches are being proposed to deal with the impact of climate change in all aspects of harvest strategies, although the general focus has been on incorporation of environmental drivers into stock assessments (e.g., Skern-Mauritzen et al. 2016; Marshall et al. 2019; Pepin et al. 2022; Trenkel et al. 2023). This approach is not always possible or appropriate, and the response of harvest strategies to climate change will require adjustments across the entire fisheries management system (Karp et al. 2019; Bryndum-Buchholz et al. 2021; Free et al. 2023). Here we outline the range of approaches currently being utilised to account for climate change impacts within the full harvest strategy process. We summarise the key lessons learnt across a range of jurisdictions: Australia, Canada, the EU, the North Pacific, the South Pacific and New Zealand, which represent a range of fishery types, data availability, climate conditions and management approaches. Understanding the various options that have been implemented within these jurisdictions will aid agencies who are required to account for climate change impacts within management processes. While this discussion is not as comprehensive as a systematic literature review, it does represent the experiences of various jurisdictions attempting to address the issue.

## 2 | Methods of Incorporating Climate Change Into Harvest Strategies

The techniques for including climate change impacts within harvest strategies generally fall into two categories: (a) those associated with the assessment process and (b) those associated with how the results of assessments are used for management decision-making. Most investigations into ways to account for climate change impacts have focused on the first of these (e.g., Skern-Mauritzen et al. 2016; Marshall et al. 2019; Pepin et al. 2022; Trenkel et al. 2023). There are, however, a broad range of methods to account for climate change within the management process (Figure 1, where modifying assessment approaches make up a small proportion of the available options, see shaded vs. unshaded). Harvest strategies operating in data-poor environments will often be limited to modifying decision rules, whereas more options are available for data-rich cases.

### 2.1 | Specification of Harvest Strategies

It is important to specify the harvest control rules (HCRs) used within a harvest strategy. HCRs can be implemented within a stock assessment or as empirical rules derived from data inputs or simple models. In the context of climate change, HCRs are expected to meet pre-specified objectives under a range of plausible future scenarios (Blamey et al. 2022), which can be checked by testing the harvest strategy under simulated climate change conditions (e.g., Mildenberger et al. 2022). Commonly, these tests are conducted using Management Strategy Evaluation (MSE, see below). However, simple simulation testing (without the full feedback loop of MSE) may also provide insight on the performance of catch-setting approaches and determine candidate options to take forward in more intensive MSE testing (e.g., Kapur and Franklin 2017; Lindkvist et al. 2017; Diop et al. 2018; Le Bris et al. 2018; Bessell-Browne et al. 2022; Goto et al. 2022). Another common component of harvest strategies is exceptional circumstance considerations, and these involve specification of conditions when a harvest strategy should not be followed due to unforeseen circumstances (de Moor et al. 2022).

A review of HCRs used in the United States and their performance under climate change conditions (Free et al. 2023) found that threshold fishing mortality ($F$) rules (where $F$ is reduced once biomass drops below certain thresholds) may be more effective than other HCRs at preventing overfishing while maintaining catch and profits under both increasing climate variability and directional change (Kritzer et al. 2019; Mildenberger et al. 2022; Wiedenmann et al. 2017). The application of environmentally linked HCRs is rare, as they require substantial data inputs but are also reliant on stable and predictable environmental relationships (which is not guaranteed under a changing climate)

**TABLE 1** | Examples of mechanisms for climate change impacting fish stocks and fisheries.

| Ecological response type | Example mechanism | Examples of the impact of change | Example references |
|---|---|---|---|
| Range shifts | Whole ecosystem | *Sardinella aurita* has shifted north in following long-term sea surface temperature increases | Sarre et al. (2024) |
| | Expansion (generally poleward) | Estimates of movement up to 72 km per decade of the leading edge of expansion | Poloczanska et al. (2016) |
| | | More than 60 species have recorded range extensions into Tasmania (Australia) | Gervais et al. (2021) |
| | | American lobster has increased its range to the north | Pinsky et al. (2013) |
| | | Snapper populations In New Zealand have extended south | Langley (2024) |
| | Contraction (margin contracts to core distribution) | The seaweed *Scytothalia dorycarpa* contracted by ~100 km off Western Australia following a marine heat wave | Smale and Wernberg (2013) |
| | Tropicalisation | Temperate benthic assemblages in Western Australia are being increasingly inhabited by warm water species, while cool water species recede | Vergés et al. (2019), Wernberg et al. (2016) |
| | Depth | Deeper movement of common dentex in the NW Mediterranean and bonefish in Puerto Rico to regulate body temperature | Aspillaga et al. (2017), Brownscombe et al. (2017) |
| Productivity and abundance | Recruitment | While increased temperatures result in faster growth of 131 larval fish species, this also means more food is required to sustain this growth, resulting in starvation in some circumstances and increased variability in recruitment | Lo-Yat et al. (2011) |
| | | Small increases in temperature can dramatically increase egg mortality of tropical species such as tropical damselfish | Gagliano et al. (2007) |
| | | 60% of assessments in the RAM legacy database (Ricard et al. 2011) demonstrated changes in recruitment unrelated to spawning biomass | Sellinger et al. (2024) |
| | Growth | Increasing summer temperatures have reduced the growth of gilthead seabream in the NW Mediterranean | Heather et al. (2018) |
| | | Growth of Atlantic cod varies by a factor of two with changing temperatures | Brander (1995) |
| | | Increased temperatures are predicted to reduce the average body size of fish species, increasing the proportion of smaller individuals | Audzijonyte et al. (2020) |
| | Mortality | Changing predator–prey dynamics can impact average values of natural mortality ($M$) for walleye pollock | Dorn and Barnes (2022) |
| | | Tagging studies show that sockeye salmon have increased $M$ outside normal temperature regimes | Eliason et al. (2011) |
| | | Trophic interactions resulting from the replacement of forage fish by crustaceans in Newfoundland-Labrador resulted in increased $M$ for cod | Rose and O'Driscoll (2002) |
| | | Mass mortality events of fish species have been observed following marine heatwaves | Pearce and Feng (2013) |
| | | Heatwave-induced mortality of more than 10 billion snow crabs in the eastern Bering Sea linked to reduced spatial distribution and starvation | Szuwalski et al. (2023) |
| | Phenology change | Increased temperatures result in faster growth rates of fish species such as Arctic charr | Kotowych et al. (2023) |
| | | Timing of migration has changed for some coastal fishes off Rhode Island, which temporally changes trophic interactions and can influence the productivity of migrators and other species in the food web | Langan et al. (2021) |
| | | Zooplankton and larval fish phenology have become asynchronous in the California Current | Asch (2015) |
| | Disease/pathogens | Disease and parasite loads are anticipated to become more prevalent as temperatures increase. One example is the increase in proliferative kidney disease in wild and farmed salmonid populations | Bruneaux et al. (2016) |

(Continues)

TABLE 1 | (Continued)

| Ecological response type | Example mechanism | Examples of the impact of change | Example references |
|---|---|---|---|
| Condition | Knock on effects on product quality, toxicity, etc | Warming of the East Australian Current has increased the prevalence of parasites in broadbill swordfish, dramatically reducing meat quality | Brolin et al. (2024) |
| | | Ocean warming and increased storm intensity are increasing the habitat for ciguatoxic organisms, increasing the incidence of ciguatera poisoning | Gingold et al. (2014) |
| | | 50% reduction in protein content in Atlantic salmon with increased water temperatures | Shalders et al. (2022) |
| | | Stressed fish have lower meat quality; e.g., the fatty acid of red cusk-eel is affected by high water temperatures | Zhang et al. (2023) |

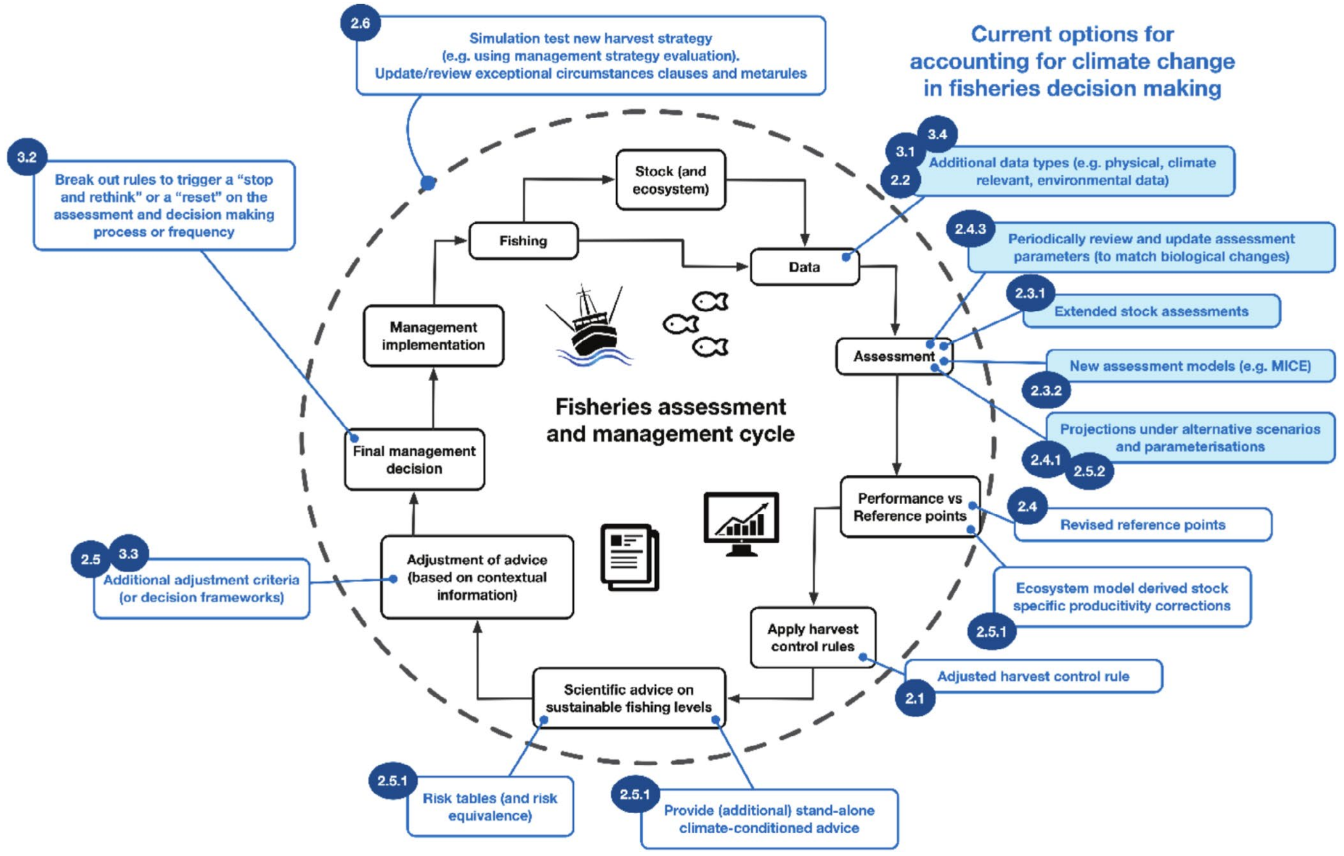


FIGURE 1 | How approaches for incorporating climate into harvest strategies connect into the management cycle, and how climate change impacts may be incorporated. Numbers next to each option link to the section within which they are discussed. Shading relates to data- and assessment-related options (shaded) and other approaches (unshaded).

and only show marginal increases in performance compared to simpler rules (Punt et al. 2014).

## 2.2 | Monitoring to Support Management in a Changing Climate

Assessments must be tailored to the information available, or monitoring adjusted to deliver (at least as a minimum) what the assessment requires as inputs. Monitoring can be adjusted or expanded given climate change (Pinsky and Mantua 2014). Novel data sources, such as environmental data, may be required to understand potential linkages between the environment and population dynamics, and these linkages can be incorporated into harvest strategies and the evaluation thereof.

Historically, fishery monitoring has typically provided time series of total removals and an index of relative abundance (usually a fishery catch-per-unit-effort index), often along with limited fishery age- or size-composition data so that traditional single-species assessment methods that do not account for climate drivers can be applied. Some regions have relied on fishery-independent surveys, as these are not subject to most of the biases associated with fishery-dependent data. Monitoring data provide information on biological parameters, such as maturity, growth and distribution shifts that may be impacted by climate change. However, accounting for climate change when providing management advice will increase the needs for monitoring, perhaps substantially.

Models with climate drivers require information on those drivers. It is generally important to (a) consider a priori hypothesis-supported environmental drivers to avoid finding relationships between environmental variables and model parameters that break down with additional data (Haltuch, Tolimieri, et al. 2019) and (b) appreciate that relationships may change through time as climate change intensifies or is mitigated (Free et al. 2023).

Analytical methods that rely on indices of abundance may provide biased estimates as species change in abundance owing to climate change-induced distribution shifts. This will likely impact commercial catch-per-unit-effort substantially as fishers will change targeting practices to adjust to a new reality. A combination of range shifts due to environmental change without modification of monitoring systems can result in loss of data, such that existing assessments may no longer be feasible. This will mean that the design of fishery-independent surveys may require adjustment, particularly as species move out of their traditional areas (Link et al. 2011) and across jurisdictional boundaries (Free et al. 2023). This is already evident in the Bering Sea, where surveys now regularly occur in the northern Bering Sea owing to past and expected ongoing changes in species distribution (e.g., O'Leary et al. 2022).

Approaches that assume population parameters change over time in response to environmental (and climate) effects require the collection of sufficient data to quantify such changes. Changes over time in recruitment usually require time series of age compositions, while the data needed to assess time variation in parameters such as length-, weight- and maturity-at-age may require additional monitoring information. Some extended single-species and ecosystem models require information on diet (and how it changes over time and spatially), possibly leading to increased data needs.

## 2.3 | Assessing Stock Status

Indicators used in harvest strategies, such as biomass and fishing mortality, are informed by monitoring data, mostly based on quantitative stock assessments, although some make use of empirical indicators (e.g., Plagányi et al. 2018; Kapur et al. 2024). Other approaches implement empirical or simple model-based indicators to inform management decision-making and use complex stock assessments to assess whether the harvest strategy is performing as expected (e.g., Hillary et al. 2022).

Data will be limited in many situations, and in some cases, there may be almost no ecosystem and stock-specific data. However, a decision on fisheries exploitation needs to be made regardless of the information available. A range of data-limited assessment methods are available to assess stock status under these circumstances. However, they often do not account for climate change, although these simpler assessment methods can be modified to do so using time-varying parameters (Kokkalis et al. 2024). Data-limited assessment methods are also in development that consider climate impacts (e.g., Bahri et al. 2021; Roux et al. 2022).

### 2.3.1 | Extended Stock Assessments

One way to incorporate climate change into stock assessments is through direct incorporation of environmental correlates (e.g., SEDAR 2014; Johnson et al. 2015; Punt et al. 2024). However, this is possible for only a few stocks globally because usually there is no known relationship between a biological process and a single environmental variable, or there are insufficient data to support the increased complexity. However, it is an explicit and falsifiable way to include climate change impacts in population models. One of the main difficulties encountered with this approach is that an inappropriate covariate can be selected in the absence of detailed process understanding, resulting in relationships that fail or change over time (Walters and Collie 1988; Myers 1998; Haltuch and Punt 2011). There is thus a need to monitor the relationships between the biological processes and environmental drivers to ensure that they are maintained.

Successful examples of extended assessment application include Pacific cod (*Gadus macrocephalus*) and yellowfin sole (*Limanda aspera*) off Alaska, where survey catch is linked to bottom temperature (Hulson et al. 2022; Spies et al. 2022); US West Coast sablefish, where sea level is linked to recruitment (Haltuch, A'mar, et al. 2019) and tropical rock lobster (*Panulirus ornatus*) in the Torres Strait, where sea surface temperature is related to natural mortality (Plagányi et al. 2019). Of note is that these examples all include fishery-independent indices of abundance within assessments.

Reviews of the global application of extended stock assessments revealed they are implemented in relatively few situations (2% of 1200 global assessments; Skern-Mauritzen et al. 2016). Investigations in the US have also revealed limited inclusion of quantitative ecosystem impacts within stock assessments, where the most common inclusions were habitat, environmental conditions and predation (11%, 14% and 1% of assessments, respectively, Marshall et al. 2019). However, most of these assessments were in some of the most data-rich regions globally, suggesting extended stock assessments will not be a viable option for most species (Skern-Mauritzen et al. 2016; Marshall et al. 2019).

### 2.3.2 | Multi-Species and Ecosystem Models

These models can be used to explore climate-fisheries interactions and their implications for fisheries production and management (Kaplan et al. 2020; Rovellini et al. 2024). While multi-species models can be used for assessments to inform catch-setting processes (e.g., Karp et al. 2019), the more common use is to understand system-scale processes or in "what-if" explorations of future management options. This is because these models can explore the impacts of multiple combinations of drivers simultaneously.

Models of Intermediate Complexity for Ecosystem assessments (MICE) include key species and their direct drivers (such as predators, prey, habitat, climate drivers and effort dynamics). These models are being applied to examine climate-associated questions (e.g., Plagányi et al. 2011, 2014). Several MICE-type models incorporating climate-stock relationships are used to inform management (Plagányi et al. 2022; Tulloch et al. 2019).

End-to-end ecosystem models incorporate even more of the system, albeit at a cost of increased model uncertainty, representing environmental influences on habitats and entire food webs (Christensen et al. 2015; Heneghan et al. 2021; Fulton et al. 2024). The representation of fishing dynamics in these models varies among applications, with some including sophisticated effort dynamics models and full representation of the management decision-making process (e.g., Fulton et al. 2024; Maury et al. 2024). These models are being used to provide insights into possible effects of climate change on fished systems at regional and global scales (Fulton et al. 2024; Section 2.5.2).

## 2.4 | Revised Management Reference Points

It seems intuitive to consider modifying management reference points to account for the influence of climate change, given that reference points in single-species fisheries management have traditionally related to stock sizes at specific points in time (e.g., prior to targeted exploitation) and depend on productivity at that time. Differing methods of incorporating this time variation are explored below.

### 2.4.1 | Dynamic Reference Points

The most common way to adjust management reference points is to implement time-varying parameters within assessments. Changes to recruitment, natural mortality, growth, weight-at-age, length-weight relationships, fecundity and maturity impact the calculation of reference points, changing targets and biomass reference levels (*x*- and *y*- axes in Figure 2). Allowing for time-varying parameters, such as weight-at-age, is common in data-rich regions (e.g., the North Pacific and Europe) but is less so in data-limited regions. In addition, some components of production (e.g., natural mortality) are difficult to measure directly and therefore are only rarely modelled explicitly within assessments, making time-varying estimation exceedingly challenging.

The performance of dynamic HCRs under time-varying production, implemented via the stock-recruitment relationship, has been examined for data-limited situations without a fully age-structured assessment, and Collie et al. (2021) found that biomass-linked HCRs can partially compensate for time-varying production, even with static inputs.

### 2.4.2 | Dynamic $B_0$

Dynamic $B_0$ represents the reference levels of unfished biomass (matching the definition used for reference points) under current prevailing environmental conditions (MacCall et al. 1985). Estimates of dynamic $B_0$ represent the population size that would have resulted had no fishing occurred, but all biological parameters were as estimated in the assessment. Using dynamic $B_0$ within an assessment to calculate reference points allows for factors other than fishing to impact population size through time and provides a mechanism to account for changing productivity when the specific driver of the change is unknown. This is important because the direct driver of productivity change is often unknown or results from a combination of factors, with the influence varying through time. Reference points change through time under dynamic $B_0$, but this is not the case under static $B_0$ (the equilibrium conditions estimated before the commencement of fishing, Figure 2).

Stock biomass has been expressed relative to dynamic $B_0$ by the Western and Central Pacific Fisheries Commission (WCPFC) to support management decision-making for ~10 years (WCPFC 2012; Berger et al. 2013), while other jurisdictions (e.g., US, Australia, and New Zealand) are examining the consequences of its use (e.g., Szuwalski et al. 2023; Bessell-Browne et al. 2022, 2024; Figure 2). To date, testing has revealed limited differences in performance between static and dynamic $B_0$ when productivity varies without trend (Berger 2019; Bessell-Browne et al. 2022). However, HCRs based on dynamic $B_0$ result in increased exploitation rates and reduced absolute population size, with a small increase in catch, along with greater assessment bias under declining productivity (Szuwalski et al. 2023; Bessell-Browne et al. 2024).

Other research has highlighted challenges with dynamic $B_0$, including assumptions related to future recruitment, confounding of fishery and climate impacts that are difficult to disentangle, and how performance varies if changes in biological parameters are attributed to climate incorrectly (Haltuch and Punt 2011). Given these challenges, dynamic $B_0$ may be more useful within an MSE context to define the performance metrics used to rank management strategy options rather than direct use within assessment-based HCRs to provide catch advice. However, management systems should consider options for adjusting biomass reference points to current productivity conditions when there are clearly ongoing mismatches between assessments/management and stock production (Roux et al. 2022).

### 2.4.3 | Regime Shifts and Changes in Reference Points

Incorporating a step change in biological parameters, often referred to as a regime shift, is another way to incorporate climate change impacts into stock assessments and associated reference points. A regime shift is considered to have occurred when there has been a permanent shift in the ecosystem state, with the system not expected to return to its original state (Rocha et al. 2015).

Britten et al. (2016) and Sellinger et al. (2024) investigated the relationship between spawning stock size and recruitment for 127 and 432 global stocks, respectively, identifying potential time variation and regime shifts. The results demonstrated that there was time variation in recruitment for most of the stocks investigated and that environmental conditions were more often

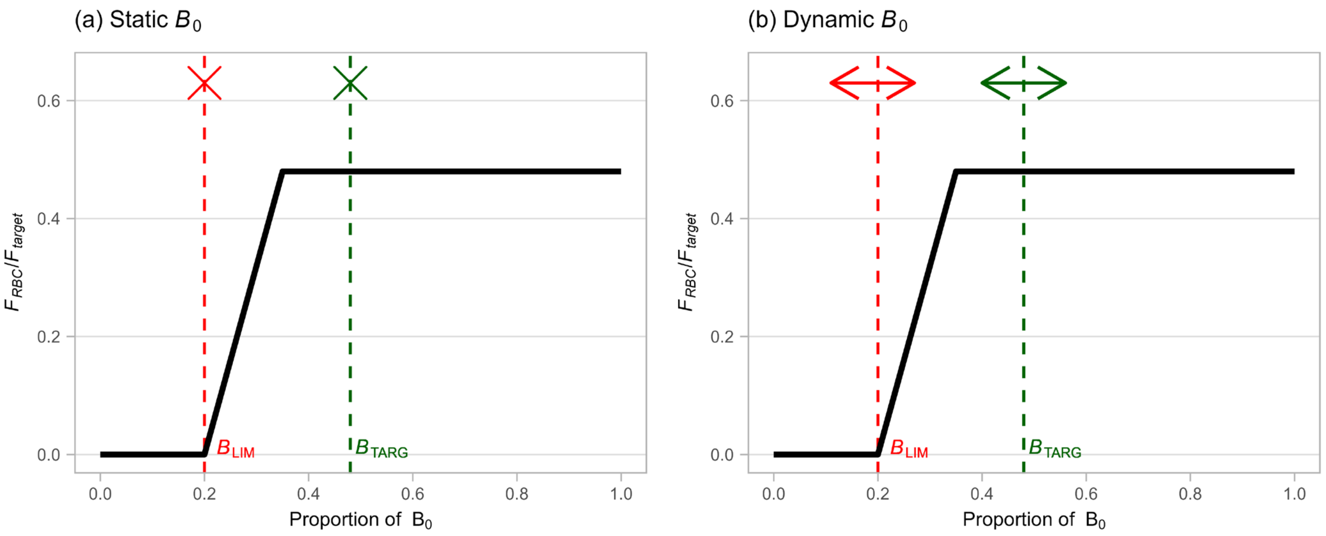


**FIGURE 2** | Illustration of (a) static $B_0$, and (b) dynamic $B_0$ harvest control rules. The solid lines represent the HCR, the dashed red lines show the limit reference point and the dashed green lines show the target reference point. $F_{RBC}/F_{target}$ is the fishing mortality rate that directs the stock towards the target reference point. Coloured crosses represent a part of the HCR that does not change through time, while arrows represent the ability to change.

correlated with recruitment than spawning biomass (Britten et al. 2016; Sellinger et al. 2024). These results highlight that there are several types of relationships between recruitment and spawning stock size and that a regime shift is less likely to occur than a gradual ongoing change.

A regime shift is incorporated in the assessment and management process for walleye pollock (*Theragra chalcogramma*) in the Gulf of Alaska. A regime shift in productivity was implemented because regime changes in environmental conditions were experienced in the North Pacific Ocean in 1977 and 1989 (Hare and Mantua 2000; Anderson and Piatt 1999). Reference points are consequently based on the post-1977 recruitment estimates (A'mar et al. 2009). A regime shift in recruitment is included in the assessment and HCR for Jackass morwong (*Nemadactylus macropterus*) in Australia because the recruitment of this stock had been estimated to be consistently below the historical average (Wayte 2013). However, subsequent assessments revealed that it was likely an ongoing decline in recruitment rather than a single step change, and the species has subsequently been assessed as overfished (Day et al. 2021). Another example of a regime shift that was not maintained was the Iberian sardine (*Sardina pilchardus*), where a regime shift to a lower productivity was observed and implemented in the assessment, only for the species to later experience a period of strong recruitment (ICES 2019). These examples highlight the challenges of detecting a regime shift that is then maintained in perpetuity and that incorrect implementation of a regime shift can lead to adverse outcomes. Moreover, it is difficult to detect a regime shift until some time after it has occurred due to the lag in the detection of recruits entering a fishery.

## 2.5 | Alternative Approaches

Stock assessments and the application of HCRs feed into the decision-making process, which will usually have some flexibility in terms of how the results of stock assessments and HCRs are used. Generally, this involves including the effects of external factors in the management advice following the stock assessment. Such approaches can be quantitative or qualitative. So the way that climate advice is provided can be more qualitative than the other options described above, given the lack of knowledge of climate drivers and their effects on marine systems. This approach allows climate change impacts to be considered within the management process but does not add unnecessary complexity. This is important because simplicity is often a goal of harvest strategies, as complex processes make stakeholder engagement more challenging and often increase monitoring and data needs. There is no need to modify monitoring and assessments or include additional complexity if a simple approach can be shown to be robust to climate impacts. The two-stepped and risk table approaches are examples of such adjustment processes.

### 2.5.1 | Modified Climate-Sensitive Catch Advice

Fisheries and Oceans Canada has developed an approach that applies post hoc conditions to assessment model output in a two-step manner, leading to advice for sustainable catches from a stock assessment, along with climate-conditioned advice (Duplisea et al. 2021). The climate-conditioned advice aims to be risk-equivalent so managers using this advice retain the same level of risk tolerance in managing fisheries as they did when the environment and production were considered unimpacted by climate change (Bourdages et al. 2022; Roux et al. 2022).

Ecosystem models are being used in Europe to derive stock-specific corrections to estimates of sustainable fishing mortality to account for productivity changes ($F_{ECO}$) (Bentley et al. 2021). $F_{ECO}$ can alter estimates of sustainable fishing mortality depending on whether conditions are worse or better for stock production. Although not initially intended to be used to account for climate change impacts, it has the potential to do so because climate drivers are included in the ecosystem models used to compute $F_{ECO}$.

Risk tables are used in the northeast Pacific (Dorn and Zador 2020). They provide a qualitative means of considering additional advice, including environmental change, for decision-making, with the aim of better incorporating uncertainty. This process essentially produces a buffer leading to reduced total allowable catches when climate risk is considered high. However, there is no formal link between risk tables and buffer sizes, meaning there is some subjectivity in the process.

Adjusting catch to account for climate change while applying static reference points is a temporary solution allowing timely management advice to be provided. Ultimately, repeatedly adjusting catch or effort in an attempt to compensate for climate-related productivity changes suggests that the science-management system is mismatched to the stock production. The management system should then adjust biomass reference points to current productivity conditions (Roux et al. 2022). This would also apply when using $F_{ECO}$ where the ecosystem model is misspecified compared to the assessment model. There will also be multi-species fisheries where no combination of HCRs for single species will maintain all species above the limit reference point (e.g., Pérez-Rodríguez et al. 2017). Determining decision rules, where depleted stocks have no prospect of recovery due to climate-induced productivity changes, may be required in many regions.

### 2.5.2 | Projections Under Alternative Harvest Strategies and Climate Scenarios

Ensembles of ecosystem model projections have been used to inform the potential future abundance of fish stocks at global and regional scales under collaborative efforts such as FISH-MIP (Blanchard et al. 2017; Tittensor et al. 2021; Cinner et al. 2022), with the United Nations Food and Agricultural Organisation (FAO) recently releasing a report with projections for each Exclusive Economic Zone and high seas area (Blanchard and Novaglio 2024). Ecosystem models have also been used in more specifically targeted work to inform management. For example, counterfactual analyses have been carried out for southeast Australia to understand impacts on productivity and the likely contribution of climate to stock status and historical management performance (Fulton et al. 2024).

## 2.6 | Management Strategy Evaluation

Harvest strategies can be evaluated based on projected system dynamics under climate scenarios and pre-specified (but unchanging) management rules or levels of fishing pressure (e.g., Punt et al. 2024; Hollowed et al. 2024). They can also be evaluated more dynamically using MSE—where a model is used to represent a "virtual world" for testing management options but with full dynamic representation of the decision-making processes and that of updating assessments based on monitoring data (Punt et al. 2016; Haltuch, Brooks, et al. 2019).

MSE can be used when a relationship between an environmental variable and a biological process may be known but not sufficiently to incorporate directly into an assessment, or where there are hypotheses of different pathways for the impact of various stressors (Punt et al. 2014). MSE can consider multiple environmental drivers, broader changing human use of a system and larger sets of species. A comprehensive overview of methods for incorporating climate impacts within MSE is available in the literature (e.g., Punt et al. 2014; Surma et al. 2018; de Moor 2024; Peterson et al. 2025).

### 2.6.1 | MSE Testing of Assessment Methods and HCRs

A harvest strategy can account for climate change in several ways, such as the incorporation of environmental variables within the assessment or HCR. MSE can be conducted as a first step to test the performance of the new methods under plausible future scenarios, including those with climate-induced changes in productivity. If a method does not perform as expected under the initial testing, then, depending on specific policy objectives, there would be no point in including it in more formal harvest strategy design and testing.

Szuwalski et al. (2023) and Bessell-Browne et al. (2024) highlighted how dynamic $B_0$ HCRs, which do not alter the target fishing mortality rate, increase harvest rates at low population sizes under declining productivity conditions and are examples of how MSE can identify flaws in potential adaptation responses to climate impacts. These studies highlight how MSE can shortcut the development of harvest strategy options and avoid costly outcomes from unintended consequences of well-meant actions.

### 2.6.2 | MSE Testing Robustness of Harvest Strategies to Future States

MSE testing of all aspects of a harvest strategy and evaluating its performance under a range of differing, plausible future conditions is required to ensure that chosen harvest strategies are robust to climate change. Such an approach is considered best practice before implementing a new harvest strategy (Punt et al. 2016).

A goal of harvest strategies is often simplicity, and it may not be necessary to develop complex assessment methods and decision rules if simple alternatives perform just as well under the range of plausible future scenarios, and MSE can be used to identify these. For instance, MSE was used to evaluate the performance of alternative potential harvest strategies for redleg banana prawns (*Penaeus indicus*) in Northern Australia. There is evidence for a relationship between the southern oscillation index, rainfall and catch-per-unit-effort for this species (Plagányi et al. 2019, 2022). An MSE included these climate drivers in operating models and tested the performance of harvest strategy options. This led to a harvest strategy that was found to be robust to predicted future climate impacts, which was subsequently implemented (Blamey et al. 2022).

Southern bluefin tuna (*Thunnus maccoyii*) is another example where climate change impacts were considered within an MSE but not the assessment or decision rule. In this example, potential climate change impacts were tested for within the operating model (Hillary et al. 2019). The chosen harvest strategy for this stock was found to be robust to the identified potential changes and included an 'exceptional circumstances' clause that can be invoked if conditions experienced are outside those tested within the MSE (Hillary et al. 2019).

Harvest strategies for data-limited fisheries may be in the form of more static measures, such as allowing catch of only one sex and seasonal or gear restrictions. While such approaches do not vary the management response depending on the results of an indicator, they can be tested using MSE to determine their performance under a range of expected future conditions. They can also include other harvest strategy elements, such as exceptional circumstances clauses. An example of this type of application is the Oregon Dungeness crab, which is managed by restricting catch to males and limiting gear use, but includes monitoring for exceptional circumstances (Oregon Department of Fish and Wildlife Marine Resources Program 2022).

Other MSEs have highlighted how misspecification and bias in an assessment can increase the risk of overfishing (Mazur et al. 2023), as can a failure of fisheries management to appreciate spatial redistribution (Jacobsen et al. 2022). Exploration of HCRs in multi-species and ecosystem models highlighted the different pathways through which climate change can influence an ecosystem, leading to different effects, which may require harvest strategy responses (Guo et al. 2020). A consistent finding across many MSEs is that harvest strategies designed to maintain stability in catches have a greater associated risk of overfishing, leading ultimately to fisheries closures (Siple et al. 2019; Mildenberger et al. 2022; Free et al. 2023).

These examples demonstrate the potential of MSE to assist in developing harvest strategies that are robust to impacts of climate change, irrespective of whether a specific driver between an environmental variable and a biological process is known or not. They also highlight that an appropriate harvest strategy may not incorporate environmental variables as part of the assessment or HCR and that complicated assessments and HCRs are not necessarily required.

## 3 | Selecting an Approach: Key Lessons

### 3.1 | Conducting Assessments Is Only Part of the Response

Most of the literature on climate within fisheries science has focused on quantifying impacts of climate change on physical processes and ecosystems, including using population models. However, the aim of fisheries science is to support management decision-making, and that occurs primarily through the application of harvest strategies. There is a broad range of harvest strategy options available to account for climate change within management systems by linking assessments with the provision of management advice using reference points and ultimately catch limits. Appropriate harvest strategies will vary, given the ecological context of the species fished and the quality and quantity of available data. However, it may be possible to respond to changing environmental conditions without incorporating climate directly into stock assessments. For data-rich species, this is because new monitoring data (e.g., climate indices (ENSO, PDO, etc.), or specific environmental properties that relate to the climate change mechanism, such as sea surface temperature, etc.) could allow management to respond to system changes, while data-poor species require alternative approaches to the development of harvest strategies and the incorporation of climate change impacts.

### 3.2 | Expect the Unexpected

Climate change is associated with unexpected future conditions. While some climate impacts can be anticipated, conditions are (and will increasingly be) outside of those observed before. Multiple jurisdictions have found that climate change will require management to respond to unexpected conditions and stock responses, and management systems need sufficient flexibility in all aspects of the management process for this to occur. This may even require specific "breakout" rules, where changes in abundance, catch or other indicators trigger a change in the frequency of assessments or even a review of entire management approaches (if they are found to not be performing as anticipated).

Reference points, rebuilding strategies for overfished stocks and the management decision process are areas that may require flexibility. For example, several species in Australia's Southern and Eastern Scalefish and Shark Fishery have been assessed to be below their limit reference points (AFMA 2024). Targeted fishing of some of these species has been prohibited for over 15 years, but there is no evidence of recovery. Determining whether recovery has been impacted by changing climatic conditions is a key challenge. These are exacerbated if data collection is reduced once a stock is assessed as depleted.

To date, most of the focus of research into changing productivity conditions has been on declining productivity, but "climate winners" also need to be managed. For example, several species in New Zealand have undergone large increases in productivity and have subsequently been assessed to be above unfished levels (Fisheries New Zealand 2024). The management response has been to adjust reference points and move to absolute, rather than relative, limit reference points (Fisheries New Zealand 2024).

Increased productivity is generally considered as being positive, but this is not always the case. For example, there have been multiple years of record-setting recruitment of sablefish in the northeast Pacific, which has resulted in increased bycatch constraints. This is because high catches of small sablefish have meant that catch limits for some fishery sectors have been reached, limiting fishing for other target species. This increased abundance has exacerbated pre-existing market price declines as small fish flood the market. This demonstrates that what might be considered a positive change may have unintended consequences, depending on the management system and market conditions. It also further highlights the complexities of productivity changes and the need to respond to unintended consequences.

### 3.3 | There Needs to be a Framework for Dealing With Species With Differing Data Availability

The ideal harvest strategy depends on data availability and in particular ongoing data collection.

#### 3.3.1 | Data Rich: Extended Stock Assessments and MSE-Tested Harvest Strategies

Some species have the resources and data to conduct extended stock assessments that incorporate environmental covariates, and MSE testing can be used to assess if harvest strategies are robust to anticipated climate impacts. This may negate the need for ad hoc precautionary buffers.

#### 3.3.2 | Data Moderate and Data Limited: Precautionary MSE-Tested Strategies and Qualitative Risk Tables

Most stock assessments cannot include environmental drivers due to lack of data. In addition, assessments for stocks without fishery-independent data will be uncertain. These factors reduce the confidence in the assessments and associated harvest strategies under changing environmental conditions. These challenges will become more pronounced as data become sparser. One way to overcome this challenge is to adopt a "climate buffer", which reduces catch limits by a pre-specified amount to account for climate change-related uncertainty (Free et al. 2023). However, in the northeast Pacific, which has adopted a risk table approach (Dorn and Zador 2020), the size of climate buffers has been based on discussions rather than using pre-determined quantitative rules, which increases subjectivity in the process. This approach also assumes that environmental effects are always negative, which may not be appropriate in all cases.

### 3.4 | Data Collection Requirements Will Increase or Change

How a fishery is managed will reflect the management system and associated policies. It will also be driven, in part, by understanding of underlying processes impacting biology, the quality of data available and the complexity of stock assessments. Current data collection protocols may only need minor adjustments to ensure they continue to perform as expected in jurisdictions that already have extensive data collection programmes, such as in the North Pacific and Atlantic. Such adjustments could be to the spatial area covered in fishery-independent surveys (Link et al. 2011).

Where data collection is already limited, current protocols will likely not provide sufficient information to inform management decisions in a quantitative way as climate change continues to intensify. This is apparent in regions such as Australia and New Zealand, where data collection costs are funded by fishery levies and some fisheries are low value. In addition to low-value fisheries, this will also be the case in many data- and capacity-limited regions. Data collection for these data-limited stocks will either need to be increased to inform quantitative assessments, or more precautionary, data-limited approaches will need to be adopted.

### 3.5 | Comparison of Approaches

The lessons outlined above fit within the adaptive management framework (Walters 2007). It is increasingly apparent that the adaptability of management systems is important as climate change impacts intensify. This is particularly the case when large changes occur outside of conditions previously observed. Such situations will necessitate experimentation with management approaches and quick reactions if performance is not as expected. This will generally require increased or modified data collection, and few options will be available in data-limited situations. No single approach will work in all cases due to differences among management systems, resources available, societal objectives and environmental conditions. Rather, a structured decision-making process that is flexible and adaptable will be required because climate change impacts will increase uncertainty in the management decision-making process, and acknowledgement of this uncertainty is required.

Table 2 presents a qualitative summary of the key characteristics of the approaches investigated in this paper and highlights the trade-offs when choosing an option in relation to the data requirements, relative costs and associated uncertainty. In general, extended stock assessments and ecosystem models have the greatest data requirements and cost, with marginally lower uncertainty than some of the other options. Revised reference points have moderate data and cost requirements and relatively good handling of uncertainty. MSE analyses have low data requirements, although the value of outputs increases with increased data, a higher relative cost and good uncertainty handling. Changes to the decision-making framework through two-tier approaches or risk tables have the lowest data requirements and relative cost and may be the only feasible means of incorporating climate change impacts for data-limited fisheries.

## 4 | General Discussion and Conclusions

There is currently no internationally agreed approach or best practice method for accounting for climate change impacts within harvest strategies, and such an agreement is unlikely to occur. While a range of approaches are being considered and/or tested, to date, there is limited implementation in actual fisheries. This is owing to the lack of (or substantial uncertainty related to) a scientific basis for accounting for climate effects and/or a management system that is unable (or unwilling) to make use of such information.

As systems change, there is a strong desire by all involved to understand the change first, usually by identifying mechanisms of impact, before responding. Consequently, there is a need for better processes to improve understanding of climate impacts on ecosystems and stock productivity and for ongoing fishery monitoring as well as process studies. The relative cost of each approach is important and will place some options out of the reach of nations with smaller budgets or capacity. However, a detailed knowledge of drivers and impacts is not a necessary reason to avoid modifying management practices.

**TABLE 2** | Qualitative evaluation of data requirements, relative cost and (epistemic) uncertainty associated with the different climate-related harvest strategy approaches.

| Approach | Data requirements | Setup cost | Ongoing cost | Uncertainty | Example |
|---|---|---|---|---|---|
| Assessing stock status | | | | | |
| Extended stock assessments | +++ | $$$ | $$ | ++ | Pacific cod (Hulson et al. 2022) |
| Ecosystem models | ++++ | $$$$ | $$ | ++ | Gulf of Alaska (Rovellini et al. 2024) |
| Revised reference points | | | | | |
| Dynamic $B_0$ | ++ | $$ | $$ | +++ | WCPFC assessments (WCPFC 2012) |
| Regime shifts | ++ | $$ | $$ | +++ | Walleye pollock (A'mar et al. 2009) |
| Management strategy evaluation | | | | | |
| New methods/control rules | + | $$$ | NA | ++ | Dynamic $B_0$ HCRs (Bessell-Browne et al. 2024) |
| Harvest strategy | ++ | $$$$ | $ | ++ | Redleg banana prawns (Blamey et al. 2022) |
| Decision-making framework | | | | | |
| Modified catch advice | + | $ | $ | ++++ | Two-tier approach in Canada (Duplisea et al. 2021) |
| Projections | +++ | $$$ | $$ | ++ | Southeast Australia (Fulton et al. 2024) |

The speed of environmental change observed over the past three decades or more, but particularly the last 10–15 years, has placed fisheries science and its capacity to provide advice reliably and confidently under increasing pressure. The issue is only growing more pressing given that the rate of climate change is accelerating. Nations are responding in different ways given their individual capacity and the forms of change they are experiencing. Some common themes and lessons are emerging, but this nascent field will continue to develop rapidly in coming years, benefitting from the sharing of methods, lessons and insights across the globe.

There is increasing awareness from stakeholders that implementation of harvest strategies that are robust to climate change is required. However, most fisheries worldwide will be operating in data- and cost-constrained environments, and so simple solutions may initially be required, followed by more complex approaches where possible.

Early work investigating means of incorporating climate change within fisheries management suggested the most effective approach may be designing resilient harvest strategies rather than incorporation of environmental variables within assessments (Walters and Parma 1996). While assessment methods have improved since then, and there are some successful examples of extended stock assessments, this approach (simple resilient harvest strategy solutions) still appears to be one of the best-performing approaches globally and has been widely adopted. An additional benefit of this approach is its utility regardless of data availability, although increased precaution is required in data-limited settings.

Despite the best efforts of scientists and managers, there is no clear path to determine future conditions, and surprises are to be expected. This uncertainty surrounding future environmental conditions and resulting ecological change needs to be considered within harvest strategies to ensure they continue to perform as intended. The necessary level of precaution to take is also unclear, and risk tolerance differs among jurisdictions (e.g., Free et al. 2023). Science can help evaluate levels of precaution, for example, using MSE to assess the effects of "buffers" on stock status and foregone catch (e.g., Mildenberger et al. 2022). These buffers could be applied in situations where productivity decreases require increased precaution and also where increased production necessitates less precaution. Ultimately, the tools and approaches presented here will differ depending on the degree of risk-aversion that the management system has adopted. This, in turn, should reflect societal preferences and can be expected to vary by fishery and by nation.

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### Data Availability Statement

The authors have nothing to report.

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