Received: 17 August 2022 | Revised: 22 November 2022 | Accepted: 23 November 2022

DOI: 10.1111/faf.12724

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Harvest control rules used in US federal fisheries management and implications for climate resilience

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Funding information
Environmental Defense Fund; Walton Family Foundation

Abstract

Climate change is altering the productivity of marine fisheries and challenging the effectiveness of historical fisheries management. Harvest control rules, which describe the process for determining catch limits in fisheries, represent one pathway for promoting climate resilience. In the USA, flexibility in how regional management councils specify harvest control rules has spawned diverse approaches for reducing catch limits to precautionarily buffer against scientific and management uncertainty, some of which may be more or less resilient to climate change. Here, we synthesize the control rules used to manage all 507 US federally managed fish stocks and stock complexes. We classified these rules into seven typologies: (1) catch-based; (2) constant catch; (3) constant escapement; (4) constant F; (5) stepped F; (6) ramped F and (7) both stepped and ramped F. We also recorded whether the control rules included a biomass limit ('cut-off') value or were environmentally linked as well as the type and size of the buffers used to protect against scientific and/or management uncertainty. Finally, we review the advantages and disadvantages of each typology for managing fisheries under climate change and provide seven recommendations for updating harvest control rules to improve the resilience of US federally managed fisheries to climate change.

KEYWORDS
acceptable biological catch, catch limit, catch quota, climate change, Magnuson–Stevens Act, overfishing limit

1 | INTRODUCTION

The general goal of fisheries management is to find and implement a socially, economically and politically acceptable trade-off among competing fisheries objectives. These objectives often involve maintaining large and stable yields while also conserving marine resources and ecosystems for future generations (Walters & Martell, 2005). Climate change complicates the ability of traditional fisheries management to navigate these trade-offs and achieve its objectives for society (Szuwalski & Hollowed, 2016). Climate change has already resulted in significant shifts in fisheries productivity (Free et al., 2019), distributions (Pinsky et al., 2013) and phenology (Poloczanska et al., 2016), and continued climate change is expected to intensify these shifts (Bryndum-Buchholz et al., 2019;

IPCC, 2019). Enhancing the resilience of fisheries to climate change will require adjustments throughout the entire fisheries management system (Bryndum-Buchholz et al., 2021; Karp et al., 2019).

Harvest control rules (HCRs), which constitute pre-defined procedures for setting catch limits based on the current or projected state of a fishery (Punt, 2010), represent one of several tools in the fisheries management toolbox that can be adapted to enhance climate resilience. There are three classes of harvest control rules. Model-based control rules set catch limits based on estimates of stock size from stock assessments (Kvamsdal et al., 2016). Empirical control rules are specified using indices of stock size derived from scientific surveys (i.e., catch per unit effort; e.g., de Oliveira et al., 1998). Finally, data-limited control rules derive catch limits using historical catch and expert knowledge (e.g., Newman et al., 2015). Model-based rules are generally preferred, because they utilize best-available estimates of absolute stock size to derive catch limits and can use model-based estimates of confidence to buffer against scientific uncertainty. Empirical rules are convenient, because they do not require stock assessments, which makes them less costly, more transparent and more reactive (Punt, 2010); however, they can be challenging to parameterize given the lack of information on absolute stock size. Data-limited rules are required for stocks without reliable indices of abundance, which are numerous, even in data-rich regions (Berkson & Thorson, 2015). Data-limited rules must generally be highly precautionary to avoid overfishing, which often results in considerable foregone yield (Wiedenmann et al., 2013).

Traditionally, harvest control rules have adopted one of three 'shapes' (Figure 1) with respect to stock size—constant catch, constant escapement or constant fishing mortality (F)—each with its own advantages and disadvantages (Deroba & Bence, 2008; Restrepo & Powers, 1999). Constant catch rules avoid the need for stock assessments and theoretically facilitate stable catches; however, establishing an appropriate level of constant catch is challenging as constant catches lead to high exploitation rates at low stock sizes. Constant escapement rules hold stock size as close to the target size as possible by setting catches equal to the difference between the current and target sizes. They are generally thought to maximize long-term yields, but result in highly variable catch limits, including years with zero harvests. As a result, these rules are generally only viable for fisheries that exploit a large number of independent stocks and are therefore buffered against the economic impacts of high catch variability (e.g., salmon fisheries on the west coast of the United States and Canada). Constant F rules set the catch equal to a fixed proportion of the current stock size; thus, they limit catch variability while also being responsive to fluctuations in stock size (i.e., lower catch limits at lower stock sizes).

Threshold F rules, a fourth approach to setting harvest control rules, reduce fishing mortality rates when stock sizes fall below a specified size threshold and are increasingly used to account for scientific uncertainty, prevent overfishing and expedite rebuilding (NPFMC, 2020b; PFMC, 2020b). These rules may also provide inherent resilience to uncertainty and variability resulting from climate

change (Kritzer et al., 2019). Curved threshold F rules are often identified as optimal in studies seeking to dynamically maximize catch or profits from a fishery (e.g., Hawkshaw & Walters, 2015) but are generally simplified into straight lines for tactical fisheries management (e.g., Walters, 1975). In their simplest forms, threshold F rules are specified using two biomass (or abundance) reference points: (1) a *threshold value* below which fishing mortality is reduced (often, but not necessarily, equal to the target value); and (2) a *limit value* below which fishing mortality is prohibited (if equal to zero, then fishing is permitted across all stocks sizes but is reduced as stock size declines) (Figure 2b). A number of modelling studies suggest that threshold F rules may be more effective than constant F rules at maintaining high catches while preventing overfishing under both increasing climate variability and directional climate change (Kritzer et al., 2019; Mildenberger et al., 2022; Wiedenmann et al., 2017). For example, Wiedenmann et al. (2017) evaluated the performance of various harvest control rules in a management strategy evaluation model and found that threshold F rules reduced rebuilding times and generated larger long-term yields than constant F rules. Furthermore, whereas the ability for constant F rules to prevent overfishing deteriorated with increasing assessment uncertainty, threshold F rules were equally effective at preventing overfishing under both low and high-uncertainty scenarios (Wiedenmann et al., 2017).

There are a number of opportunities to tune harvest control rules to better achieve fisheries objectives under climate change. On the more sophisticated, but arguably more controversial end of the spectrum, control rules could be directly parameterized to

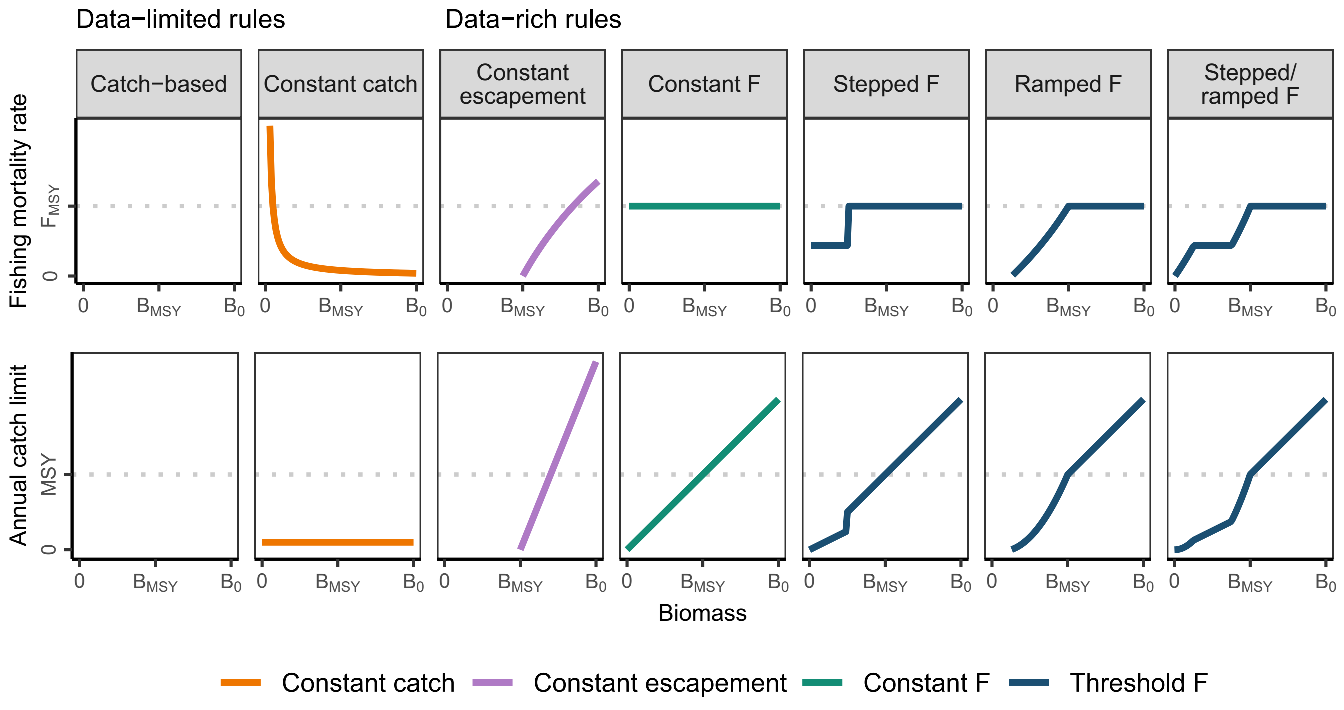

FIGURE 1 Illustrations of the seven harvest control rule (HCR) typologies used in US federal fisheries management. Data-limited control rules are used in the absence of a reliable stock assessment and generally use catch histories to inform catch limits. The shape of catch-based control rules is unknown given the lack of available biomass estimates for stocks managed using these rules. Although the data-rich control rules are generally model-based (i.e., use stock assessment output to define the *x*-axis of the rule), they could theoretically be based on an index of abundance from a scientific survey (i.e., an empirical control rule). See Table S2 for definitions of the biomass and fishing mortality reference points.

consider the impacts of the environment on productivity (Hofmann & Powell, 1998). There are two divergent perspectives on how to approach this (Kaplan et al., 2020). The 'investment' perspective views unharvested fish as an investment in future yields and recommends increasing harvest intensity as productivity declines (Costello et al., 2001). Conversely, the 'stabilization' perspective recommends decreasing harvest intensity as productivity declines to reduce variability in yields by preventing the boom-and-bust dynamics that get reinforced by the 'investment' approach (Parma, 1990). In practice, environmentally linked control rules have been rare due to their large data requirements, reliance on stable and predictable environmental relationships, and marginal ability to improve objectives over simpler rules (Punt et al., 2014). On the less sophisticated but arguably more reliable end of the spectrum, control rules can be modified to buffer against the additional scientific uncertainty introduced by climate variability. This can be achieved by optimizing (1) the fishing mortality rate buffers used to protect against uncertainty across all stock sizes (Da-Rocha et al., 2016) and/or (2) the biomass threshold and limit values used to safeguard against low biomass under high uncertainty (Figure 2). In general, the tuned combination of these approaches performs best (Mildenberger et al., 2022).

In the United States, harvest control rules for federally managed fisheries may take any of the above-described forms, provided that they comply with the precautionary principle, which accounts for scientific uncertainty in setting catch limits that prevent overfishing (Restrepo et al., 1998). The 2006 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act established the legal framework for implementing the precautionary principle by requiring: (1) that annual catch limits be set for the majority of federally managed stocks (exemptions for stocks managed with international agreements or with life cycles less than 1 year); (2) that these catch limits restrict the probability of overfishing to less than or equal to 50%; and (3) that the probability of overfishing be reduced with increasing scientific uncertainty (Federal Register, 2009) (Figure 3). The general procedures for setting catch limits differ based on data quality and the availability of a reliable stock assessment. For data-rich stocks, an *Overfishing Limit* (*OFL*), the maximum catch that does not result in overfishing, is derived from a stock assessment. Next, an *Acceptable Biological Catch* (*ABC*), which must be less than or equal to the OFL given scientific uncertainty, is derived based on the magnitude of uncertainty in the OFL and the management organization's risk tolerance policy. Finally, an *Annual Catch Limit* (*ACL*), which must be less than or equal to the ABC, is derived based on other socioeconomic or ecological considerations. For data-limited stocks, these management values are derived through catch-based procedures and expert-based judgment of scientific uncertainty.

The Magnuson–Stevens Act awards the eight US Regional Fishery Management Councils charged with managing fisheries in federal waters considerable flexibility in developing harvest control rules that meet these requirements. This flexibility has resulted in

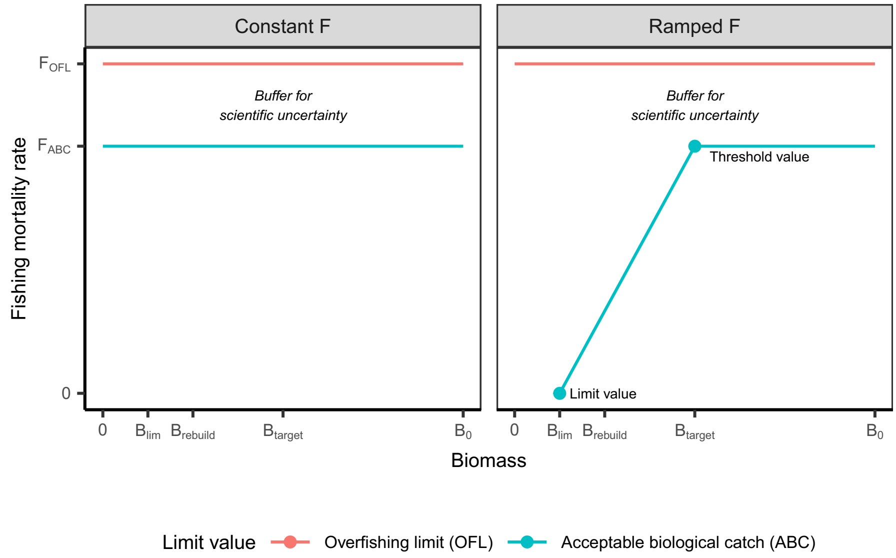

FIGURE 2 Illustration of the reference points and parameters commonly used to define harvest control rules and buffer them against scientific uncertainty. In both constant F and ramped F control rules, precautionary buffers are used to reduce the OFL to the ABC to protect against scientific uncertainty. In their simplest forms, ramped F rules are specified using two biomass (or abundance) reference points: (1) a *threshold value* below which fishing mortality is reduced (often, but not necessarily, equal to the target value); and (2) a *limit value* below which fishing mortality is prohibited (if equal to zero, then fishing is permitted across all stocks sizes but is reduced as stock size declines). See Table S2 for definitions of all other biomass and fishing mortality reference points.

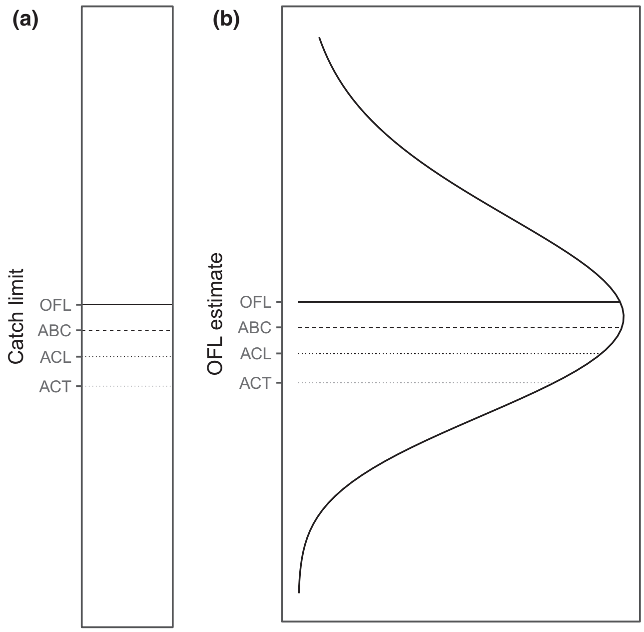

FIGURE 3 Relationship between catch limit reference points under US federal law. In general, the following equation must be followed: ACT ≤ ACL ≤ ABC ≤ OFL. There are two approaches for reducing the OFL to the ABC in consideration of scientific uncertainty: (a) the reduction is performed using a simple percentage buffer, for example the ABC is 75% of the OFL; or (b) the ABC is calculated as a percentile of the OFL posterior distribution, for example the ABC is the 40th percentile of the OFL distribution, reflecting a probability of overfishing (P*) of 40%.

significant regional heterogeneity in harvest control rule specifications, which could lead to regional differences in the resilience or vulnerability of fisheries to climate change. First, there is considerable variability in the type, quality and frequency of stock assessment methods used to estimate overfishing limits (Berkson & Thorson, 2015; Marshall et al., 2019; Neubauer et al., 2018). Second, the councils employ different risk tolerance policies for reducing OFLs to ABCs in consideration of scientific uncertainty (FLSM, 2012). Finally, the councils employ different procedures for reducing both ABCs and ACLs in consideration of socioeconomic or ecological objectives besides maximizing yields. In many cases, these procedures even vary among the many Fishery Management Plans implemented by one council. A synthetic understanding of the heterogeneous landscape of harvest control rules used in US federally managed fisheries is needed to facilitate cross-council learning and to identify opportunities for honing the current suite of control rules to promote climate resilience.

Here, we synthesize the harvest control rules used to manage all US federally managed fish stocks and discuss the opportunities to improve the resilience of these rules to climate change. We extracted the control rules specified in all 45 US Fishery Management Plans (Table S1) and visualized them using a standardized plotting framework and vocabulary. We then categorized them into one of the seven following control rule typologies ('shapes'): (1) catch-based; (2) constant catch; (3) constant escapement; (4) constant F; (5) stepped F; (6) ramped F; and (7) stepped/ramped F and recorded whether they included a biomass limit value or were environmentally linked. When possible, we also recorded the type and size of the buffers used to protect against scientific and/or management uncertainty. Finally, we reviewed the advantages and disadvantages of each typology for managing fisheries under climate change and provide recommendations for updating harvest control rules to improve the resilience of US federally managed fisheries to climate change.

2 | METHODS

We reviewed the 45 Fisheries Management Plans (FMPs) and Fishery Ecosystem Plans (FEPs), collectively referred to as management plans hereafter, used by the eight US Regional Fishery Management Councils (FMCs) and extracted the harvest control rules specified in each plan (Table S1). The approaches for specifying harvest control rules varied across and within management plans. In some cases, the same control rule was used for all stocks listed in a management plan, while in other cases, different control rules were used for stocks of different species or data-quality 'tiers'. The harvest control rules were also specified using different biomass and harvest metrics, the *x*- and *y*-axes of control rules, respectively. For example, while most management plans specified the harvest axis (*y*-axis) in terms of fishing mortality rates, some used catch (e.g., Pacific Groundfish plan) or the probability of overfishing (e.g., Mid-Atlantic plans). Similarly, some management plans specified the biomass axis (*x*-axis) of their control rules in terms of biomass while others used biomass relative to the target biomass (e.g., B/B_{MSY}). Furthermore, harvest control rules were specified using different reference point proxies (e.g., B_{MSY}, $B_{40\%}$ and $B_{20\%}$) and different nomenclature for limit and threshold values. For example, the Pacific Coast Groundfish plan refers to the biomass limit as a 'minimum abundance threshold', while the Coastal Pelagic Species plan refers to this value as a 'cut-off'. Note that, for many data-rich stocks, catch limits are set for multiple years into the future by applying the harvest control rule to projected population sizes.

To ease the comparison of harvest control rules across management plans, we plotted the control rules using harmonized axes and reference point nomenclatures whenever possible. The harmonized plots illustrate the control rules expressed in terms of both fishing mortality rate and catch. The *x*-axis of each plot reflects the *x*-axis used to specify the control rule in the management plan (i.e., B/B_{MSY} or biomass). When possible, we labelled the reference point values shown in Table S2 on each plot. When additional values were required to specify the control rule, those values were also plotted. In general, we created these plots assuming logistic population dynamics (Schaefer, 1954) for a theoretical population with a carrying capacity (*k*) of 1.0 and an intrinsic growth rate (*r*) of 0.2. For salmon, we used a higher intrinsic growth rate ($r = 0.8$) to allow our plots to better match the scale of the plots depicted in the original management plans. For stocks in which the magnitude of the ABC buffer is selected based on a target probability of overfishing (P*), we derived the target ABC assuming that the OFL estimate is log-normally distributed with a coefficient of variation (CV) of 0.5 ($\sigma = \log(CV^2 + 1)$). See Figure 3 for an illustration of the difference between specifying a buffer using a simple percent reduction (e.g., ABC = 75% of the OFL point estimate) or using the P* approach (e.g., ABC = 40th percentile of the OFL posterior distribution and thus, a 40% chance of resulting in overfishing).

After plotting the harvest control rules on harmonized axes, we categorized them into the seven typologies illustrated in Figure 1. For data-limited stocks without stock assessments, stock size is unknown. Thus, these stocks are managed using harvest control rules that employ either: (1) *catch-based* procedures that update catch recommendations based on catch time series and additional information, such as expert knowledge or trends in an index of abundance; or (2) simpler *constant catch* rules that use the same catch limit every year. For data-rich stocks with stock assessments, harvest control rules can consider estimates of stock size. These stocks are managed using control rules that fall into three categories: (3) *constant escapement* rules, which maintain the same level of escapement across stock sizes; (4) *constant F* rules, which apply the same fishing mortality rate (F) across stock sizes; and *threshold F* rules, which reduce fishing mortality rates below a threshold stock size using (5) *stepped*; (6) *ramped*; or (7) *stepped/ramped* rules. *Ramped* reductions in F may be either linear or curved. In some cases, the data-rich control rules employ *biomass limits* that prevent harvest below a certain stock size, and in rare cases, data-rich control rules may vary harvest rates based on environmental conditions (i.e., they are *environmentally linked*). Thus, we also recorded whether ramped control rules were linear or curved and whether data-rich control rules included biomass limits or were environmentally linked.

Finally, we synthesized this information into a database describing the harvest control rules used for every federally managed stock. The database includes the following attributes for each stock: council name, management plan name, species name, stock name, control rule typology, control rule attributes (i.e., ramp type, biomass limit flag and environmental-link flag) and the sizes of the uncertainty buffers used to manage the stock. We determined the control rule typology and attributes by assigning the appropriate control rule to each stock managed under a fishery management plan. In many cases, this was straightforward: the stock was assigned the harvest control rule prescribed specifically for that stock or species in the management plan. In other cases, this required knowledge of the current data-quality tier for the stock. To resolve these cases, we contacted council staff members for information on the current data-quality tiers prescribed to their stocks and assigned stocks the control rule associated with their tier. We also asked council staff members for information on the size of the buffers currently used to protect against scientific and management uncertainty. When this could not be provided, we extracted this information from stock assessment documents or other documents on the council website. Because data-quality determinations, control rule typologies, stock statuses and buffer sizes can vary from year to year, our results represent a snapshot of recent US federal fisheries management. Finally, we asked council staff members to review the database and associated harvest control rule summaries (Appendix A) for accuracy. Ultimately, the database and summaries were reviewed and confirmed by the New England, Mid-Atlantic, South Atlantic and North Pacific councils.

All data analyses and visualization were performed in R (R Core Team, 2021) and all data and code are available on GitHub here: https://github.com/cfree14/us_fmps.

3 | RESULTS

Federally managed fish stocks are managed using a diverse array of harvest control rules whose composition varies by regional management council (Figure 4). Approximately two thirds of all stocks are managed using data-rich control rules. Of these, only Mid-Atlantic shortfin squid (*Illex illecebrosus*, Ommastrephidae) and a few North Pacific salmon (*Oncorhynchus* spp., Salmonidae) stocks are managed using constant escapement rules; the remainder are split between constant F and threshold F rules (Figure 4). Threshold F rules are used for nearly all stocks in the Mid-Atlantic with reliable stock assessments. Threshold F rules are used for more than half of the stocks in the Pacific and North Pacific with reliable stock assessments (Figure 4). The remainder are managed using primarily constant F rules, though a few North Pacific salmon stocks are managed using constant escapement rules (Figure 4). Only a small percentage of stocks in New England with reliable assessments are managed using threshold F rules. Threshold F rules are not used by the South Atlantic, Gulf of Mexico, Caribbean or Western Pacific Fishery Management Councils or by NOAA in its management of Highly Migratory Species (Figure 4). In the Caribbean, the use of threshold F rules is precluded by the absence of stock assessments. However, in the other councils, the availability of operational stock assessments and the use of constant F rules implies that threshold F rules could be considered as an alternative to constant F rules in these regions.

The magnitude of the uncertainty buffers used in harvest control rules varies widely by council, management plan, species and stock (Figure 5). Among the stocks whose ABC buffers were set using a specified probability of overfishing, the South Atlantic council was generally more precautionary (P* median = 30%) than the Pacific (P* median = 45%) or Mid-Atlantic councils (P* median = 45.5%) (Figure 5a). Among the stocks whose ABC buffers were set using a simple percent reduction, the magnitude of these reductions was similar and generally occurred in the 75% to 80% range (i.e., ABC = 75%–80% of the OFL) (Figure 5b). Exceptionally large reductions were used by the Pacific council for: Northern anchovy (*Engraulis mordax*, Engraulidae), Pacific mackerel (*Scomber japonicus*, Scombridae) and market squid (*Doryteuthis opalescens*, Loliginidae) (ABC = 25% of OFL). Across councils, ACLs were generally equivalent or close to (>98% of) the ABC (Figure 5c). Exceptionally large reductions were used by the Pacific council for southern copper rockfish (*Sebastes caurinus*, Sebastidae) (ACL = 49% of ABC), yelloweye rockfish (*Sebastes ruberrimus*, Sebastidae) (64%), Pacific cod (*Gadus macrocephalus*, Gadidae) (83%) and dover sole (*Solea solea*, Soleidae) (84%). ACTs were rarely specified across stocks and were generally large (>75%) proportions of the ACL (Figure 5d).

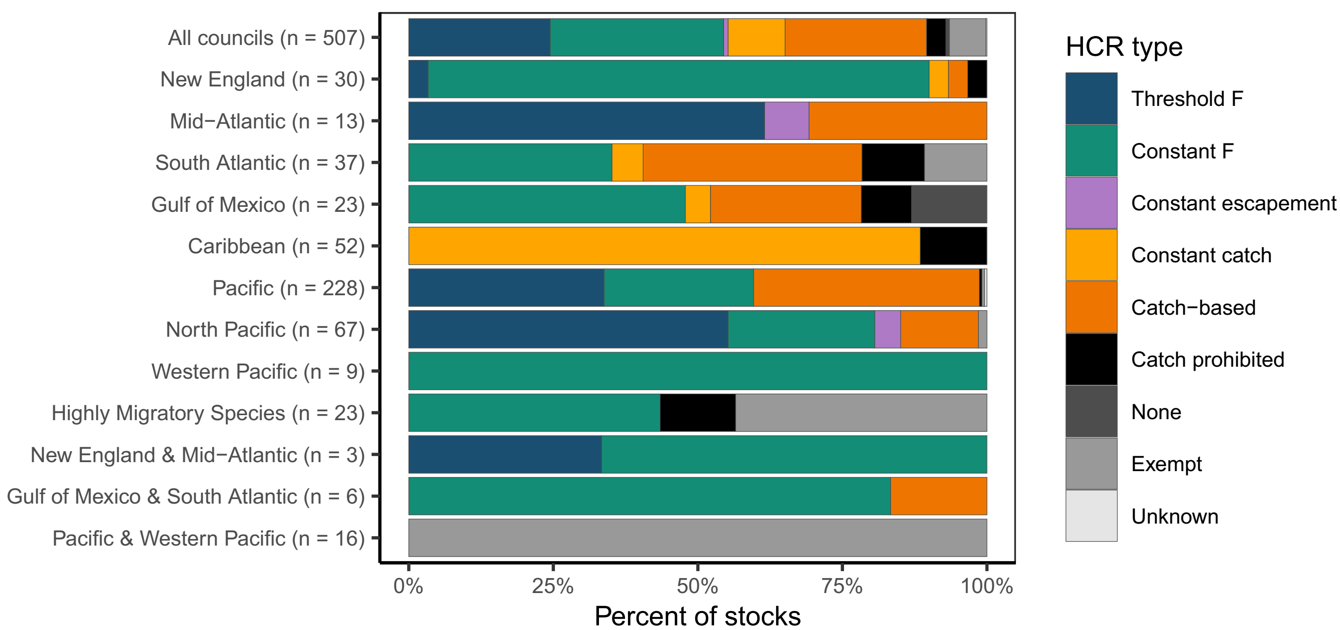

FIGURE 4 Percent of US federally managed fish stocks and stock complexes managed using each harvest control rule (HCR) typology by US regional fishery management council. The top row represents all stocks and stock complexes. Some stocks are jointly managed by two fishery management councils (bottom three rows of the figure). Control rule typology often depends on data-quality determinations and may vary from year to year; thus, the control rule typologies presented here represent a snapshot of recent US federal fisheries management.

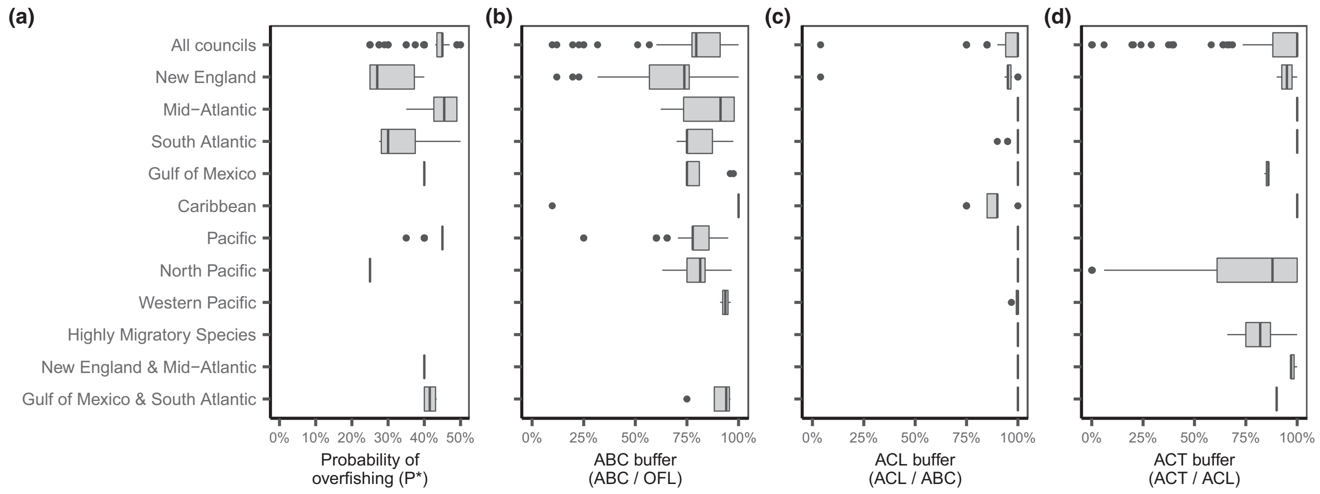

FIGURE 5 Distribution of precautionary buffers used to buffer against either scientific or management uncertainty by US regional fishery management council. To account for scientific uncertainty, the OFL is reduced to an ABC using either (a) a probability of overfishing (P*) or (b) a percent reduction. To account for management uncertainty, councils sometimes use percent reductions to (c) reduce the ABC to an ACL and (d) to reduce the ACL to an ACT. In the boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers. Buffer values often depend on data-quality determinations and may vary from year to year; thus, the buffer values presented here represent a snapshot of recent US federal fisheries management.

4 | DISCUSSION

The harvest control rules used in US federal fisheries management are highly diverse and vary widely both across and within management councils and management plans. They differ in their general shape (e.g., threshold F, constant F and constant catch), specification (e.g., *y*-axis specified in terms of catch, fishing mortality or probability of overfishing), choice of buffers used to account for scientific and/or management uncertainty, and consideration of other ecological and/or socioeconomic objectives. For example, the ramped/stepped F control rule used to manage Klamath River and Sacramento River fall Chinook salmon (*Oncorhynchus tshawytscha*, Salmonidae) (PFMC, 2021b) is unique among data-rich stocks more commonly managed using constant, ramped or stepped F rules. Furthermore, the Mid-Atlantic council is the only council to specify a threshold-based rule in terms of the probability of overfishing (P*) (MAFMC, 2020). The New England council is the only council to use empirical control rules that vary allowable fishing mortality based on a survey-based index of abundance for selected stocks (Georges Bank Atlantic cod, *Gadus morhua*, Gadidae; North and South red hake, *Urophycis chuss*, Phycidae; and the skate complex) (NEFMC, 2018). Similarly, the Pacific sardine (*Sardinops sagax*, Clupeidae) stock is the only stock managed using an environmentally linked control rule that varies allowable fishing effort based on sea surface temperature (PFMC, 2021a). Finally, the Bering Sea and Aleutian Island groundfish management plan is the only plan to place an ecosystem-wide catch limit (2 million mt) on its actively managed stocks (NPFMC, 2020a).

This diversity reflects the ability for councils to tailor fisheries management based on regional fisheries contexts, objectives and risk tolerance, but may also contribute to regional differences in their vulnerability to climate change. There is widespread recognition of the importance of fisheries management that is robust and responsive to climate impacts within the councils (e.g., MAFMC, 2022; PFMC, 2020a) and optimizing harvest control rules for climate change is one pathway for increasing climate resilience. In the remainder of the paper, we detail seven recommendations for councils to consider as they plan for the impacts of climate change on their fisheries. We encourage councils to consider: (1) replacing constant F rules with threshold F rules, which are often more resilient to climate change, for data-rich stocks with stock assessments; (2) fine-tuning the parameters that define control rules, whether they are constant or threshold-based, in consideration of climate change impacts; (3) developing data-moderate empirical control rules for stocks currently managed using data-limited catch-based rules; (4) strategically selecting the catch-based methods and precautionary measures used to manage data-limited fisheries for which only catch-based rules are possible; (5) prioritizing the previous four points over the development of environmentally linked control rules; (6) establishing ecosystem-based catch limits that consider ecosystem dynamics; and (7) using management strategy evaluations that consider climate change impacts to guide these determinations.

4.1 | Consider replacing constant F rules with threshold F rules

The wider adoption of threshold F harvest control rules has potential to improve the resilience of federally managed fisheries to climate change. Although inherent trade-offs among harvest control rules mean that no rule is a panacea (Deroba & Bence, 2008), threshold F rules exhibit consistent advantages that have led to their selection over constant F rules in many regions in the USA and abroad (Kvamsdal et al., 2016). While constant F rules commonly offer lower catch variability, higher short-term catch, and sometimes, higher long-term catch than threshold F rules, threshold F rules commonly reduce the risk of overfishing, avoid overfished declarations that trigger austere rebuilding plans and hasten rebuilding timelines, which can lead to higher long-term catches than constant F rules (Mildenberger et al., 2022; Wiedenmann et al., 2017). Climate change may make these advantages even more attractive to managers and stakeholders weighing trade-offs among alternative rules. First, the performance of threshold F rules is often more robust to uncertainty and variability than constant F rules (Wiedenmann et al., 2017) and climate change is a common and growing contributor to this uncertainty (Wiedenmann & Legault, 2022). This robustness stems from the precautionary nature of threshold F rules at low biomass levels, which allows these rules to rebuild stocks more quickly regardless of the reason for biomass decline (i.e., whether due to overfishing, uncertain stock assessments, or environmental shocks). Second, threshold F rules commonly perform better than constant F rules under directional climate change that lowers future productivity (Kritzer et al., 2019; Wiedenmann, 2019). A notable exception is for short-lived species whose spasmodic fluctuations in population size due to large environmentally driven recruitment deviations challenge the deterministic concept of MSY (Caddy & Gulland, 1983; Sæther et al., 1996). For these species, constant F rules with appropriate uncertainty buffers are often more effective than threshold F rules at reducing risk while maximizing yields (Mildenberger et al., 2022).

In the United States, strong statutory mandates for rebuilding overfished stocks often makes constant F rules behave as threshold F rules; however, these de facto threshold F rules do not achieve the same benefits as explicit threshold F rules. The 1996 Sustainable Fisheries Act amendments to the Magnuson-Stevens Act require that overfished stocks are rebuilt in a period of time 'as short as possible' and not to exceed 10 years, with a few exceptions based on life history, environmental conditions and international agreements (NMFS, 1996). This means that when stocks are declared legally overfished ($B/B_{MSY} < 0.5$), the original harvest control rule is scrapped for a rebuilding plan that re-derives annual catch limits that allow the stock to rebuild on schedule. Although this results in timely rebuilding when effectively implemented (Methot et al., 2014), it results in a precipitous, rather than gradual, change in catch. By comparison, threshold F rules rebuild as or more quickly than status quo rebuilding plans while also leading to more gradual changes in catch and to a smaller chance of needing a rebuilding plan (Benson et al., 2016). Furthermore, threshold F rules avoid the need for complex rebuilding plan forecasts and thus achieve these benefits with fewer financial resources (Benson et al., 2016). For these reasons, a National Academy of Sciences committee evaluating US rebuilding plans advocated for the wider use of threshold F rules given their robustness to assessment uncertainties, environmental variability and effects of other ecological interactions (NRC, 2014).

There are two pathways for increasing the adoption of threshold F harvest control rules within the US federal fisheries management system. The first pathway is to replace constant F rules with threshold F rules in the management plans of data-rich regions where the availability of stock assessments makes both rules possible. This is relevant in the New England, South Atlantic, Gulf of Mexico, Pacific and North Pacific regions where there are already data-rich stock assessments to support constant F rules (Figure 4). In these regions, the availability of reliable stock assessments allows for the immediate adoption of model-based threshold F control rules. The second pathway is to amend management plans in data-limited regions to prepare for the implementation of threshold rules should stock assessments become available. This pathway is relevant in the Caribbean region where the lack of historical assessments has necessitated the use of catch-based control rules and deprioritized considerations of more data-rich control rules (Figure 4). In recognition of this, the Caribbean council is currently considering revising its management plan to supplement catch-based rules with constant F rules should stock assessments become available (e.g., CFMC, 2019). In collaboration with stakeholders, the council could expand these discussions to consider threshold F rules.

4.2 | Fine-tune precautionary buffers and threshold and limit values

There are also opportunities to improve the performance of data-rich harvest control rules, whether constant or threshold-based, and their resilience to climate change by fine-tuning their parameterization. For constant rules, adjustments can be made to the precautionary buffers used to protect against scientific and/or management uncertainty. For threshold-based rules, adjustments can be made to these buffers and to the threshold and limit values that define additional precaution at low stock sizes. Although management strategy evaluations tailored to specific fisheries systems are necessary to guide tactical decisions over control rule specifications (see Section 4.7 below), many of the trade-offs between alternative control rule specifications are predictable (Figure 6). First, larger uncertainty buffers reduce overfishing risk and catch variability but at the cost of foregone yield (Figure 6a). These trade-offs are generally more pronounced for long-lived species than for short-lived species (Mildenberger et al., 2022). Furthermore, the selection of uncertainty buffers may consider current or future process variability (e.g., as a result of climate change), as higher process uncertainty can result in elevated overfishing risk and reduced long-term yields (Mildenberger et al., 2022). Second, larger threshold values reduce risk of overfishing, rebuilding times and catch variability but at the cost of reduced yields (Figure 6b). However, this risk-yield trade-off is not linearly proportional, and careful selection of threshold and uncertainty values can produce relatively minor losses in long-term yields while significantly reducing overfishing risk (Mildenberger et al., 2022). Finally, larger biomass limits reduce overfishing risk and rebuilding times but increase catch variability and can reduce

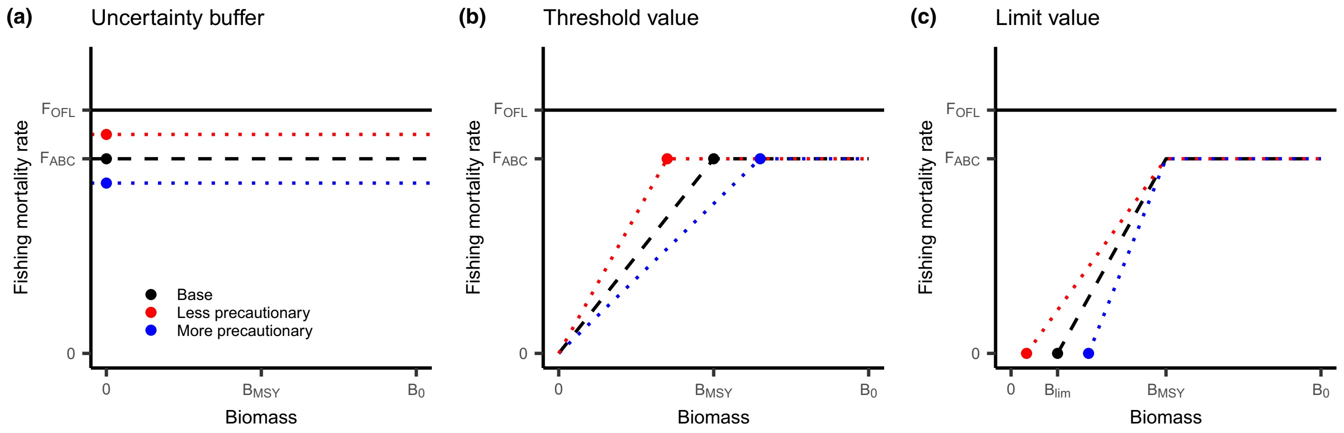

FIGURE 6 Illustrations of alternative harvest control rule specifications that vary the size of the (a) uncertainty buffer, (b) threshold value and (c) limit value. In (a), larger, more precautionary uncertainty buffers reduce overfishing risk and catch variability but at the cost of long-term yields (a). In (b), larger, more precautionary threshold values reduce risk of overfishing, rebuilding times and catch variability but also reduce long-term yields. In (c), larger, more precautionary biomass limits reduce overfishing risk and rebuilding times but increase catch variability and can reduce long-term yields.

long-term yields (Figure 6c). Catch variability increases with decreasing differences between the threshold and limit values (Mildenberger et al., 2022). (Mildenberger et al., 2022) evaluated more than 80 harvest control rule specifications and found that threshold rules that combined multiple of these precautionary elements generally produced the most favourable risk-yield trade-offs and were also the least sensitive to uncertainty in B/B_{MSY} estimates. While recognizing the importance of stock-specific management strategy evaluation to set harvest control rules, Mildenberger et al. (2022) conclude that harvest control rules should include uncertainty buffers and threshold and limit values.

4.3 | Empirical rules can replace catch-based rules or back up data-rich rules

In some cases, the development of empirical harvest control rules that adjust catch limits based on indices of abundance could be used to either replace catch-based rules or back up model-based rules. Catch-based harvest control rules without an index of abundance are generally a last resort in fisheries management as they must be highly precautionary to avoid overfishing and therefore result in considerable foregone catches and profits (Carruthers et al., 2014; Wiedenmann et al., 2013). Thus, replacing these rules with empirical harvest control rules presents an opportunity to increase catches and profits while avoiding overfishing, with or without climate change. However, the number of stocks for which this is relevant may be limited. Oftentimes, the availability of a reliable index of abundance, which is required for an empirical-based harvest control rules, implies an ability to conduct a stock assessment, which would enable the use of a more sophisticated model-based harvest control rule. However, in cases where funding or staff capacity limit the ability to conduct stock assessments, empirical harvest control rules may be worth pursuing. Furthermore, developing empirical harvest control rules as a backup for model-based control rules could provide a critical fail-safe in the event that a stock assessment model fails to pass peer review (Rademeyer et al., 2007; Wiedenmann et al., 2019), which is common in the USA and abroad (Punt et al., 2020). Additionally, in the interim between stock assessments, empirical-based harvest control rules could be used to adjust catch limits based on an index of abundance (Geromont & Butterworth, 2015). Effective empirical-based harvest control rules could ease the need for frequent assessments and allow for increased investment in less frequent but higher quality stock assessments.

4.4 | Consider climate change and additional precaution in catch-based rules

A large number of federally managed fisheries in the USA are managed using data-limited catch-based rules (Figure 4) (Berkson & Thorson, 2015; Newman et al., 2015). Although these rules generally perform poorly (Carruthers et al., 2014; Wiedenmann et al., 2013), they are required under the Magnuson-Stevens Act, which requires that all stocks, regardless of data availability, be managed using annual catch limits (Magnuson-Stevens Act Provisions; Annual Catch Limits; National Standard Guidelines, 2009). In general, these rules must be precautionary to avoid overfishing and uncertain impacts of climate change may necessitate additional precautionary buffers. There are several pathways for incorporating potential climate change impacts into the uncertainty buffers used in the rules. In the South Atlantic, Gulf of Mexico and Caribbean, where the 'Only Reliable Catch Stocks' (ORCS) working group approach (Berkson et al., 2011; Free et al., 2017) for setting catch limits is used, a question on likely climate change impacts may be added to the ORCS questionnaire used to solicit expert opinion on likely stock status and the need for precaution in setting catch limits. In other councils, where the magnitude of the precautionary approach used to manage data-limited stocks is negotiated via less-formalized approaches, guidance on how to incorporate likely climate change impacts into the decision-making process may be necessary. For example, climate vulnerability assessments (e.g., Hare et al., 2016) could be used to identify the potential need for and magnitude of additional precautionary buffers. However, it is important to remember the trade-offs inherent to additional precaution. Catch-based rules are already prone to foregoing catches and profits and additional precaution could exacerbate this performance. Thus, establishing reliable indices of abundance for these stocks or applying length-based stock assessment approaches (Chong et al., 2020) could be important next steps in improving the management of these stocks, with or without climate change.

4.5 | Deprioritize environmentally linked control rules

The direct incorporation of an environmental driver into harvest control rules is an alluring approach to adapting control rules to climate change but attempts at doing so have been rare due to large data requirements, reliance on stable and predictable environmental relationships, and marginal ability to improve objectives over simpler control rules (Punt et al., 2014). Indeed, most studies find that parameterizing control rules to include environmental covariates fails to meet management objectives under short to medium-term time scales (see (Punt et al., 2014) for a review). In fact, attempting to account for changes in productivity when none exist can lead to greater overfishing risk than stationary management approaches (Szuwalski & Punt, 2013). Pacific sardine, the only US fish stock managed using an environmentally linked harvest control rule, may be subject to this challenge. Its harvest control rule adjusts allowable fishing effort based on environmental conditions using a relationship derived from historical recruitment data and sea surface temperature (PFMC, 1998, p. 8). In general, the rule prescribes higher fishing effort in warmer years with higher recruitment and lower fishing effort in cooler years with lower recruitment. However, this sophisticated rule has been met with limited success. The rule had to be rederived in 2014 (PFMC, 2014) when it was shown that the relationship between recruitment and temperature was no longer significant when reevaluated with new data (McClatchie et al., 2010). Then, the stock collapsed during a marine heatwave in 2015, a surprise given the longstanding belief that sardine recruitment is elevated during warm years (Thompson et al., 2022), leading to the closure of the fishery. The fishery has yet to re-open and was declared a federal fisheries disaster in 2018 (Bellquist et al., 2021). Although promising applications of environmentally linked control rules could exist, they should be deprioritized relative to the recommendations discussed above.

4.6 | Explore ecosystem-based catch limits

The movement of harvest control rule specification from a single-species framework towards a more ecosystem-based approach could also yield fisheries and conservation benefits in the face of climate change. For example, an annual 2 million metric ton cap on the harvest of Eastern Bering Sea groundfish, which requires managers to reduce the harvest of selected groundfish stocks when the sum of the catch limits recommended by their individual control rules exceeds this ecosystem-based catch limit (NPFMC, 2020a), has been successful at sustaining high fisheries yields and preventing overfishing over the last three decades, despite high environmental variability (Stram & Evans, 2009). Furthermore, Holsman et al. (2020) suggest that the use of this ecosystem-based catch limit could reduce near-term losses in biomass and catch due to climate change relative to harvest control rules without a cap. While the cap is unlikely to fully mitigate the negative impacts of climate change (and could limit ability to capitalize on possible positive impacts of climate change), it is likely to forestall losses and provide managers and fishers with more time to prepare (Holsman et al., 2020). However, the cap was not established with climate change in mind, and it is possible that better outcomes could be achieved, in this fishery and in others, through strategies that adaptively optimize a cap based on ecosystem productivity (Fulton et al., 2019). In the near-term, strategies that utilize information from strategic ecosystem models to update the recommendations of tactical single-species models may represent the fastest way to integrate ecosystem advice and leverage the best parts of both approaches (Howell et al., 2021).

4.7 | Use management strategy evaluation to compare rules

The 'best' harvest control rule is context-dependent and will vary based on management objectives, life history, scientific uncertainty and environmental conditions (Deroba & Bence, 2008; Punt, 2010). The most robust method of selecting harvest control rules among alternative options is through management strategy evaluation (MSE). Management strategy evaluation models use a simulation of the entire fisheries management system to measure and compare trade-offs among alternative management strategies using pre-defined performance metrics under variable conditions and types of uncertainty (Punt, Butterworth, et al., 2016). The first step to conducting an MSE is to work with stakeholders (e.g., managers and fishers) to identify tractable harvest control rules and to define performance metrics for evaluating these rules (Feeney et al., 2019). This paper presents a useful inventory of the types of rules (Figure 1) and the range of their parameter values (Figure 5) that stakeholders can consider when designing strategies to compare. Performance metrics commonly consider the magnitude and variability of catch or profits, number of years spent overfished, number of years spent rebuilding, probability of overfishing and magnitude of overfishing, among others (see Wiedenmann et al. [2017] for a useful example). The next step is to develop operating models tailored to the life history of the species and quality of the data, skill of the assessment model and anticipated impacts of climate change in the region (Deroba et al., 2019; Kaplan et al., 2021). Critically, MSEs should consider multiple operating models with multiple assumptions about the impacts of climate change on the fishery to identify strategies that are robust to the large uncertainties associated with future climate impacts (Punt, MacCall, et al., 2016). For example, Jacobsen et al. (2022) evaluated the robustness of harvest control rules to multiple assumptions about climate-induced changes in Pacific hake (*Merluccius productus*, Merlucciidae) movements and Haltuch et al. (2019) considered robustness of control rules to changes in the productivity of sablefish (*Anoplopoma fimbria*, Anoplopomatidae) under 11 different global climate models.

Many US fishery management councils have already commissioned MSEs to guide their selection of preferred harvest control rules. In 2011, the Mid-Atlantic council funded an MSE (Wiedenmann et al., 2017; Wilberg et al., 2011) to evaluate the performance of eight different control rules: (a) a constant F of F_{MSY}, (b) a constant F of 75% of F_{MSY}, (c) three constant F rules based on different P* values, and (d) three threshold F rules specified as a ramped P* rules. They found that threshold F rules reduced rebuilding time, generated higher long-term catches and were more robust to variability in productivity, and one of these rules was ultimately selected for inclusion in the Mid-Atlantic fishery management plans (MAFMC, 2011). In 2019, the Mid-Atlantic council commissioned an expansion of the MSE (Wiedenmann, 2019) to further fine-tune the performance of this rule under multiple potential climate futures (i.e., average, good and poor future productivity). Although the threshold F rules produced lower and less stable catch than the constant F rules, they reduced the risk of overfishing and the risk of becoming overfished (especially under average or poor future productivity) and the council again selected one of the threshold F rules for implementation in its fishery management plans (MAFMC, 2020). The New England council recently revised the Atlantic herring management plan with guidance from a MSE of harvest control rules including constant catch, conditional constant catch and threshold F rules (Deroba et al., 2019; Feeney et al., 2019). They found that threshold F rules produced more variable catch than the constant rules but that they were better at avoiding low levels of herring biomass and detrimental impacts on predators such as dogfish, bluefin tuna and terns (Deroba et al., 2019), and the council ultimately selected the threshold F rule for implementation in the management plan (NEFMC, 2021). The New England council recently commissioned a MSE of harvest control rules for its groundfish management plans (Mazur et al., 2021) and is considering revisions to these plans based on the results of this ongoing work (J. Plante, pers. comm.). Continued investments in MSEs, especially those that consider climate impacts (e.g., Haltuch et al., 2019; Jacobsen et al., 2022; Kaplan et al., 2021), are critical to selecting control rules that are likely to achieve management objectives in a changing ocean.

These examples serve as useful templates for other US fishery management councils as they consider revisions to their management plans and harvest control rules. For example, the Caribbean council currently employs constant catch control rules throughout its management plans but is considering amending these plans to employ a tier-based framework that would allow for the use of data-rich rules should stock assessments become available (e.g., CFMC, 2019). The current proposal recommends constant F control rules but conducting an MSE with stakeholder engagement could empower consideration of alternative rules, including threshold F rules. Similarly, NOAA Fisheries is currently considering amendments to the Atlantic Highly Migratory Species management plan that would add a tier system that increases the size of precautionary buffers for stocks with increasing scientific uncertainty (NOAA, 2020). A management strategy evaluation model could be used to evaluate alternative buffer sizes or to consider threshold F rules. Finally, in the Gulf of Mexico council, there are less formal discussions about revising their harvest control rules, which employ constant F rules for data-rich stocks, to use threshold F rules (Cass-Calay & Porch, 2019). This decision could also be guided through management strategy evaluation.

5 | CONCLUSIONS

Enhancing the resilience of US fisheries to climate change will require adjustments throughout the fisheries management system (Karp et al., 2019), not just to harvest control rules. For example, after deriving a stock-wide catch limit via harvest control rules, managers often have to allocate this catch among different geographies (e.g., states or other pertinent management areas). As stocks shift distributions in response to climate change (Morley et al., 2018; Pinsky et al., 2013), managers will need allocation strategies that are responsive to these shifts (O'Leary et al., 2022). Furthermore, increased international cooperation will be necessary to optimally manage straddling stocks (e.g., Pacific sardine and other Pacific coastal pelagics), whose availability in US waters may shift under climate change (Gaines et al., 2018; Pinsky et al., 2018). For example, the Pacific council currently sets catch limits for Pacific sardine and other coastal pelagics assuming that a fixed proportion of stocks occur in the USA and Mexico (PFMC, 2021a), yet climate change and environmental variability will likely alter these proportions over time. Resilience to climate change can also be enhanced through adjustments occurring before setting catch limits. For example, stock assessments can incorporate environmental covariates in recruitment or natural mortality or allow for time-varying natural mortality to generate reference points that are more responsive to environmental conditions (Marshall et al., 2019). However, climate change is likely to generate novel conditions that cannot be predicted based on historical monitoring, assessment and management experience (Hilborn, 1987), and management will need to become increasingly nimble and flexible to respond to these surprises. Finally, and perhaps most importantly, efforts to enhance the socioeconomic resilience of fisher livelihoods to climate change are critical to buffering against negative climate impacts (Mason et al., 2022). Overall, the impacts of climate change on fisheries will be complex and diverse and will need to be met with equally nuanced and diverse management actions.

ACKNOWLEDGMENTS

This work was made possible by support from the Walton Family Foundation through the Environmental Defense Fund. We thank Chip Collier (SAFMC), Julia Beaty (MAFMC), Emily Muehlstein (GFMC), John DeVore (PFMC), Kit Dahl (PFMC), David Witherell (NPFMC), Sara Cleaver (NPFMC), Joshua DeMello (WPFMC), Mark Fitchett (WPFMC) and Janice Plante (NEFMC) for providing data-quality tiers and for reviewing the harvest control rule summaries and database for accuracy. We also thank Jeffrey Vieser (NOAA) for help with the StockSMART data. Finally, we are grateful to Patrick Lynch (NOAA), Julia Mason (EDF), Katie Westfall (EDF) and Kristin Kleisner (EDF) for feedback on an early draft of this paper.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

All data and code are available on GitHub here: https://github.com/cfree14/us_fmps.

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How to cite this article: Free, C. M., Mangin, T., Wiedenmann, J., Smith, C., McVeigh, H., & Gaines, S. D. (2022). Harvest control rules used in US federal fisheries management and implications for climate resilience. *Fish and Fisheries*, *00*, 1–15. https://doi.org/10.1111/faf.12724