Harvest control rules used in U.S. federal fisheries and implications for climate resilience

Christopher M. Free[1,2], Tracey Mangin[1], Halley McVeigh[1], Conner Smith[1], Steven D. Gaines[1,2]

[1] Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA
[2] Marine Science Institute, University of California, Santa Barbara, Santa Barbara, CA, 93106, USA

*** Corresponding author:** Bren School of Environmental Science and Management, University of California, Santa Barbara, 2400 Bren Hall, Santa Barbara, CA 93106-5131; 610-999-4732; cfree14@gmail.com

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 United States, flexibility in how regional fisheries management councils specify harvest control rules has spawned diverse approaches for reducing catch limits to precautionarily buffer against uncertainty, some of which may be more or less resilient to climate change. Here, we synthesize the control rules used to manage all 504 U.S. 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 ("cutoff") 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 six recommendations for updating harvest control rules to improve the resilience of U.S. federally-managed fisheries to climate change.

Keywords: climate change, fisheries management, fishery management councils, Magnuson-Stevens Fishery Conservation and Management Act, MSA, harvest control rules

Acronyms

- FMC = Fishery Management Council
- FMP = Fishery Management Plan
- HCR = Harvest Control Rule
- MSY = Maximum Sustainable Yield
- OFL = Overfishing Limit
- ABC = Acceptable Biological Catch
- ACL = Annual Catch Limit
- ACT = Annual Catch Target
- F = Fishing Mortality Rate
- B_{MSY} = Biomass that produces MSY when fished at F_{MSY}
- P* = Probability of Overfishing
- CV = Coefficient of Variation
- MSE = Management Strategy Evaluation
- MSA = Magnuson-Stevens Act
- NEFMC = New England Fishery Management Council
- MAFMC = Mid-Atlantic Fishery Management Council
- SAFMC = South Atlantic Fishery Management Council
- GFMC = Gulf of Mexico Fishery Management Council
- CFMC = Caribbean Fishery Management Council
- PFMC = Pacific Fishery Management Council
- NPFMC = North Pacific Fishery Management Council
- WPFMC = West Pacific Fishery Management Council
- NOAA = National Oceanic and Atmospheric Administration
- HMS = Highly Migratory Species
- CMS = Coastal Migratory Species
- GOA = Gulf of Alaska
- BSAI = Bering Sea & Aleutian Islands

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 exacerbate the magnitude of 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 state of a fishery (Punt, 2010), represent one tool in the fisheries management toolbox that could be tuned to enhance climate resilience. There are three classes of 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 (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 expensive, 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 the U.S. (Berkson & Thorson, 2015), and generally have to 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 catch variability (e.g., salmon fisheries on the west coasts of the U.S. 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 stocks size (i.e., lower catch limits at lower stocks sizes).

Threshold F rules, a fourth approach to setting harvest control rules that reduces fishing mortality rates when stock sizes fall below a specified size threshold, are increasingly used to account for scientific uncertainty, prevent overfishing, and expedite rebuilding (NPFMC, 2020b; PFMC, 2020b), and may provide inherent resilience to uncertainty and variability resulting from climate change (Kritzer et al., 2019). In their simplest forms, these 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 modeling 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 variability, threshold F rules were equally effective at preventing overfishing under both low and high variability 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 consider the impacts of the environment on productivity (Hofmann & Powell, 1998). However, 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). 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 could 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 are 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 Act (MSA) established the 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 <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 is less than or equal to the OFL in consideration of 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 is 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 U.S. Regional Fishery Management Councils (FMCs) charged with managing fisheries in federal waters considerable flexibility in developing harvest control rules that meet these requirements. This flexibility has resulted in 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 (FMPs) implemented by a council. A synthetic understanding of the heterogeneous landscape of harvest control rules used in U.S. federally-managed fisheries is needed to facilitate cross-council learning and to identify opportunities for modifying these rules to promote climate resilience.

Here, we synthesize the harvest control rules used to manage all U.S. 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 U.S. Fishery Management Plans 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 U.S. federally-managed fisheries to climate change.

2. Methods

We reviewed the 45 Fisheries Management Plans (FMPs) and Fishery Ecosystem Plans (FEPs), hereafter referred to as management plans, used by the eight U.S. Regional Fishery Management Councils 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 variable biomass and harvest metrics, the x- and y-axes of control rules, respectively. For example, most management plans specified the harvest axis in terms of fishing mortality rates, though some used catch (e.g., Pacific Groundfish plan) or the probability of overfishing (e.g., Mid-Atlantic plans). Similarly, some management plans specified the x-axes 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 variable reference point proxies (e.g., B_{MSY}, $B_{40\%}$, $B_{20\%}$) and variable 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 the value as a “cutoff”.

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-axes 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 labeled the reference point values shown in **Table 1** on each plot. When additional values were required to specify the control rule, those values were also plotted. In general, we created these plots using Schaefer population dynamics 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 ($\sigma=\log(CV^2+1)$).

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, sometimes, expert knowledge; 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 limit 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. We also recorded the size of the buffers used to protect against scientific and management uncertainty.

Finally, we built a database of harvest control rules used for every federally-managed stock 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 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 assigned to their stocks, and assigned each stock the control rule associated with its data-quality tier. Because data-quality determinations can vary from year to year, our results represent a single (though likely representative) snapshot of recent U.S. federal fisheries management. Ultimately, our database has the following attributes for each federally-managed stock: council name, management plan name, species name, stock name, control rule typology, control rule attributes (i.e., ramp type, biomass limit flag, environmental-link flag), and uncertainty buffer sizes.

All data analysis and visualization was 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 a few North Pacific salmon stocks are managed using constant escapement rules, and the remainder are split between constant F and threshold F rules (**Figure 4**). Threshold F rules are used for all stocks in the Mid-Atlantic with reliable stock assessments. Threshold F rules are used for about half of the stocks in the Pacific and North Pacific with reliable stock assessments (**Figure 4**). The remaining half of stocks with reliable stock assessments are managed using constant F rules with the exception of some North Pacific salmon stocks, which 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, 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 use of constant F rules implies that threshold F rules could be considered as an alternative to constant F rules.

The magnitude of the uncertainty buffers used in the harvest control rules varies widely by council, management plan, species, and stock (**Figure 5**). Among the stocks whose ABC buffers are set using a specified probability of overfishing, NEFMC-managed stocks (P* median=25%) are generally more precautionary than PFMC-managed stocks (P* median=45%) (**Figure 5A**). The Mid-Atlantic council manages its stocks using a P* of 49% above a biomass threshold ($B/B_{MSY} \geq 1.5$) but this P* ramps to zero as biomass declines. Among the stocks whose ABC buffers are set using a simple percent reduction, the magnitude of these reductions are similar and generally occur in the 75% to 80% range (i.e., ABC = 75-80% of the OFL) (**Figure 5B**). Exceptionally large reductions are used by the Pacific council for: Northern anchovy, Pacific mackerel, and market squid (ABC = 25% of OFL). Across councils, ACLs are generally equivalent or close to (>98% of) the ABC (**Figure 5C**). Exceptionally large reductions are used by the Pacific council for Southern Copper rockfish (ACL = 49% of ABC), Yelloweye rockfish (64%), Pacific cod (83%), and Dover sole (84%). ACTs are rarely specified across stocks and are generally large (>75%) proportions of the ACL (**Figure 5D**).

4. Discussion

The harvest control rules used in U.S. 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, constant catch, etc.), 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 (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 skate stocks are the only stocks managed using an empirical control rule that varies fishing mortality based on a survey-based index of abundance (NEFMC, 2018). Similarly, the Pacific sardine stock is the only stock managed using an environmentally-linked control rule that varies 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 and objectives 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 six 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)

optimizing choice of catch-based method and precautionary measures for the 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; and (6) using management strategy evaluations that consider climate change impacts to guide these determinations.

4.1 Replace 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 tradeoffs among harvest control rules means 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 U.S. 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 tradeoffs 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 biomasses, which allows these rules to rebuild stocks 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).

There are two pathways for increasing the adoption of threshold F harvest control rules within the U.S. 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 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, the generalized management strategy evaluation conducted by Mildenberger et al. (2022) provides useful insights into the tradeoffs involved in tuning control rule parameters:

- **Constant rules with uncertainty buffers:** Intuitively, increasing uncertainty buffers (i.e., by decreasing P*) reduces overfishing risk and catch variability but at the cost of foregone yield (Mildenberger et al., 2022). These tradeoffs are more pronounced for long-lived species (e.g., halibut) than for fast-lived species (e.g., anchovy). Higher process uncertainty (e.g., as a result of climate change) results in greatly elevated overfishing risk and slightly reduced long-term yields; thus, decisions regarding preferred buffer sizes are likely to vary based on current or future process variability.
- **Threshold rules without uncertainty buffers or biomass limits:** Threshold rules without uncertainty buffers or biomass limits produce larger but more variable long-term catches than constant rules with uncertainty buffers at a given level of overfishing risk. These rules outperform every other threshold-based rule across all performance metrics for fast-lived species (e.g., both higher yields and lower variability at a given level of overfishing risk). Intuitively, more precautionary rules (i.e., larger threshold values) reduce risk of overfishing and catch variability but at the cost of reduced yields.
- **Threshold rules without uncertainty buffers but with biomass limits:** Without also using a precautionary buffer, introducing a limit value to threshold rules (i.e., prohibiting fishing below some cutoff) results in worse performance than a threshold rule without a biomass limit. At a given level of overfishing risk, these rules result in both lower and more variable yields, especially for fast-lived species. However, their performance is more robust to increasing uncertainty than constant F rules or the simpler threshold F rules, which highlights the value of biomass limits in fostering climate resilience.
- **Threshold rules with both uncertainty buffers and biomass limits:** Threshold rules that combined both uncertainty buffers and biomass limits lead to more favorable risk-yield trade-offs than constant rules or threshold rules with only one of the precautionary features. Importantly, they are the least sensitive to the uncertainty in B/B_{MSY} estimates and show consistent trade-offs across life history types.

While recognizing the importance of stock-specific management strategy evaluations in setting harvest control rules, Mildenberger et al. (2022) use these results to conclude that harvest control rules should include both uncertainty buffers and threshold and limit values. They provide the following rules of thumb in setting these values:

- Threshold values should be between B/B_{MSY} values of 0.5 and 2.0 for medium-lived to long-lived species and even higher (>1.0 B/B_{MSY}) for fast-lived species.
- The uncertainty buffer should be based on a percentile of the OFL distribution and should be between 0.15 and 0.45 (and should never exceed 0.5).

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 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 (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), which is common in the U.S. and abroad (Punt et al., 2020).

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

A large number of federally-managed fisheries in the U.S. 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 tradeoffs 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., 2019) 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 U.S. fish stock managed using an environmentally-linked harvest control rule, may be subject to this challenge. Its harvest control rule adjusts 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 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 tradeoffs 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). Critically, MSEs should consider multiple operating models with multiple assumptions about 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).

Many U.S. 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 guided by 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 an 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, 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 U.S. 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 U.S. 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. Furthermore, increased international cooperation will be necessary to optimally manage straddling stocks (e.g., Pacific sardine and other Pacific coastal pelagics), whose availability in U.S. 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 U.S. 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). Finally, 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.

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Tables & Figures

Table 1. Common reference points in the harmonized harvest control rule plots.

Reference point	**Definition**
Biomass (mt)	
B_0	Unexploited biomass
B_{target}	Biomass target (e.g., B_{MSY} or its proxy)
$B_{rebuild}$	Biomass below which a stock is declared to be overfished and is thus required to enter a rebuilding program. In the U.S., overfishing is declared at half the target (e.g., B/B_{MSY}=0.5)
B_{thresh}	Biomass below which F declines
B_{limit}	Biomass below which fishing is prohibited (F=0)
Catch (mt)	
MSY	Maximum sustainable yield
Fishing mortality rate (1/yr)	
F_{OFL}	Fishing mortality rate resulting from a catch equal to the overfishing limit (OFL); often equivalent to F_{MSY}
F_{ABC}	Fishing mortality rate resulting from a catch equal to the acceptable biological catch (ABC); must be less than or equal to the F_{OFL}
F_{ACL}	Fishing mortality rate resulting from a catch equal to the annual catch limit (ACL); must be less than or equal to the F_{ABC}
F_{ACT}	Fishing mortality rate resulting from a catch equal to the annual catch target (ACT); must be less than or equal to the F_{ACL}

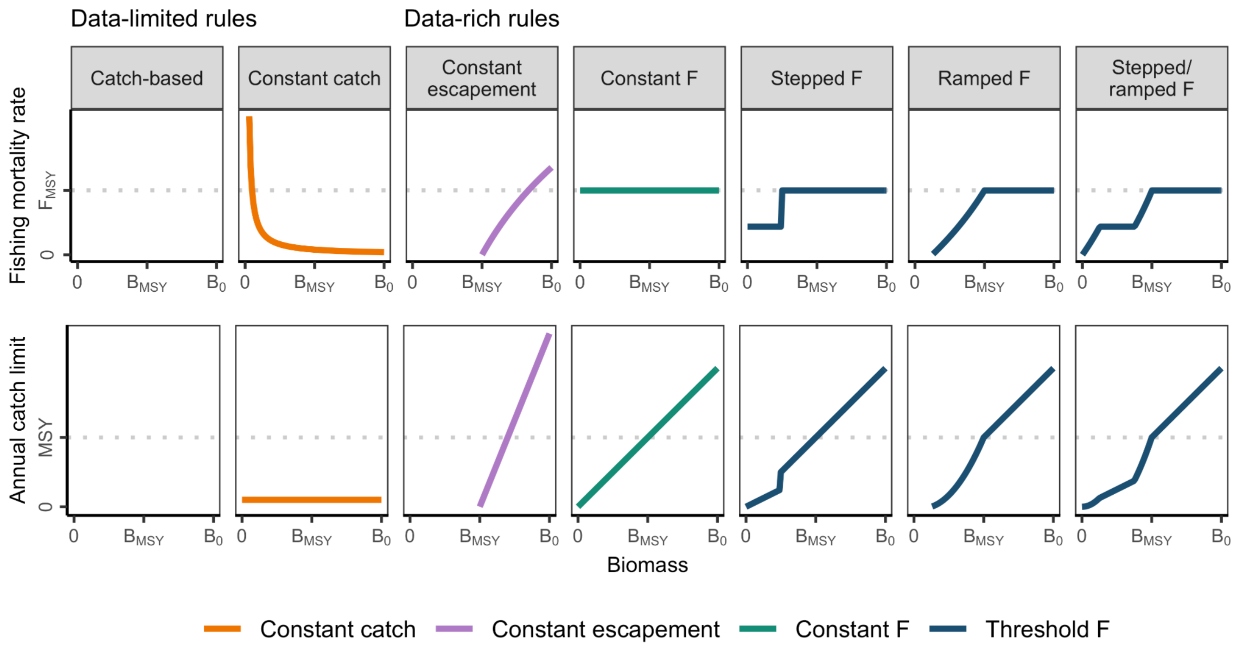

Figure 1. Illustrations of the seven harvest control rule (HCR) typologies used in U.S. federal fisheries management. Data-limited control rules are used in the absence of a reliable stock assessment and generally use catch histories to inform catch limits. The shape of catch-based control rules is unknown 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 1** for definitions of the biomass and fishing mortality reference points.

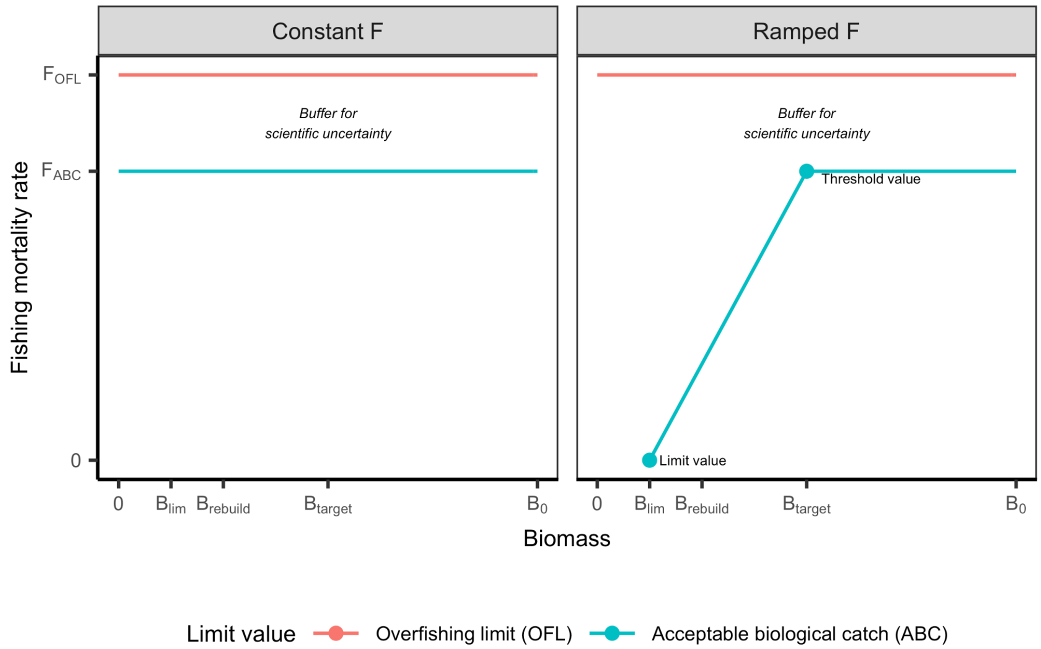

Figure 2. Illustration of the reference points and parameters commonly used to define harvest control rules and buffer them against scientific uncertainty. In both constant F and ramped F control rules, precautionary buffers are used to reduce the OFL to the ABC to protect against scientific uncertainty. 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 1** for definitions of all other biomass and fishing mortality reference points.

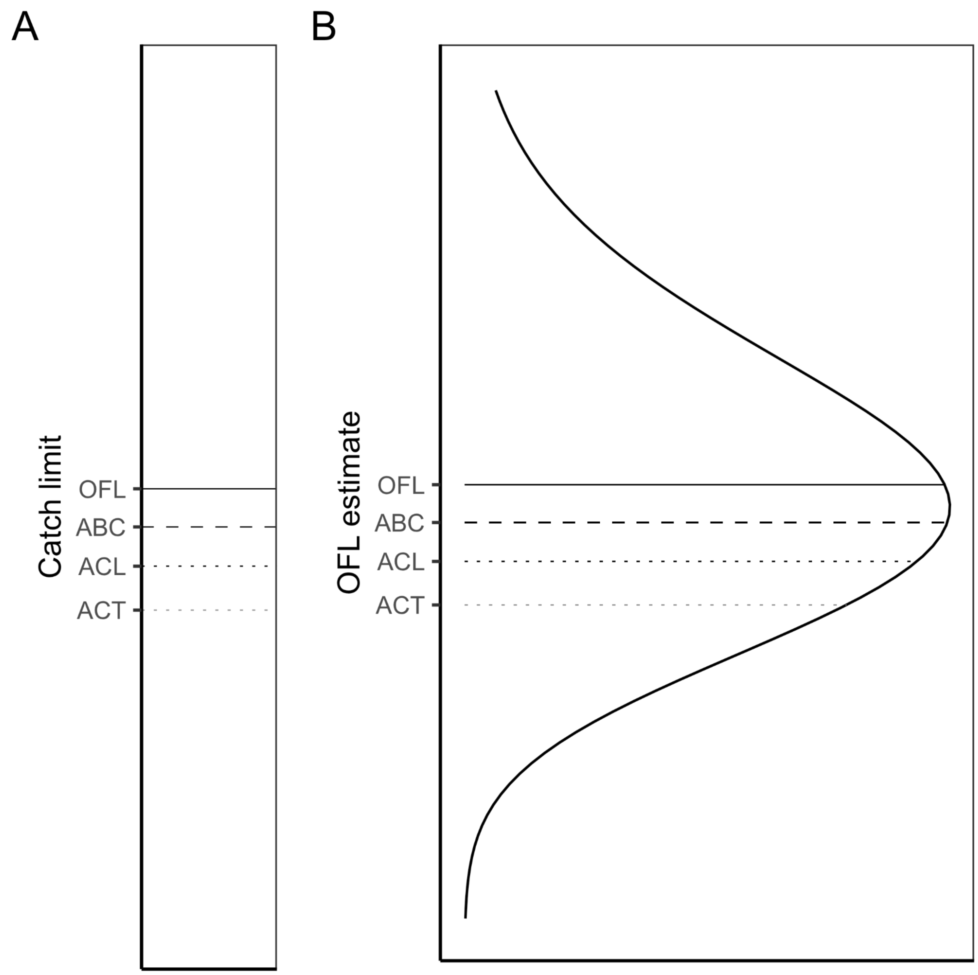

Figure 3. The relationship between catch limit reference points under U.S. federal law. In general, the following equation must be followed: ACT ≤ ACL ≤ ABC ≤ OFL. There are two approaches for reducing the OFL to the ABC in consideration of scientific uncertainty: **(A)** the reduction is performed using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

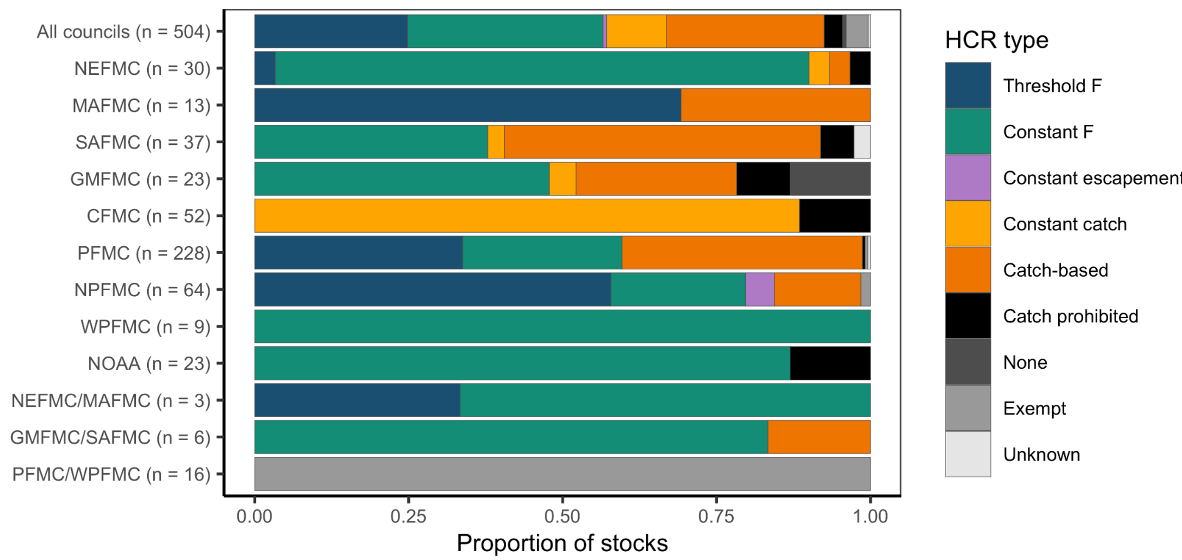

Figure 4. Proportion of U.S. federally-managed fish stocks and stock complexes managed using each harvest control rule (HCR) type by fishery management council. The top bar represents all stocks/stock complexes. Some stocks are jointly managed by two fishery management councils (bottom three rows of figure). NOAA represents the Consolidated Atlantic Highly Migratory Species Management plan.

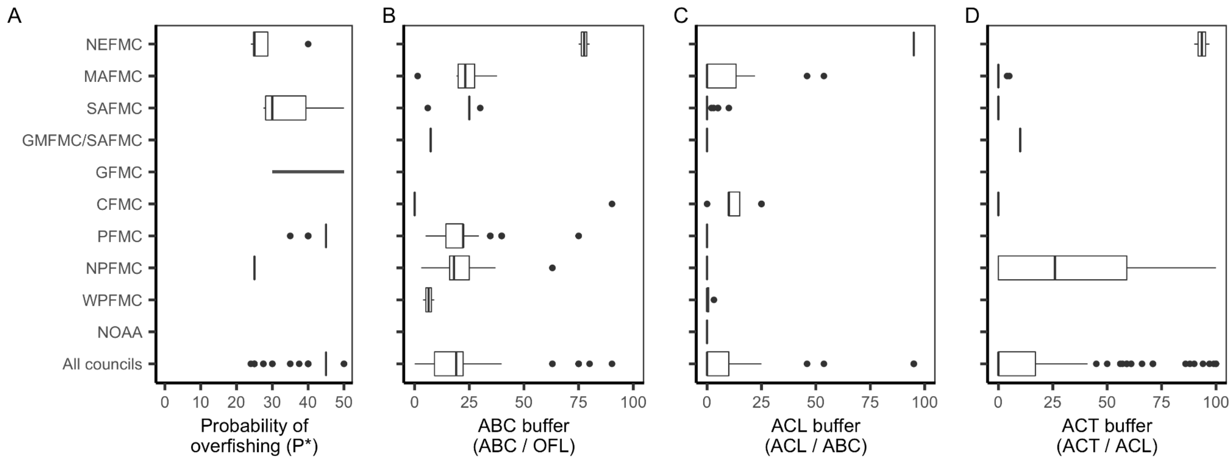

Figure 5. Distribution of precautionary buffers used to buffer against either scientific uncertainty or management uncertainty. To account for scientific uncertainty, the OFL is reduced to ABC using either either **(A)** a probability of overfishing (P*) or **(B)** a percent reduction. To account for 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. The Gulf of Mexico Council (GFMC) employs a P* values ranging from 30-50%. We were unable to find the specific values used their stocks within this range.

Supplemental Tables

Table S1. U.S. Fishery Management Plans (FMPs) and Fishery Ecosystem Plans (FEPs)[1].

#	Abbreviated FMP/FEP name	Year	Notes
New England (NEFMC)			
1	Atlantic Sea Scallop	1982	
2	Deep-Sea Red Crab	2002	
3	Northeast Multispecies	1985	
4	Northeast Skate Complex	2003	
5	Atlantic Herring	1999	
6	Atlantic Salmon	1988	
8	Monkfish (with MAFMC)	1998	
9	Spiny Dogfish (with MAFMC)	1999	
Mid-Atlantic (MAFMC)			
9	Atlantic Surfclam & Ocean Quahog	1977	
10	Bluefish	1990	
11	Mackerel, Squid, Butterfish	1978	
12	Summer Flounder, Scup, Black Sea Bass	1988	
13	Tilefish	2001	
South Atlantic (SAFMC)			
14	Dolphin & Wahoo	2004	
15	Golden Crab	1996	
16	Shrimp	1993	
17	Snapper-Grouper	1983	
18	Coastal Migratory Pelagics (with GFMC)	1983	
19	GOM & SA Spiny Lobster (with GFMC)	1982	
20	SA Corals	1984	Habitat, no fisheries
21	Sargassum	2002	Habitat, no fisheries
Gulf of Mexico (GFMC)[2]			
22	Red Drum	1986	
23	GOM Reef Fish	1984	
24	GOM Shrimp	1981	
25	GOM Corals	1984	Habitat, no fisheries
Caribbean (CFMC)[3]			
26	Reef Fish	1985	
27	Spiny Lobster	1984	
28	Queen Conch	1996	
29	Corals	1995	Habitat, no fisheries
Pacific (PFMC)			
30	Coastal Pelagic Species	2000	

31	Pacific Groundfish	1982	
32	Pacific Salmon	2016	
North Pacific (NPFMC)			
33	BSAI King & Tanner Crabs	1989	
34	BSAI Groundfish	1982	
35	GOA Groundfish	1978	
36	AK Salmon	1979	
37	AK Scallop	1995	
38	Arctic Fish	2009	HCRs but no fisheries
Western Pacific (WPFMC)			
39	American Samoa Archipelago Ecosystem	2009	
40	Hawaii Archipelago Ecosystem	2009	
41	Mariana Archipelago Ecosystem	2009	
42	Pelagic Fisheries	2009	
43	Remote Island Areas Ecosystem	2009	
Highly Migratory Species (NOAA)			
44	Atlantic HMS	2006	
45	Pacific HMS	2003	

[1] FMC=fishery management council; HCR=harvest control rule; GOM=Gulf of Mexico; SA=South Atlantic; BSAI=Bering Sea & Aleutian Islands; GOA=Gulf of Alaska
[2] The GOM Stone Crab FMP was implemented in 1979 but repealed in 2011. The WPFMC replaced its five FMPs (Bottomfish, Crustaceans, Coral Reef Ecosystem, Precious Corals, Pelagic FMPs) with five FEPs in 2009.
[3] The following three FMPs are currently under development: (1) Puerto Rico FMP, (2) St. Croix FMP, and (3) St. Thomas and St. John FMP.

Appendix A: Harvest control rules by FMP

1. New England (NEFMC)

1.1 Groundfish (Northeast multispecies)

The Northeast Multispecies FMP, often referred to as the Groundfish FMP, was implemented in 1985 and governs the management of 13 species and 20 stocks of groundfish. All stocks are managed using the same **constant F harvest control rule** in which the ABC is determined as the catch at 75% of F_{MSY}. However, if a stock is determined to be overfished and catch at 75% of F_{MSY} would not achieve the mandated rebuilding timeline, then the ABC would be set to a fishing mortality rate that would rebuild the stock within the mandated rebuilding period ($F_{rebuild}$).

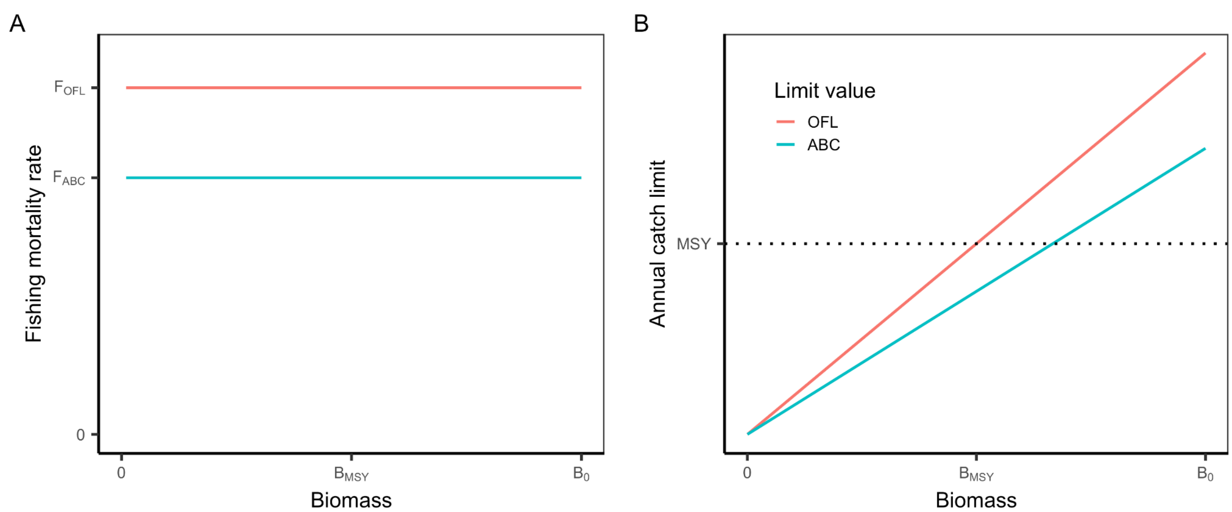

Figure A1. The harvest control rule for the NEFMC Northeast Multispecies FMP in terms of **(A)** fishing mortality rate (F) and **(B)** catch. F_{ABC} is 75% of F_{OFL}. F_{OFL} = F_{MSY} and F_{ABC} = F_{ACL}.

1.2 Small-mesh multispecies

The Northeast Small-mesh Multispecies FMP, often known as the Whiting FMP, was implemented in 2000 and governs the management of 3 species and 5 stocks of hake: two stocks of silver hake (*Merluccius bilinearis*), two stocks of red hake (*Urophycis chuss*), and one stock of offshore hake (*Merluccius albidus*). All stocks are managed using the same **constant F harvest control rule** in which the ABC is defined as a species-specific percentile of the OFL posterior and the ACL is defined as 95% of the ABC. The species-specific OFL posterior percentiles are as follows: red hake (40th percentile), silver hake (25th percentile), offshore hake (25th percentile with 4% increase).

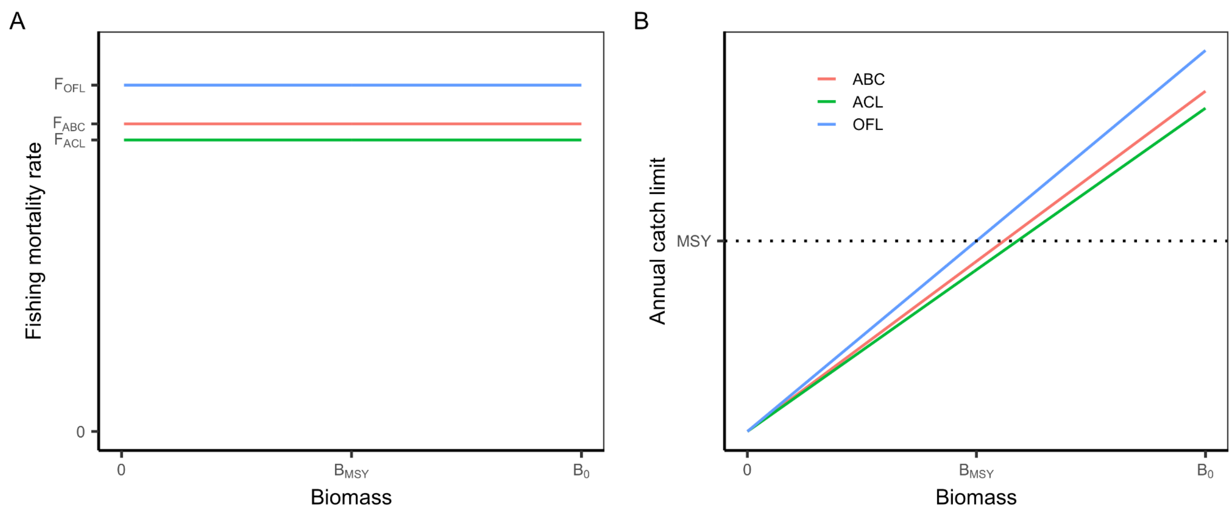

Figure A2. The harvest control rule for the NEFMC Small-mesh Multispecies FMP in terms of **(A)** fishing mortality rate (F) and **(B)** catch. The ABC is a species-specific percentile of the OFL posterior. The ACL is 95% of the ABC.

1.3 Herring

The NEFMC Herring FMP was implemented in 1999 and governs the management of the U.S. Atlantic herring (*Clupea harengus*) stock. The NEFMC updated the harvest control rule in 2021 to a **ramped F harvest control with a biomass cutoff**. This rule is used to calculate a stock-wide ACL that is then allocated to each of four management areas. When the stock is at or above 50% of B_{MSY} (or its proxy), the ABC is set at the catch associated with an F of 80% of F_{MSY} (or its proxy), When the stock is below this *threshold* value, F declines linearly to zero at a *limit* value of 10% of B_{MSY} (or its proxy). The ACL is defined as 95% of the ABC.

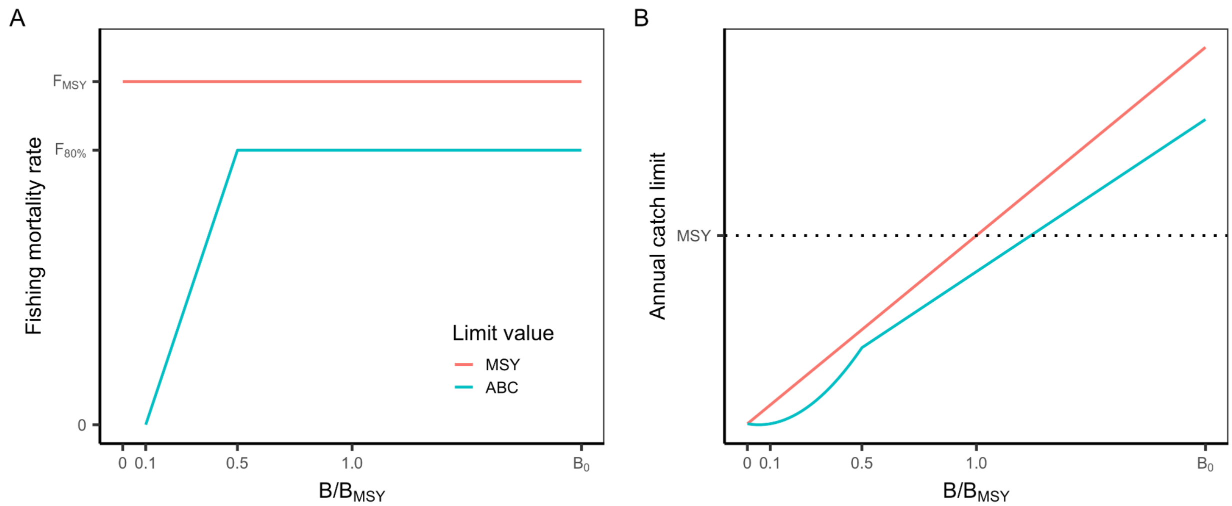

Figure A3. The harvest control rule for the NEFMC Atlantic Herring FMP in terms of **(A)** fishing mortality rate (F) and **(B)** catch.

1.4 Monkfish

The Monkfish FMP was implemented in 1998, is led by the NEFMC but is jointly governed with the MAFMC, and governs the management of monkfish (*Lophius americanus*) stocks located in a northern (NFMA) and southern (SFMA) management zone. Both stocks are managed using a **constant F harvest control rule.** When a stock assessment is conducted for one or both of the monkfish stocks, the OFL is derived by multiplying the $F_{threshold}$ (a proxy for F_{MSY}) and current biomass. The $F_{threshold}$ is 0.31 for the northern stock and 0.40 for the southern stock. The ABC, however, is set through a less typical procedure. It is calculated by multiplying current biomass by the average exploitation rate (U) during periods of stable or increasing trends in biomass. For the northern zone, the average exploitation rate is 0.18 (F=0.23) based on 1999-2006. For the southern management zone, the average exploitation rate is 0.14 (F=017) based on 2000-2006. The ACL is equal to the ABC. To account for management uncertainty, the ACT is 97% of the ACL in both management zones.

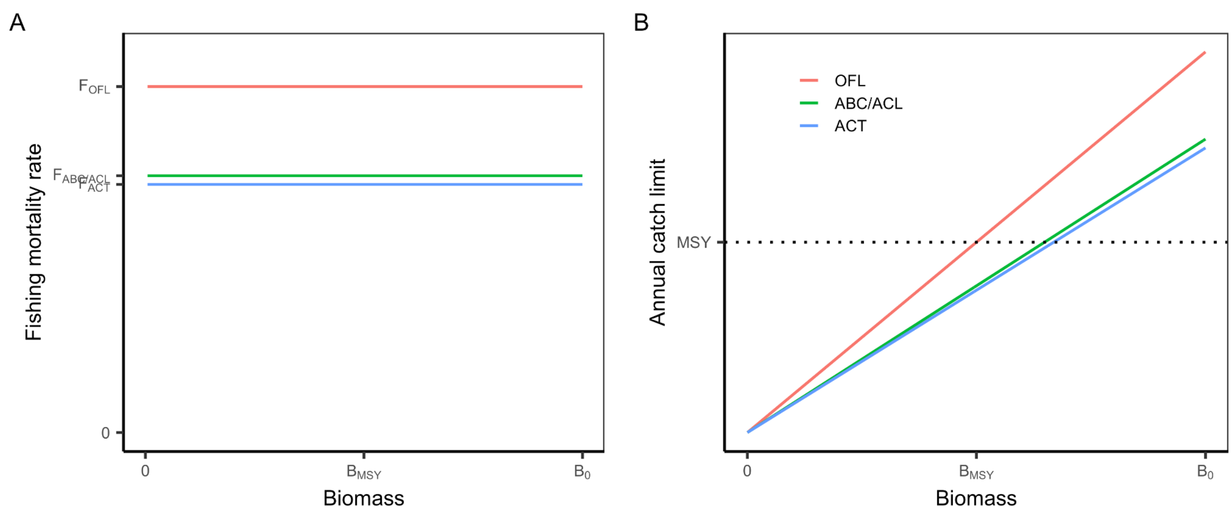

Figure A4. The harvest control rule for the NEFMC Monkfish FMP in terms of **(A)** fishing mortality rate (F) and **(B)** catch.

1.5 Skates

The NEFMC Skate FMP was implemented in 2003 and governs the management of seven skate species (**Table A1**). The skate stocks are data-limited and lack traditional quantitative stock assessments. As a result, quantitative estimates of MSY, OFL, and OY are not determined. Instead, an overfishing determination is made using an abundance index from the NMFS trawl survey (little skate based on spring survey; all others based on fall survey). If the three-year moving average of the abundance index declines by more than the average coefficient of variation, then overfishing is declared to be occurring (**Table A1**). If the abundance index falls below half of the B_{MSY} proxy (i.e., the biomass threshold), the stock is declared to be overfished. The B_{MSY} proxy is the 75th percentile of the survey years shown in Table A1 for all but barndoor skate; for barndoor skate, the B_{MSY} proxy is the average of those years. The ABC is calculated using an **empirical catch-based harvest control rule** as the median ratio of catch to the biomass index multiplied by its three-year moving average stratified mean biomass index (kg/tow). This is considered an interim procedure until an OFL can be estimated via a stock assessment. The ACL is equal to the ABC. The ACT is 90% of the ACL to account for management uncertainty, projected dead discards, and projected state landings. However, if the ABC/ACL is exceeded in a given year, the percent buffer between the ACL and ACT is increased by 1% for each 1% of ACL overage in the following year.

Table A1. Skate species managed under the NEFMC Skate FMP and the reference points used to determine their status and derive their ABCs.

Species	**Survey**	**B_{MSY} proxy (kg/tow)**	**Biomass threshold (kg/tow)**
Barndoor skate (*Dipturis laevis*)	Fall 1963-1966	1.57	0.78
Clearnose skate (*Raja eglanteria*)	Fall 1975-2007	0.66	0.33
Little skate (*Leucoraja erinacea*)	Spring 1982-2008	6.15	3.07
Rosette skate (*Leucoraja garmani*)	Fall 1967-2007	0.048	0.024
Smooth skate (*Malacoraja senta*)	Fall 1963-2007	0.27	0.134
Thorny skate (*Amblyraja radiata*)	Fall 1963-2007	4.13	2.06
Winter skate (*Leucoraja ocellata*)	Fall 1967-2007	5.66	2.83

1.6 Red crab

The NEFMC Red Crab FMP was implemented in 2002 and governs the management of Atlantic deep-sea red crab (*Chaceon quinquedens*). It employs a **constant catch harvest control rule** that calculates the ABC as the average landings from 1974-2008 (3.91 million lb of crabs). The ACL and TAL are equal to the ABC. The OFL and OY are not calculated for this data-limited fishery.

1.7 Sea scallop

The NEFMC Atlantic Sea Scallop FMP was implemented in 1982 and governs the management of Atlantic sea scallop (*Placopecten magellanicus*). It employs a **constant F harvest control rule** that sets the ABC to the catch resulting from a fishing mortality that has a 25% probability of exceeding the fishing mortality associated with OFL. The ACL is equal to the ABC. The ACL is subdivided between the two fisheries for Atlantic scallop – the limited access (LA) fishery and the limited access general category (LAGC) fishery – and an ACT is specified for each fishery. The ACT for the LAGC fishery is equal to sub-ACL for this fishery. The ACT for the LA fishery is the fishing mortality rate associated with a 25% probability of exceeding the sub-ACL.

1.8 Atlantic salmon

The NEFMC Atlantic Salmon FMP was implemented in 1988 and governs the management of Atlantic salmon (*Salmo salar*). The FMP **prohibits the commercial and recreational catch of Atlantic salmon**. All Atlantic salmon caught incidentally in other fisheries must be released in a manner that ensures maximum probability of survival.

2. Mid-Atlantic (MAFMC)

The MAFMC implements seven fishery management plans including two plans jointly managed with the NEFMC (**Table A2**). The MAFMC leads the jointly managed Spiny Dogfish FMP.

Table A2. FMPs implemented by the MAFMC.

FMP	Year
Summer Flounder, Scup, Black Sea Bass	1988
Mackerel, Squid, Butterfish	1978
Surfclams, Ocean Quahogs	1977
Bluefish	1990
Golden and Blueline Tilefish	2001
Spiny Dogfish *(led by MAFMC with NEFMC)*	1999
Monkfish *(led by the NEFMC with MAFMC)*	1998

The MAFMC employs the same multi-level approach for specifying ABC control rules for all stocks managed under the six FMPs that it leads (**Table A3**). The four levels, referred to as types, vary based on the magnitude of stock assessment uncertainty. The SSC determines which type is appropriate for each stock. Stocks in Types 1-3 have stock assessments that estimate biomass, fishing mortality, and associated reference points and can therefore be managed using the **ramped F harvest control with a biomass cutoff** outlined by the MAFMC's risk policy (**Figure A5**). This harvest control rule is unique in U.S. federal fisheries management in that the ramping is performed directly on the probability of overfishing (P*) rather than on fishing mortality (F) or catch. Stocks in Type 4 are managed using a catch-based control rule.

Table A3. ABC control rules based on the level of scientific uncertainty.

Type - ABC basis	**Data availability**	**ABC control rule**	**Stocks**
1 - Analytically-based	Stock assessment fully estimates OFL uncertainty; OFL posterior comes from assessment	Ramped F w/ cutoff	None
2 - Expert-based	Stock assessment partially estimates OFL uncertainty; OFL posterior modified by experts (SSC)	Ramped F w/ cutoff	None
3 - Empirically-based	Stock assessment does not estimate OFL uncertainty; OFL posterior entirely dictated by experts (SSC)	Ramped F w/ cutoff	All other stocks
4 - Catch-based	No stock assessment or unreliable/incomplete stock assessment;	Catch-based	Longfin squid, *Illex* squid, blueline tilefish, chub mackerel

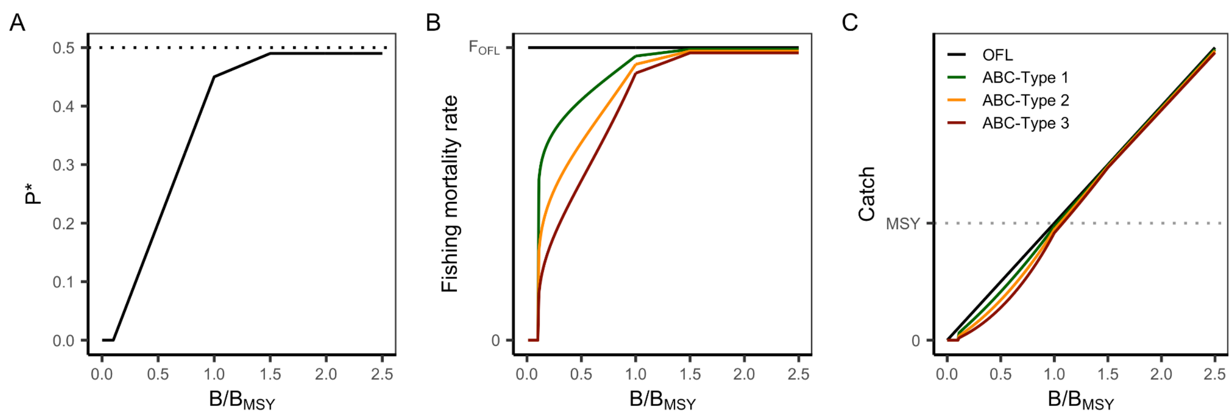

Figure A5. The **(A)** MAFMC risk tolerance policy and harvest control rules by level in terms of **(B)** fishing mortality rate (F) and **(C)** catch. P* = probability of overfishing.

3. South Atlantic (SAFMC)

The SAFMC implements eight fishery management plans including two plans jointly managed with the GFMC (**Table A4**). The SAFMC leads the jointly managed Coastal Migratory Species (CMS) FMP.

Table A4. FMPs implemented by the MAFMC (CMS=coastal migratory species).

FMP	Year	Level	HCR category
Dolphin/wahoo	2004	Level 5	Catch-based
Golden crab	1996	Level 5	Constant catch (2 million lbs)
Shrimp	1993	Not in tier-system (exempt)	*White shrimp, rock shrimp, pink shrimp:* catch-based *Brown shrimp:* unknown
Snapper-grouper	1983	Levels 1, 4, and 5	Constant F or Catch-based
CMS *(led by SAFMC with GFMC)*	1983	Not in tier-system (exempt)	Constant F
Spiny lobster *(led by GFMC with SAFMC)*	1982	Tier 3a (GFMC rule)	Catch-based
Coral	1984	Not in tier-system (habitat)	N/A
Sargassum	2002	Not in tier-system (habitat)	N/A

The SAFMC employs the same multi-level approach for specifying ABC control rules for all stocks managed under the five FMPs for fished resources that it leads (**Table A5**). The five levels vary based on the level of data availability and corresponding magnitude of stock assessment uncertainty. The SSC determines which type is appropriate for each stock. Only stocks in Level 1 have stock assessments that estimate biomass, fishing mortality, and associated reference points. Stocks in Levels 2-5 have decreasing data availability and increasing stock assessment uncertainty. Level 1 stocks are managed using a **constant F harvest control** in which the magnitude of the P* buffer is set based on expert scoring of four assessment dimensions. Stocks in Levels 2-5 are managed using various catch-based control rules.

Table A5. ABC control rules implemented by the SAFMC based on the level of scientific uncertainty.

Level	Data availability	ABC control rule	Stocks
Level 1	**Stock assessment:** adequate data to support quantitative assessment	**Constant F:** Stock assessment or other quantitative assessment used to derive OFL with estimates of uncertainty; P* used to derive ABC; the value of P* is set based on expert scoring of four assessment dimensions	Black Sea Bass, Blueline Tilefish, Gag, Golden Tilefish, Greater Amberjack, FLK/EFL Hogfish, Mutton Snapper, Red Grouper, Red Porgy, Red Snapper, Snowy Grouper, Vermillion Snapper, Wreckfish, Yellowtail Snapper
Level 2	**No stock assessment;** but reliable catch time series and life history data support DB-SRA	**Catch-based:** DB-SRA used to derive OFL with estimates of uncertainty; P* used to derive ABC; the value of P* is set based on expert scoring of four assessment dimensions	None
Level 3	**No stock assessment** and inadequate data to support DB-SRA; requires a higher degree of "informed expert judgment" than Level 2	**Catch-based:** DCAC used to derive ABC (OFL not provided) without estimates of uncertainty; within this approach, there are four-tiers based on data availability	None
Level 4	**No stock assessment;** "only reliable catch stocks" (ORCS)	**Catch-based:** OFL and ABC derived on case-by-case basis; guided by ORCS approach to determine catch statistic and scalar	Atlantic Spadefish, Bar Jack, Black Grouper, Cubera Snapper, GA-NC Hogfish, Gray Snapper, Gray Triggerfish, Lane Snapper, Margate, Red Hind, Rock Hind, Scamp, Silk Snapper, Tomtate, White Grunt, Yellowedge Grouper
Level 5	**No stock assessment** and no reliable catch time series	**Catch-based:** OFL and ABC derived on case-by-case basis; guided by decision tree; options include: 3rd highest catch from 1999-2008; median catch from 1999-2008	Almaco Jack, Banded Rudderfish, Blackfin Snapper, Coney, Dolphin, Golden Crab, Graysby, Jolthead Porgy, Knobbed Porgy, Lesser Amberjack, Misty Grouper, Queen Snapper, Sailor's Choice, Sand Tilefish, Saucereye Porgy, Scup, Speckled Hind, Wahoo, Whitebone Porgy, Warsaw Grouper, Yellowfin Grouper, Yellowmouth Grouper
N/A	N/A	**Catch prohibited**	Goliath Grouper, Nassau Grouper

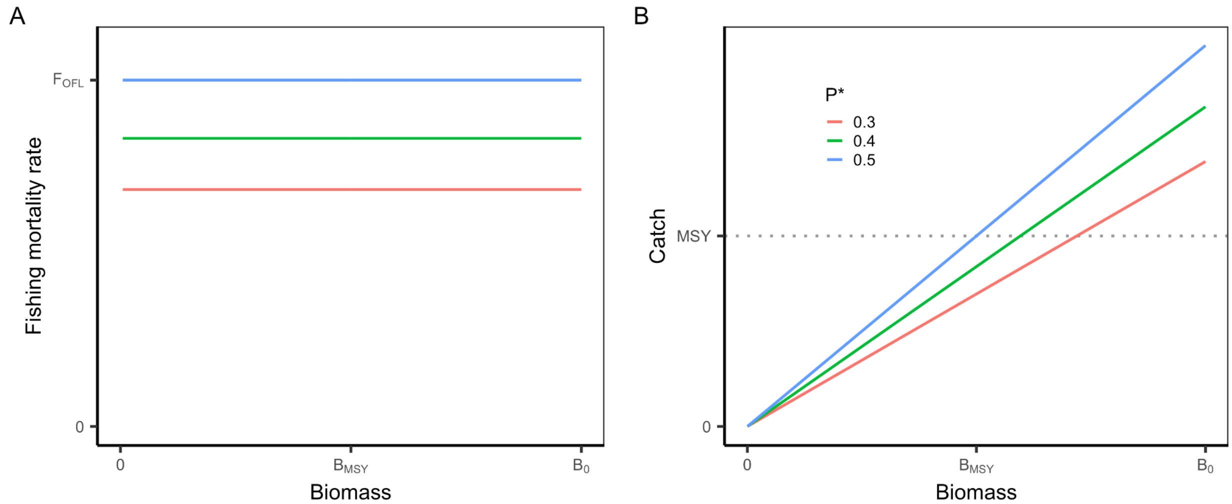

Figure A6. The harvest control rule for Level 1 stocks in SAFMC FMPs for fished resources in terms of **(A)** fishing mortality rate (F) and **(B)** catch.

4 Gulf of Mexico (GFMC)

The GFMC implements six fishery management plans including two plans jointly managed with the GFMC (**Table A6**). The GFMC leads the jointly managed Spiny Lobster FMP.

Table A6. FMPs implemented by the GFMC.

FMP	**Year**	**Tier**	**HCR category**
Reef fish	1984	Many	Constant/catch-based
Shrimp	1981	NA	Catch-based/none
Red drum	1986	No harvest	N/A
Spiny lobster *(led by GFMC with SAFMC)*	1982	3a	Catch-based
Coastal Migratory Pelagic *(led by SAFMC with GFMC)*	1983	1	Constant
Coral	1984	Habitat	N/A

The GFMC employs the same multi-level approach for specifying ABC control rules for all stocks managed under the four FMPs for fished resources that it leads (**Table A7**). The four levels vary based on the level of data availability and corresponding magnitude of stock assessment uncertainty. The SSC determines which type is appropriate for each stock. Stocks in Tier 1-2 have stock assessments that estimate biomass; Tier 1 stocks directly estimate the OFL and its uncertainty while Tier 2 stocks do so indirectly. Stocks in Tier 3 do not have stock assessments but do have a time series of landings; Tier 3a is for stocks not judged to be experiencing overfishing while Tier 3b is for stock judged to be experiencing overfishing . Tier 1 and 2 stocks are managed using a **constant F harvest control** in which the magnitude of the P* buffer is determined based on expert review. Stocks in Levels 2-3b are managed using various catch-based control rules.

The GFMC may also incorporate management uncertainty into its control rules by specifying an ACL or ACT. When an ACT is used, the ACL is usually set to the ABC. When an ACT is not used, the control rules can also guide the council in determining appropriate reductions in ABCs to yield ACLs. The ACL/ACT control rule relies on indicators of management success, including the history of exceeded catch limits, the precision of landings data, whether the ACL applies to a single stock or a complex, and the status of the stock. Buffers resulting from the application of the control rule are typically between 15 and 20% for non-ITQ managed fisheries. ITQ fisheries have stricter monitoring and reporting requirements, resulting in less management uncertainty, and thus are usually assigned buffers between 0% and 5%.

Table A7. ABC control rules implemented by the GFMC based on the level of scientific uncertainty.

Level	Data availability	Control rules	Stocks
Tier 1	- Assessment - MSY/proxy estimate - Uncertainty quantified	**Constant F:** - OFL directly from assessment - ABC = yield at P*, where P* is between 0.3 and 0.5	Cobia, Gag, Gray Snapper, Gray Triggerfish, Greater amberjack, Hogfish, King Mackerel, Mutton Snapper, Red grouper, Red Snapper, Spanish Mackerel, Vermilion Snapper, Yellowtail Snapper
Tier 2	- Assessment - No MSY/proxy estimate - But alternative OFL estimate - Uncertainty quantified	**Constant F:** - OFL indirectly from assessment - ABC = yield at P*, where P* is 0.3 as a default, but can be 0.4 or 0.5	Lane Snapper
Tier 3a	- No assessment - Landings data available - Expert opinion suggest recent landings sustainable	**Catch-based:** - OFL = mean recent landings plus two standard deviations - ABC = mean of landings plus a determined number of SDs (0, 0.5, 1, or 1.5)	Almaco jack, Banded rudderfish, Black grouper, Blackfin Snapper, Blueline tilefish, Cubera Snapper, Golden Tilefish, Goldface tilefish, Lesser amberjack, Queen Snapper, Silk Snapper, Snowy grouper, Speckled hind, Spiny Lobster, Warsaw grouper, Wenchman, Yellowedge grouper, Yellowfin grouper, Yellowmouth grouper, **Scamp (moving to Tier 1 soon)**
Tier 3b	- No assessment - Landings data available - Expert opinion suggest recent landings unsustainable	**Catch-based:** - OFL = mean landings - ABC = 75% of OFL as default	(none in this tier)
No harvest			Goliath grouper, red drum

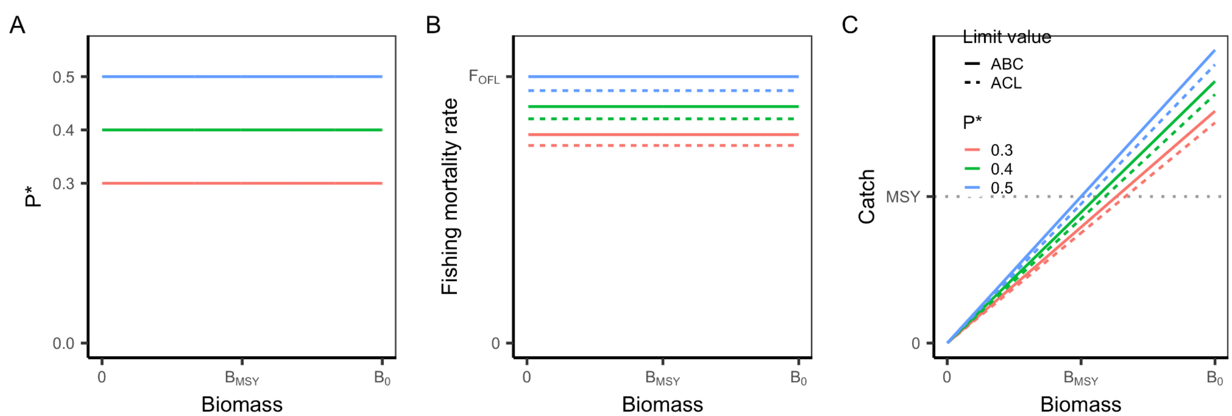

Figure A7. The harvest control rule for Tier 1 and 2 stocks in GFMC FMPs for fished resources in terms of **(A)** fishing mortality rate (F) and **(B)** catch.

5. Caribbean (CFMC)

5.1 Existing rules

5.1.1 Reef fish

The CFMC Reef Fish FMP was implemented in 1985 and governs the management of 11 fisheries management units (FMUs). The FMP manages all stocks using **catch-based harvest control rules** that vary by island and fisheries management unit (**Table A8**).

Table A8. Catch-based harvest rules used in the CFMC Reef Fish FMP.

Limit	**Island[1]**	**FMU[2]**	**Rule**
MSY	PR	Grunts, goatfishes, squirrelfish, scups/porgies, jacks, triggerfish/filefish, boxfish, wrasses	MSY proxy = median annual landings during reference period
MSY	STT/STJ/STX	All	MSY proxy = mean annual landings during reference period
MSY	PR	Surgeonfish, angelfish, tilefish	MSY proxy = 3 x maximum recreational landings
OFL	PR	All	OFL = MSY proxy adjusted based on expert opinion
OFL	STT/STJ/STX	All	OFL = MSY proxy
ABC	All	All	ABC = OFL
ACL/OY	All	Surgeonfish, angelfish	OY = ACL = ABC * 0.75
ACL/OY	All	Grunts, goatfishes, squirrelfish, scups/porgies, jacks, triggerfish, filefish, boxfish, tilefish	OY = ACL = ABC * 0.90

[1] All islands = Puerto Rico (PR), St. John (STJ), St. Thomas (STT), St. Croix (STX)
[2] All FMUs = grunts, goatfishes, squirrelfish, scups/porgies, jacks, triggerfish/filefish, boxfish, wrasses, angelfish, surgeonfish, tilefish

5.1.2 Queen conch

The CFMC Queen Conch FMP was implemented in 1997 and governs the management of queen conch (*Strombus gigas*). The FMP manages all stocks using **catch-based harvest control rules** that vary by island.

Table A9. Catch-based harvest rules used in the Queen Conch FMP.

Limit	**Island[1]**	**Rule**
MSY	PR/STX	MSY proxy = mean annual landings from 1999-2005
MSY	STT/STJ	MSY proxy = mean annual landings from 2000-2005
OFL	All	OFL = MSY proxy
ABC/ACL/OY	All	OY = ACL = ABC = specified by SSC

[1] All islands = Puerto Rico (PR), St. John (STJ), St. Thomas (STT), St. Croix (STX)

5.1.3 Spiny Lobster

The CFMC Spiny Lobster FMP was implemented in 1981 and governs the management of spiny lobster (*Panulirus argus*). The FMP manages all stocks using **catch-based harvest control rules** that vary by island.

Table A10. Catch-based harvest rules used in the Spiny Lobster FMP.

Limit	**Island[1]**	**Rule**
MSY	PR	MSY proxy = median annual landings during reference period
MSY	STT/STJ/STX	MSY proxy = mean annual landings during reference period
OFL	PR	OFL = MSY proxy adjusted using expert opinion
OFL	STT/STJ/STX	OFL = MSY proxy
ABC	All	ABC = OFL
ACL/OY	All	ACL = OY = ABC * 0.90

[1] All islands = Puerto Rico (PR), St. John (STJ), St. Thomas (STT), St. Croix (STX)

5.2 Proposed rules

The proposed island-based FMPs would use the same multi-level approach for specifying ABC control rules for all of its stocks.

Table A11. ABC control rules proposed by the CFMC based on the level of scientific uncertainty.

Tier	Data availability	Control rules	Notes
1	**Data-rich:** stage-structured stock assessment using time series of catch, abundance index, and stage composition	**Constant F:** OFL = F_{MSY} * B ABC = OFL * buffer	
2	**Data-moderate:** stock assessment using time series of catch and an abundance index (no stage structure)	**Constant F:** OFL = F_{OFL} * B ABC = OFL * buffer	
3	**Data-limited:** data-limited or out-of-date assessment available	**Constant F:** OFL = F_{MSY} * B ABC = OFL * buffer	
4a	**Data-limited:** no assessment available and the stock has relatively low vulnerability to fishing pressure	**Catch-based:** OFL = scalar * 75th percentile of reference period landings ABC = OFL * buffer	Reference period, scalar (≤3), and buffer (≤0.9) set by SSC
4b	**Data-limited:** no accepted assessment available and the stock has relatively *high* vulnerability to fishing pressure	**Catch-based:** OFL = scalar * mean of reference period landings ABC = OFL * buffer	Reference period, scalar (<2), and buffer (≤0.9) set by SSC

6. Pacific (PFMC)

6.1 Groundfish

The PFMC Groundfish FMP was implemented in 1982 and governs the management of 87 groundfish species. The FMP employs a multi-level approach for specifying ABC control rules based on the level of data availability and the corresponding magnitude of stock assessment uncertainty (**Table A12**). Stocks in Categories 1 and 2 have stock assessments and are managed using a **ramped F harvest control rule with a biomass cutoff**. The size of the ABC buffer is generally larger for data-moderate Category 2 stocks than for data-rich Category 1 stocks. When a Category 1 or 2 stock is at or above its B_{MSY} proxy, the ABC is set at the catch associated with its F_{MSY} proxy multiplied by the ABC buffer. However, when the stock is below this *threshold* value (B_{thresh}), the ABC declines linearly to zero at a *limit* value (B_{lim}) that varies based on species. The default B_{thresh} is $B_{25\%}$ for flatfish and $B_{40\%}$ for all other species. The default B_{lim} is $B_{5\%}$ for flatfish and $B_{10\%}$ for all other species. Stocks in Category 3 are managed using a **catch-based harvest control rule**.

Table A12. ABC control rules based on the level of scientific uncertainty.

Category	Data availability	Control rule	Stocks
1	**Data-rich:** a reliable quantitative stock assessment (e.g., age/length composition data included) is available	**Ramped w/ cutoff:** the selection of P* is based on level of variability in the biomass estimates (σ)	
2	**Data-moderate:** a less reliable quantitative stock assessment (e.g., age/length composition data not included) is available	**Ramped w/ cutoff:** the choice of P* is more precautionary than for Category 1 stocks by either (1) using a buffer of 0.25 or (2) doubling the CV of Category 1 stocks	
3	**Data-limited:** no reliable abundance index is available so catch-based methods are used	**Catch-based:** OFL based on DB-SRA, DCAC, or a historical catch statistic and the P* buffer is more precautionary than for Category 1 or 2 stocks by either (1) using a buffer of 0.50 or (2) quadrupling the CV of Category 1 stocks	All other species

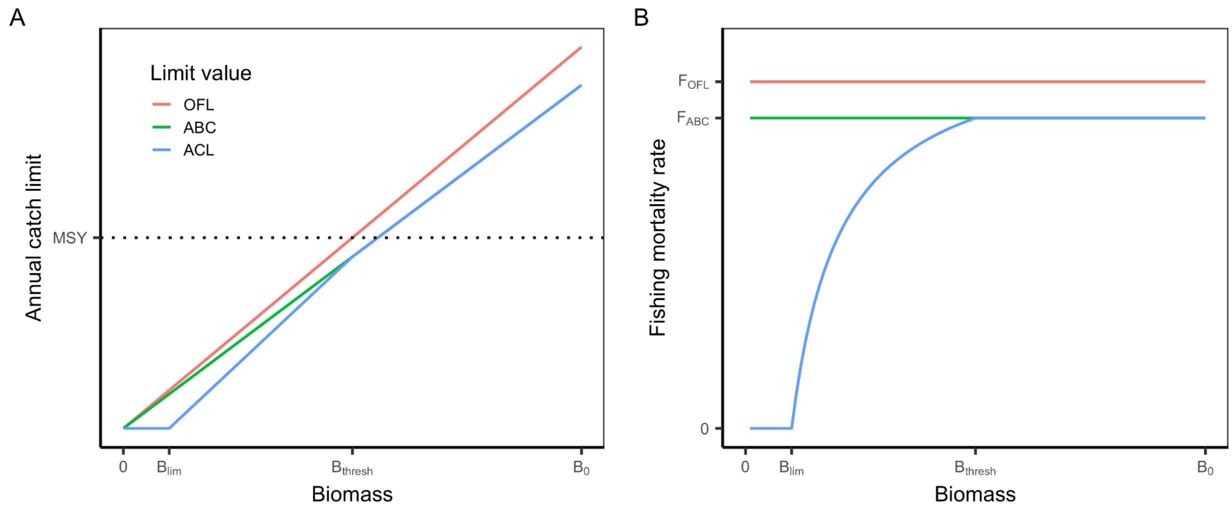

Figure A8. A conceptual illustration of the harvest control rule used to establish catch limits for Category 1 and 2 groundfish stocks. The OFL is derived from F_{MSY} or its proxy values. The default F_{MSY} proxy values are as follows: $F_{50\%}$ for rockfish and elasmobranchs, $F_{45\%}$ for roundfish, $F_{40\%}$ for whiting, and $F_{30\%}$ for flatfish. The default B_{thresh} is $B_{25\%}$ for flatfish and $B_{40\%}$ for all other species. The default B_{lim} is $B_{5\%}$ for flatfish and $B_{10\%}$ for all other species.

6.2 Coastal Pelagics

The PFMC Coastal Pelagic FMP was implemented in 2000 and governs the management of 3 actively managed species, 3 monitored species, and krill species whose harvest is prohibited (**Table A13**). Actively managed species are managed using a **ramped harvest control rule with a biomass cutoff** using the system of equations shown in **Table A13** and parameters in **Table A14**. The HCR for Pacific sardine rule includes an exploitation rate that is **environmentally-linked** to sea surface temperature in the CalCOFI survey. Monitored species are managed using catch-based harvest control rules using the system of equations shown in **Table A13**. Harvest is not allowed for prohibited species (all krill species).

Table A13. Harvest control rules used in the PFMC Coastal Pelagic Species FMP.

Tier	Control rules
Active Pacific chub mackerel	**Ramped with biomass cutoff:** OFL = B * F_{MSY} * distribution ABC = B * F_{MSY} * distribution * buffer HG = (biomass - cutoff) * fraction * distribution
Active Pacific sardine	**Ramped with biomass cutoff and environmental-link:** E_{MSY} = -18.46452 + 3.25209*T - 0.19723*T^2 + 0.0041863*T^3; where T = 3-yr running average of CalCOFI SST OFL = B * E_{MSY} * distribution, E_{MSY} = [0-0.25] ABC = B * E_{MSY} * distribution * buffer; E_{MSY} = [0-0.25] HG = pmin(maxcat, (biomass - cutoff) * E_{MSY} * distribution); E_{MSY} = [0.05-0.20]
Monitored Northern anchovy, jack mackerel, market squid	**Catch-based:** OFL = MSY proxy ABC = OFL * 0.25 ACL ≤ ABC, based on OY considerations
Prohibited All krill species	No harvest

Table A14. Parameters for the HCRs of the actively managed species.

Parameter	Definition	Pacific sardine	Pacific chub mackerel
cutoff (mt)	Lowest biomass at which directed harvest is allowed	150,000 mt	18,200 mt
fraction (%)	Percent of the biomass above the cutoff that can be	5-20% depending on SST (higher in warm years, lower	30%

	taken by the fishery	in cool years)	
distribution (%)	Average percent of biomass assumed to be in US waters	87%	70%
maxcat (mt)	Maximum allowable catch	200,000 mt	None (appears limited to 40,000 mt by markets)
buffer	ABC buffer	~90%	~90%

Table A15. Assumed distribution of actively managed and monitored species in the U.S. Exclusive Economic Zone (EEZ).

Species	**% of distribution on US EEZ**
Pacific sardine	87
Pacific chub mackerel	70
Northern anchovy - central stock	82
Northern anchovy - northern stock	Unknown (some in Canada)
Jack mackerel	65
Market squid	N/A

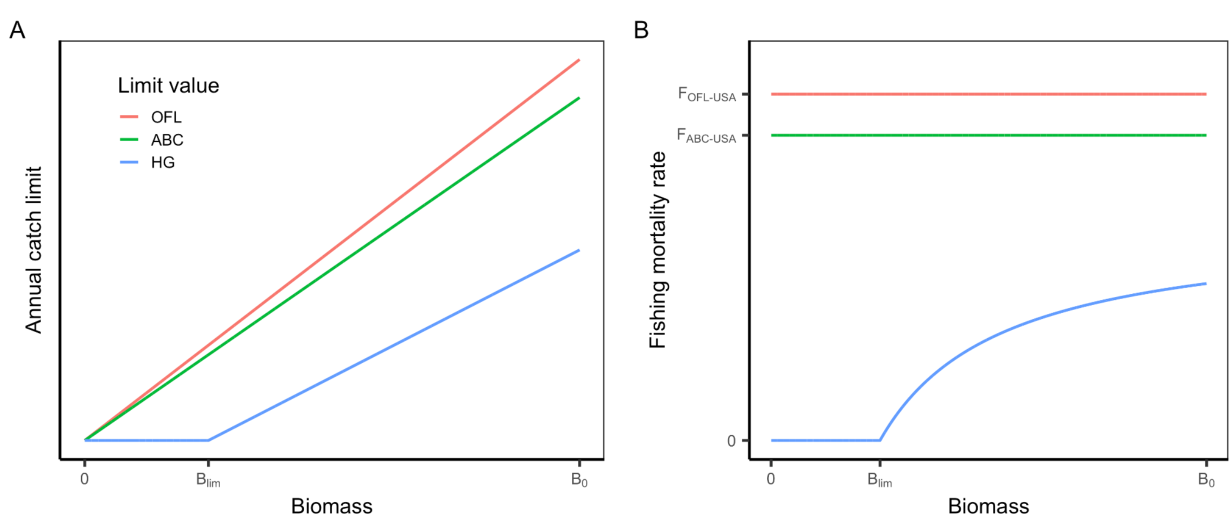

Figure A9. The harvest control rule for Pacific chub mackerel.

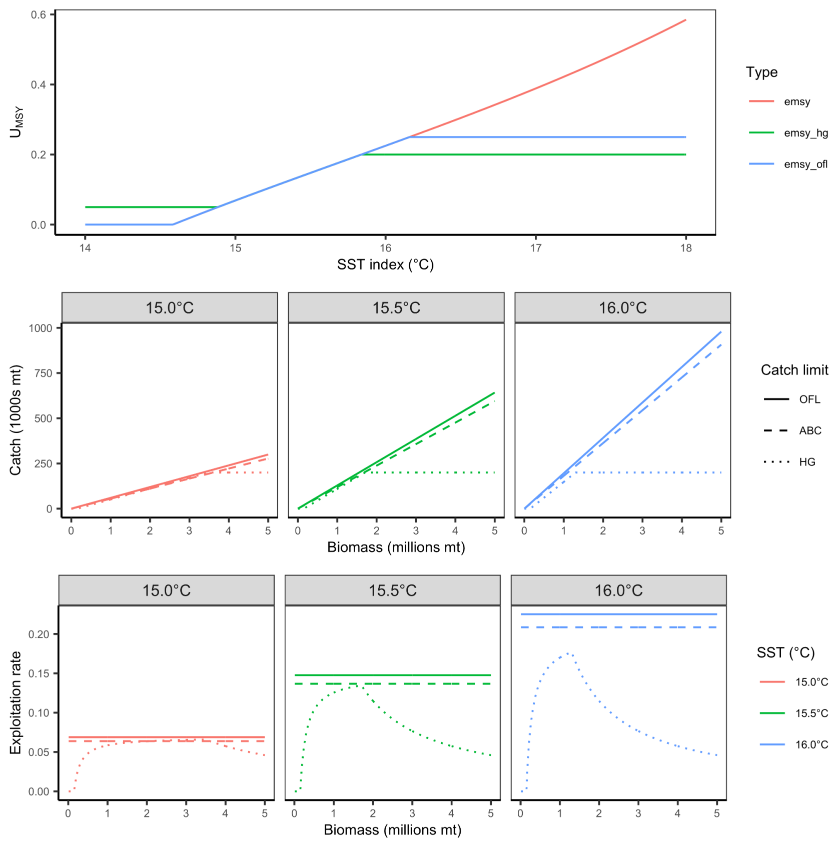

Figure A10. The environmentally-linked harvest control rule for Pacific sardine.

6.3 Salmon

The PFMC Salmon FMP was implemented in 2016 and governs the management for Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), and pink salmon (*Oncorhynchus gorbuscha*) (odd numbered years only). The majority of salmon stocks are managed using the default **constant F harvest control rule**. However, the Puget Sound Coho salmon stock is managed using a stepped harvest control rule and the Klamath River and Sacramento River Fall Chinook salmon stocks are managed using a **ramped/stepped F harvest control rule**. Under the default rule, the magnitude of the ABC buffer varies by tier. For Tier 1 stocks, in which F_{MSY} is estimated directly, $F_{ABC} = F_{MSY}$ x 0.95 whereas $F_{ABC} = F_{MSY}$ x 0.90 for Tier 2 stocks, in which a proxy value is used Under the default rule, the ACL is equal to the ABC.

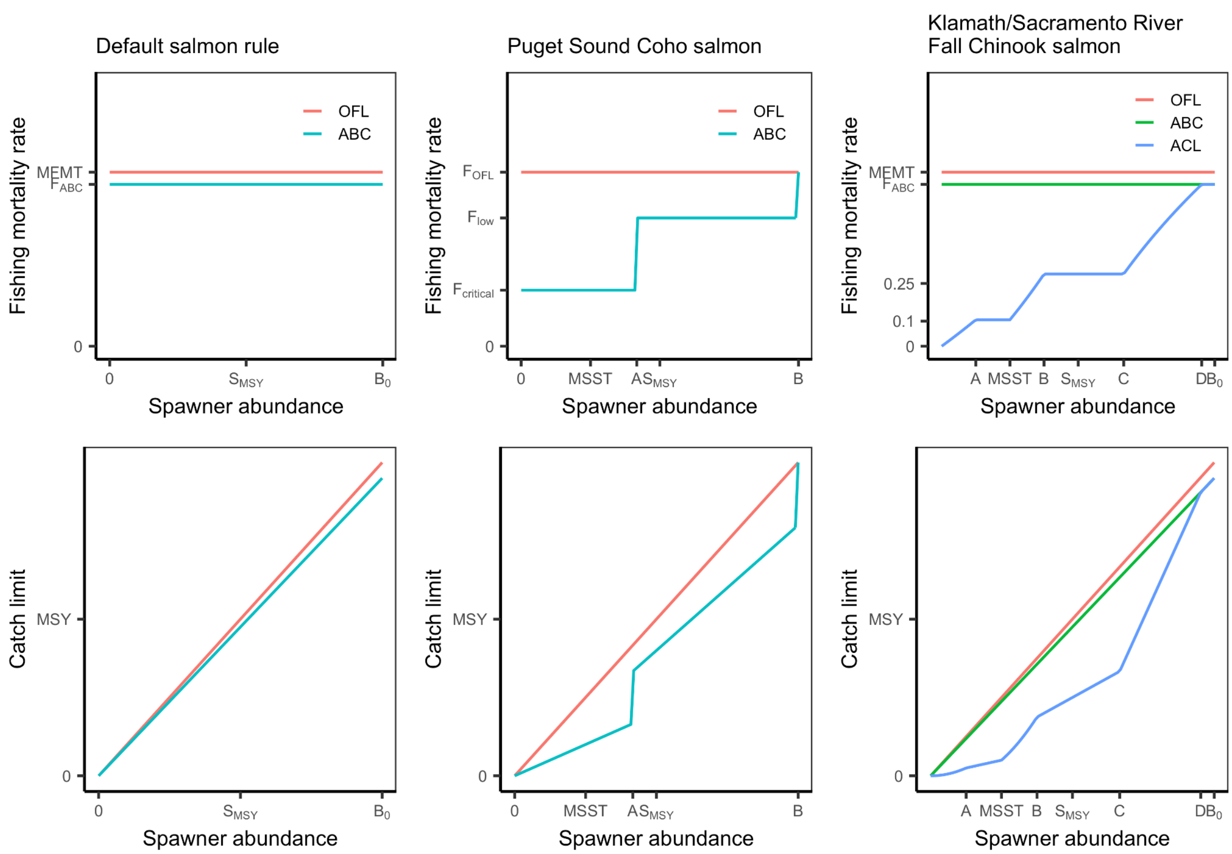

Figure A11. Harvest control rules for Pacific salmon.

7. North Pacific (NPFMC)

7.1 GOA & BSAI Groundfish

Groundfish in the North Pacific are managed under FMPs for the Gulf of Alaska (GOA), implemented in 1978, and for the Bering Sea and Aleutian Islands (BSAI), implemented in 1982. Both FMPs manage groundfish stocks using the same multi-level approach for specifying ABC control rules (**Table A16**). The five levels, referred to as tiers, vary based on the level of data availability and corresponding magnitude of stock assessment uncertainty. The SSC determines which tier is appropriate for each stock. Stocks in Tiers 1-3 are managed using **ramped F harvest control rules with biomass cutoffs** with increasing precaution to buffer against scientific uncertainty. Stocks in Tiers 4-5 are managed using **constant F harvest control rules** with increasing precaution to buffer against scientific uncertainty. Stocks in Tier 6 lack estimates of biomass and are managed using a **catch-based harvest control rule**.

Table A16. Six-tier system for setting OFLs and ABCs in the GOA & BSAI Groundfish FMP.

Tier	Data availability	Control rules	Stocks
1	B, B_{MSY}, F_{MSY} w/ uncertainty	**Ramped w/ cutoff:** F_{OFL} ~ arithmetic mean of F_{MSY} posterior F_{ABC} ~ harmonic mean of F_{MSY} posterior	**GOA:** None **BSAI:** Eastern Bering Sea pollock Yellowfin sole Northern Rock sole
2	B, B_{MSY}, F_{MSY}, $F_{35\%}$, $F_{40\%}$	**Ramped w/ cutoff:** F_{OFL} ~ B_{MSY}, F_{MSY} F_{ABC} ~ B_{MSY}, F_{MSY}, $F_{35\%}$, $F_{40\%}$	**GOA:** None **BSAI:** None
3	B, $B_{40\%}$, $F_{35\%}$, $F_{40\%}$	**Ramped w/ cutoff:** F_{OFL} ~ $B_{40\%}$, $F_{35\%}$ F_{ABC} ~ $B_{40\%}$, $F_{40\%}$	**GOA:** Pollock, Pacific cod, Sablefish, Northern and southern rock sole, Rex sole, Arrowtooth flounder, Flathead sole, Pacific ocean perch, Northern rockfish, Rougheye & blackspotted rockfish, Dusky rockfish, Deepwater flatfish (Dover) (also in 6) **BSAI:** Aleutian Islands pollock, Eastern Bering Sea Pacific Cod, Sablefish, Greenland Turbot, Arrowtooth flounder, Kamchatka flounder, Flathead sole, Alaska plaice, Pacific ocean perch, Northern rockfish, Rougheye & blackspotted rockfish, Atka mackerel

4	B, $F_{35\%}$, $F_{40\%}$	**Constant:** $F_{OFL} = F_{35\%}$ $F_{ABC} = F_{40\%}$	**GOA:** Other rockfish (also in 5 and 6) **BSAI:** Sharpchin rockfish
5	B, natural mortality (M)	**Constant:** $F_{OFL} = M$ $F_{ABC} = M * 0.75$	**GOA:** Shallow water flatfish (excluding northern and southern rock sole), Shortraker rockfish, Thornyhead rockfish, Skates, Sharks (also in 6) **BSAI:** Shortspine thornyhead, Shortraker rockfish, Longnose skate, Sculpin complex, Yellowfin sole, Butter sole, Starry flounder, English sole, Sand sole, Alaska plaice, Silvergray rockfish, Splitnose rockfish, Stripetail rockfish, Bocaccio, Chilipepper, Darkblotched rockfish, Greenstriped rockfish , Harlequin rockfish, Northern rockfish, Pygmy rockfish, Redbanded rockfish, Redstripe rockfish, Vermilion rockfish Widow rockfish, Yellowmouth rockfish, Yellowtail rockfish, Big skate
6	Reliable catch from 1978-1995	**Catch-based:** OFL = average catch from 1978-1995 ABC = OFL * 0.75	**GOA:** Atka mackerel, Octopus, Squid complex **BSAI:** Aurora rockfish, Shortbelly rockfish, Canary rockfish, China rockfish, Copper rockfish, Quillback rockfish, Rosethorn rockfish, Tiger rockfish, Yelloweye rockfish, Giant octopus, Atka mackerel

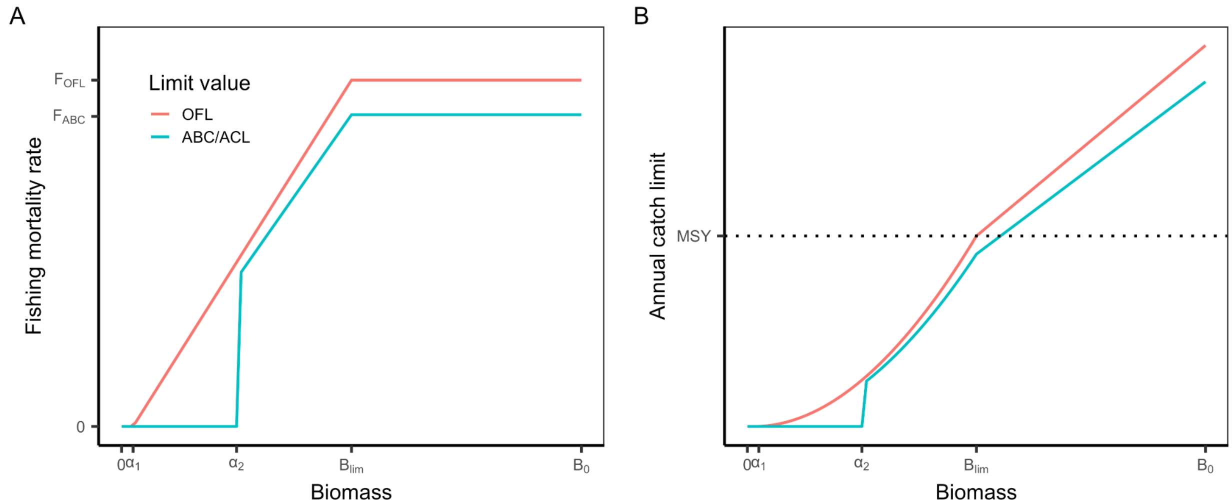

Figure A12. Harvest control rules for GOA and BSAI groundfish stocks in Tiers 1-3.

7.2 BSAI King and Tanner Crabs

The BSAI King an Tanner Crab FMP was implemented in 1989 and governs the management of four red king crab (*Paralithodes camtschaticus*), two blue king crab (*Paralithodes platypus*), two golden (brown) king crab (*Lithodes aequispinus*), one tanner crab (*Chionoecetes bairdi*), and one snow crab (*Chionoecetes opilio*) stocks in the Bering Sea and Aleutian Islands management area. It excludes the following stocks managed by the State of Alaska: Aleutian Islands tanner crab, Dutch Harbor red king crab, St. Matthew golden king crab, and St. Lawrence blue king crab. It implements a **ramped F harvest control rule with a biomass cutoff** for stocks with data availability (Tiers 1-4) and a **catch-based control rule** for stocks without data availability (Tier 5). For stocks in Tiers 1-4, the equations for describing the ramped rule with the biomass cutoff are the same; they differ only in the availability of B_{MSY}, F_{MSY}, or their proxy values. For stocks in Tier 5, the OFL is set equal to the average catch from a time period deemed by experts to represent the production potential of the stock. The ABC is set as less than or equal to the 90% of the OFL (the size of the buffer varies based on scientific uncertainty and is set by the SSC). The ACL is equal to the ABC.

Table A17. Five-tier system for setting OFLs and ABCs in the BSAI King and Tanner Crab FMP.

Tier	Data availability	ABC control rule	Stocks
1	B, B_{MSY}, F_{MSY} w/ uncertainty	Ramped w/ cutoff	
2	B, B_{MSY}, F_{MSY} w/out uncertainty	Ramped w/ cutoff	
3	B, $B_{35\%}$, $F_{35\%}$	Ramped w/ cutoff	EBS snow crab, Bristol Bay red king crab, EBS Tanner crab and Aleutian Island golden king crab
4	B, $B_{35\%}$, M	Ramped w/ cutoff	St. Matthew blue king crab, Pribilof Islands blue king crab, Pribilof Islands red king crab, and Norton Sound red king crab)
5	No reliable estimates of B or M	Catch-based	Pribilof Islands golden king crab, and Western Aleutian Islands red king crab

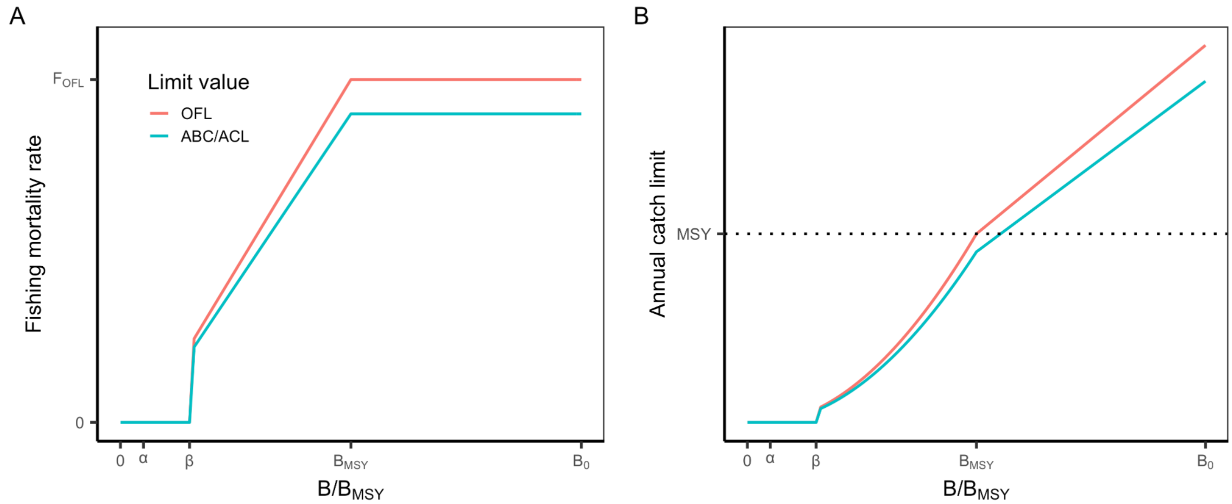

Figure A13. The harvest control rule for the NPFMC BSAI King and Tanner Crab FMP in terms of **(A)** fishing mortality rate (F) and **(B)** catch. F_{ABC} <= 90% of F_{OFL}. F_{OFL} = F_{MSY} and F_{ABC} = F_{ACL}.

7.3 Salmon

The NPFMC Salmon FMP was implemented in 1979 and was comprehensively revised in 1990 and again in 2011. The NPFMC delegates the regulatory authority for implementing the FMP to the Alaska Department of Fish and Game. The FMP manages North Pacific salmon stocks falling into three tiers (**Table A18**). Chinook salmon managed under the Pacific Salmon Treaty represent Tier 1. Although they are exempt from the MSA ACL requirement since they are managed under an international agreement, they set ACLs based on a monitored abundance index that results in an **empirical downward sloping harvest control rule.** Tier 2 and 3 stocks are managed using a **constant escapement harvest control rule**.

Table A18. Harvest control rules for NPFMC salmon stocks.

Tier	Stocks	Harvest control rule
Tier 1	Chinook salmon managed under Pacific Salmon Treaty	Exempt from ACL requirement because managed under international agreement; however, a segmented linear relationship is used
Tier 2	Coho salmon managed by the ADFG	Constant escapement
Tier 3	Coho, pink, chum, and sockeye salmon managed as mixed-species complexes by the ADFG	Constant escapement

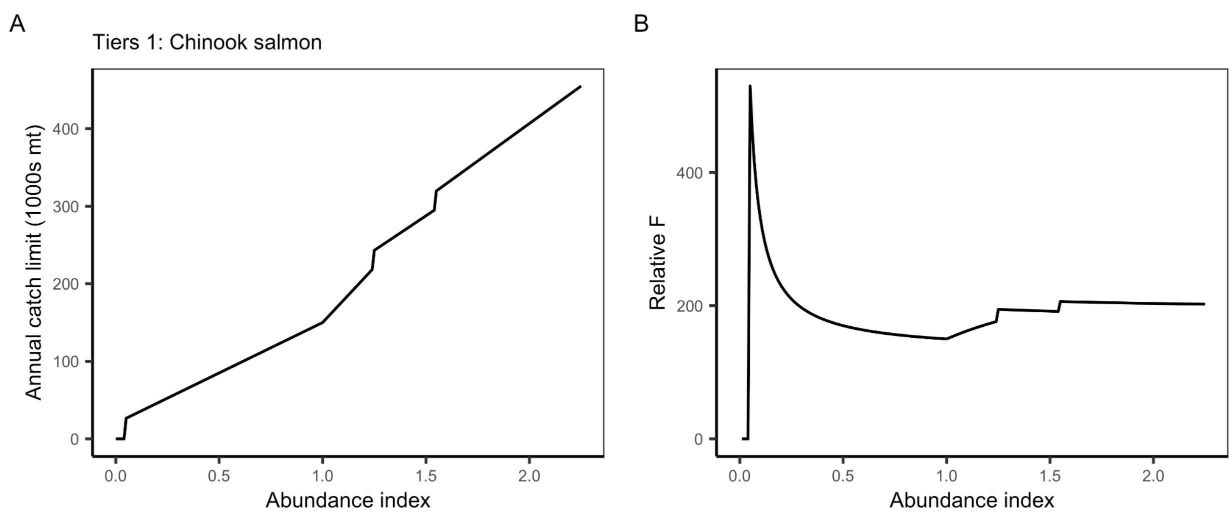

Figure A14. The harvest control rule for Tier 1 salmon stocks in terms of **(A)** catch and (B) relative fishing mortality rate (catch / abundance index).

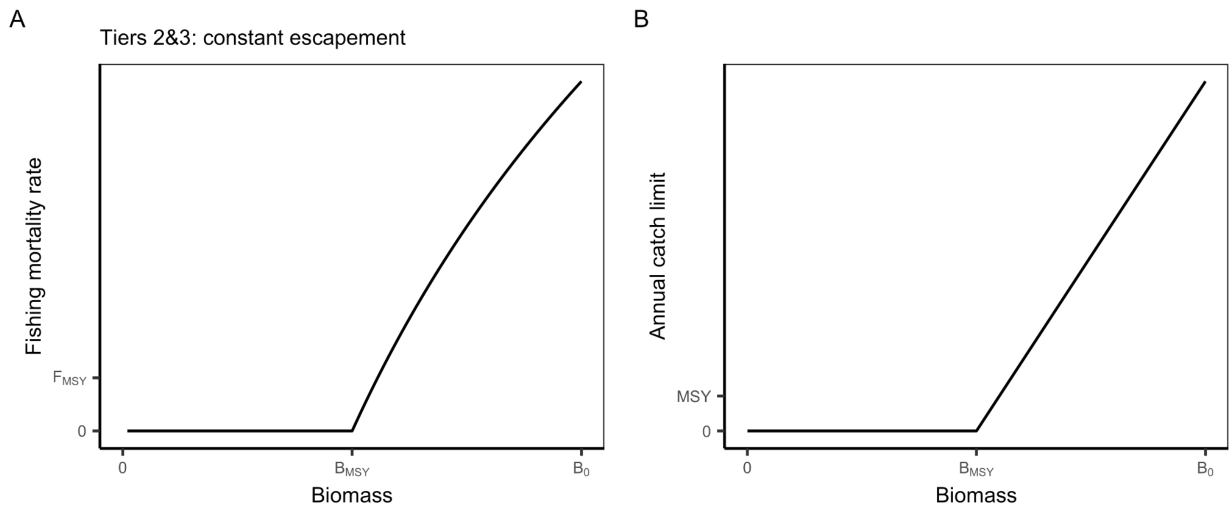

Figure A15. The harvest control rule for Tier 2 and 3 salmon stocks in terms of **(A)** fishing mortality rate (F) and **(B)** catch. In this example, escapement is set equal to B_{MSY}.

7.4 Scallop

The NPFMC Scallop FMP was implemented in 1995 and governs the management of scallop fisheries in nine management zones (scallop registration areas) off the coast of Alaska. The FMP covers weathervane scallops (*Patinopecten caurinus*), which are targeted in the fishery, and other scallop species that are not targeted. The FMP employs a **constant F harvest control rule** when an estimate of biomass is available. If no biomass estimate is available, then it is managed using a **constant catch rule** (OFL = 1.284 million lbs; ABC = 90% of the OFL). The F_{OFL} is calculated using a natural mortality (M) estimate of 0.13/yr as an F_{OFL} proxy. F_{ABC} is 90% of the F_{OFL}.

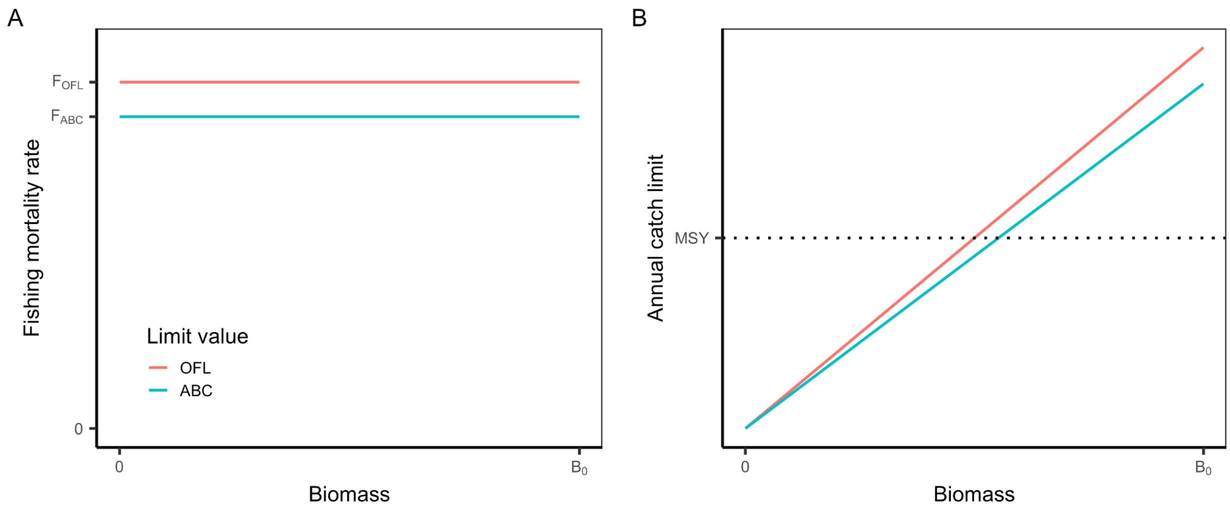

Figure A16. The harvest control rule for NPFMC scallops.

7.5 Arctic Fish Resources

There are no fisheries currently authorized to operate in the Arctic; however, the FMP specifies rules for if and when commercial fisheries are authorized. The FMP species OFL and ABC values for finfish using a five-tier system and for crabs using a four-tier system.

Table A18. Finfish tiers.

Tier	Data availability	Category
1	B, B_{MSY}, F_{MSY}	Ramped w/ biomass cutoff
2	B, B_{MSY}, F_{MSY}, $F_{35\%}$, $F_{45\%}$	Ramped w/ biomass cutoff
3	B, $B_{40\%}$, $F_{35\%}$, $F_{40\%}$	Ramped w/ biomass cutoff
4	B, $F_{35\%}$, $F_{40\%}$	Constant
5	B, M	Constant

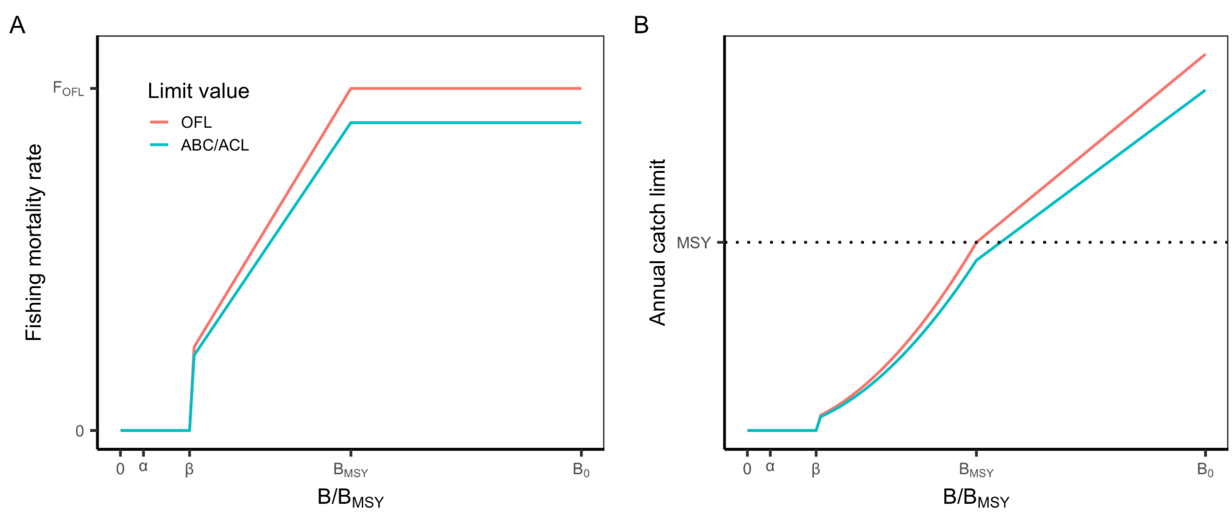

Figure A17. Harvest control rule for Tier 1, 2, and 3 finfish stocks in the Arctic Fish Resources FMP. For Tier 4 stocks, $F_{OFL} = F_{35\%}$ and $F_{ABC} \leq F_{40\%}$. For Tier 5 stocks, F_{OFL} = M (natural mortality) and $F_{ABC} \leq 0.74*M$.

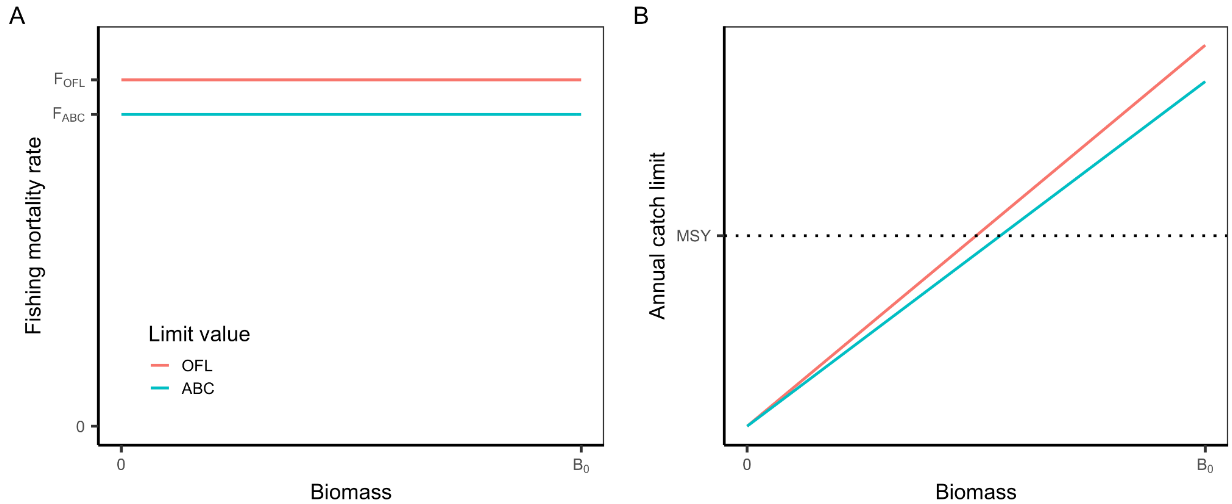

Figure A18. Harvest control rule for Tier 4 and 5 finfish stocks in the Arctic Fish Resources FMP. For Tier 4 stocks, $F_{OFL} = F_{35\%}$ and $F_{ABC} \leq F_{40\%}$. For Tier 5 stocks, F_{OFL} = M (natural mortality) and $F_{ABC} \leq 0.74$*M.

Table A19. Crab tiers.

Tier	Data availability	Category
1	B, B_{MSY}, F_{MSY} w/ uncertainty	Ramped w/ biomass cutoff
2	B, B_{MSY}, F_{MSY}	Ramped w/ biomass cutoff
3	B, $B_{35\%}$, $F_{35\%}$	Ramped w/ biomass cutoff
4	B, B_{MSY}, M	Ramped w/ biomass cutoff

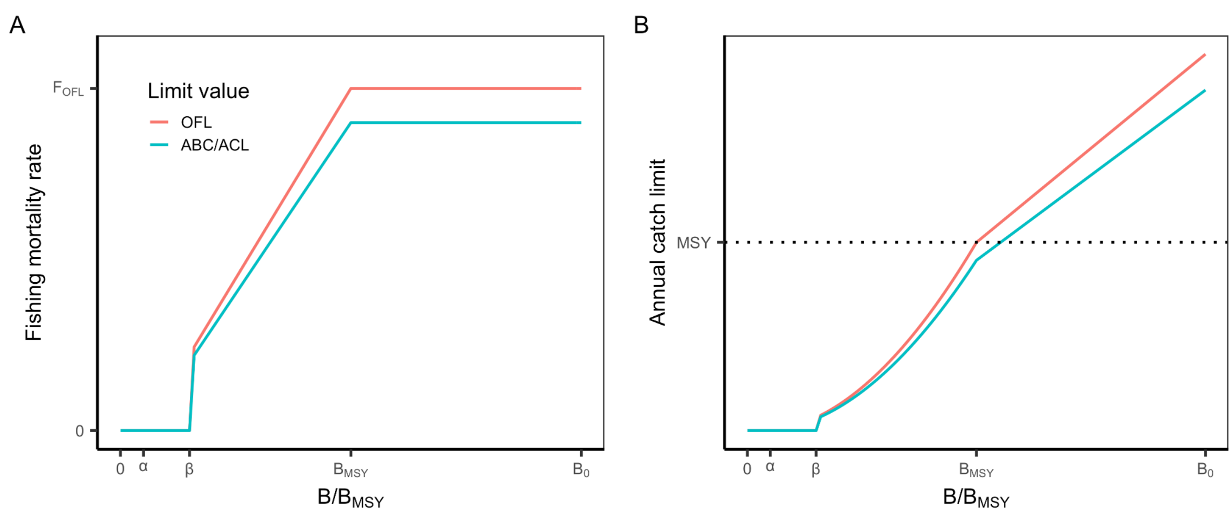

Figure A19. Harvest control rule for crab stocks in the Arctic Fish Resources FMP.

8. Western Pacific (WPFMC)

The WPFMC replaced its five species-based Fishery Management Plans (FMPs) with five place-based Fishery Ecosystem Plans (FEPs) in 2009. These FEPs comprise plans for the following ecosystems: American Samoa Archipelago, Hawaii Archipelago, Mariana Archipelago, Pacific Pelagic Fisheries of the Western Pacific Region, Pacific Remote Island Areas.

The WPFMC employs the same multi-level approach for specifying ABC control rules for all of the stocks that it manages (**Table A20**). The five levels, referred to as tiers, vary based on the magnitude of stock assessment uncertainty. The SSC determines which type is appropriate for each stock. Stocks in Tiers 1-4 are managed using a **constant F harvest control rule** with increasing precautionary buffers between the OFL and ABC. Stocks in Tier 5 lack estimates of biomass and are managed using a catch-based harvest control rule.

The WPFMC has designed two procedures for reducing the ABC to an ACL based on management uncertainty. In order of decreasing data requirements, the methods for calculating the magnitude of the buffer are: (1) a comprehensive Social, Economic, Ecological, and Management (SEEM) analysis that accounts for objectives beyond accounting for management uncertainty; and (2) an expert-based analysis that considers only management uncertainty. The ACL may additionally be reduced to an ACT.

Table A20. ABC control rule categories and specifications by tier of data availability.

Tier	Data availability	ABC control rule	Stocks
1	OFL and uncertainty from traditional assessment model and are reliable	**Constant F:** ABC = percentile of OFL posterior (P*)	MHI Deep 7 BF, Uku
2	OFL and uncertainty from traditional assessment model but are unreliable	**Constant F:** ABC = percentile of OFL posterior (P*)	Kona Crab, Territorial BF
3	OFL and uncertainty from DCAC and are not reliable	**Constant F:** ABC = percentile of OFL posterior (P*)	
4	OFL and uncertainty are unknown; MSY is known but there is no fishery	**Constant F:** F_{ABC} = 0.70 * F_{MSY} (91% of MSY)	Precious Corals, Deepwater Shrimp
5	OFL and uncertainty and MSY are unknown; but catch data are available	**Catch-based:** ABC = scalar * median catch (scalar = 1.00, 0.67, 0.33 for under, fully, overexploited stocks, respectively)	

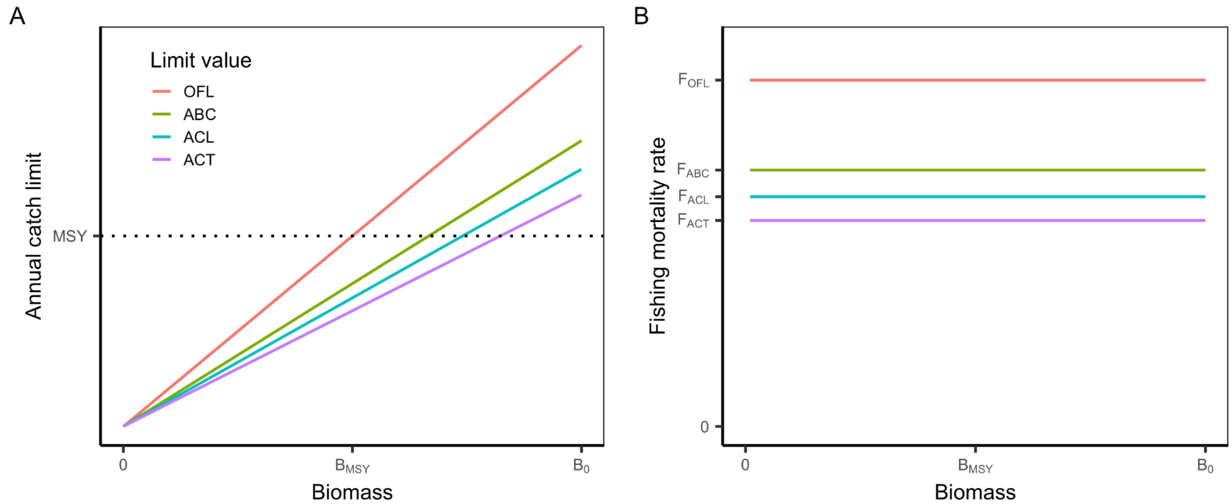

Figure A20. The harvest control rule used in all of the WPFMC FEPs in terms of **(A)** fishing mortality rate (F) and **(B)** catch.

9. Highly Migratory Species

9.1 Atlantic

The Atlantic Highly Migratory Species (HMS) FMP was implemented in 2006 and governs the management of highly migratory species. Many of the stocks and stock complexes are governed under additional international agreements and are therefore **exempt from the annual catch requirement**. Annual catch limits, if they are used, are set through a process that we do not document here. Others are managed using a **constant F harvest control rule** with precautionary buffers of various sizes.

9.2 Pacific

The Pacific Highly Migratory Species (HMS) FMP was implemented in 2003 and governs the management of highly migratory species. These species are governed under additional international agreements and are therefore **exempt from the annual catch requirement**. Annual catch limits, if they are used, are set through a process that we do not document here.