Should harvest control rules for male-only fisheries include reproductive buffers? A Bering Sea Tanner crab (*Chionoecetes bairdi*) case study

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Abstract

Highly variable recruitment and a complex harvest strategy resulted in dramatic inter-annual changes in historical catches, including prolonged closure periods, for Bering Sea Tanner crab (*Chionoecetes bairdi*). Current management regulations, linked to recent frequent closures, led to an industry-initiated cooperative effort to reevaluate the harvest control rule (HCR) that forms part of the State of Alaska harvest strategy. Management strategy evaluation (MSE) was used to assess conservation and economic trade-offs of fifteen HCR options that differed in how females were considered. Several male-only HCRs performed similarly to those that accounted for females. However, the inclusion of both sexes reflected conservation and economic objectives while acknowledging the uncertainty around reproductive dynamics. The HCR selected by the Alaska Board of Fisheries included a threshold for opening the fishery based on mature male biomass (MMB), scalars based on relative levels of mature female biomass (MFB) and MMB that determine the exploitation rate on MMB, and a maximum exploitation cap on industry-preferred sizes of legal males. This work illustrates how manager-stakeholder collaboration may enable improved fishery management. Our analysis provided managers with a tool to facilitate productive and transparent dialogue with industry, with the goal of accounting for conservation and economic objectives, given some of the underlying biological uncertainty associated with reproductive dynamics. This study demonstrates that the inclusion of reproductive buffers in HCRs for male-only fisheries may be able to better achieve conservation goals without sacrificing economic performance.

Keywords: management strategy evaluation, harvest control rule, trade-off, eastern Bering Sea, *Chionoecetes bairdi*, mature female biomass, Tanner crab, reproductive buffer

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1. Introduction

Fisheries management is continually evolving, and stakeholder input has become increasingly common (Smith et al*.,* 1999). Tools for exploring management options can be valuable in creating productive and transparent dialogue among managers and stakeholders given competing objectives. Managers often try to balance conservation and economic trade-offs associated with possible regulatory action. However, presenting the costs and benefits of management options to stakeholders can be particularly challenging especially when multiple agencies are involved in shared management.

Bering Sea and Aleutian Island (BSAI) crab stocks are co-managed by federal (National Marine Fisheries Service, NMFS) and state (Alaska Department of Fish and Game, ADF&G) agencies, where a Fishery Management Plan (FMP) developed by the North Pacific Fishery Management Council (NPFMC) establishes a cooperative management regime that defers crab management to the State of Alaska with federal oversight. The annual stock assessment, reviewed by the NPFMC Crab Plan Team and adopted by the NPFMC Scientific and Statistical Committee (SSC) establishes stock status, the Overfishing Level (OFL), and the Allowable Biological Catch (ABC; the OFL reduced to account for scientific uncertainty, Supplementary Appendix S.I). Annual maximum harvest levels (i.e., total allowable catches, TACs) are determined by ADF&G according to State commercial fishery regulations established by the Alaska Board of Fisheries (BOF) (ADF&G, 1990) such that the sum of all fishery mortality in the directed and non-directed fisheries is less than or equal to the federal ABC (NPFMC, 2011). The OFL and ABC for BSAI crab stocks are calculated, in part, based on the ratio of current mature male biomass (MMB) to reference levels.

Eastern Bering Sea (EBS) Tanner crab (*Chionoecetes bairdi*) range from Bristol Bay, Alaska, USA, to the southwest of Saint Matthew Island, with commercial concentrations in Bristol Bay and around the Pribilof Islands (Fig. 1). Tanner crab exhibit substantial temporal variation in biomass, resulting in dramatic fluctuations in the magnitude of landings (Fig. 2; Supplementary Fig. S1). While our understanding of mechanisms driving abundance trends is limited, complex interactions among physiological tolerances to fluctuating abiotic conditions and large-scale ecosystem reorganization are likely contributing factors. EBS Tanner crab are managed by ADF&G via 3-S management (size-sex-season measures: harvest of only large mature males and no fishing during spring molting and mating periods). However, the influence of male-only harvest on female reproductive output is poorly understood. Male-only harvest policies can lead to unbalanced sex ratios in crab fisheries, which has been suggested as a contributing factor to historical declines in some Gulf of Alaska crab stocks (Orensanz et al., 1998). For example, unbalanced sex ratios could result in reproductive failure (i.e., females that are unmated) and a reduction in egg production.

Tanner crab experience a terminal molt to morphometric maturity (Stevens et al., 1993; Tamone et al., 2007), and trends in historical selectivity indicate that the fishery prioritizes clean, "new shell" crab (i.e., generally crab that have terminally molted within the most recent 1-2 years; B. Daly, ADF&G pers. obs.) over darker, "old shell" crab with significant epifauna (generally considered more than two years post terminal molt). Managers of EBS Tanner crab use MMB as a proxy for production of fertilized eggs, largely due to uncertainties related to identifying the component of the mature male population that participates in mating, their safeguarding of vulnerable females during mating periods, and defining optimal sex ratios (NPFMC, 2008). This is further complicated by the fact that mature female *Chionoecetes* crabs can mate with multiple males during a single season and can store sperm via spermathecae, which can subsequently be used to fertilize embryos in the absence of males for one to two years (Paul, 1984). Additionally, uncertainty in molt timing of males may impact the likelihood of which males participate in mating, which confounds estimates of sex ratios (Donaldson et al*.*, 1981).

Given biological uncertainties, the ADF&G harvest strategy for EBS Tanner crab has evolved with advancements in understanding of life history and improvements to assessment models. 3-S management was implemented in the 1970s based on economic considerations of market value and meat yield, fishing opportunity, protection of females for reproduction, and the intent to allow at least one mating season for mature males prior to harvest (Zheng and Pengilly, 2011). In the late 1970s the Bering Sea underwent a significant regime shift, and a strong correlation exists between the increase in groundfish biomass and the subsequent reductions of commercial crab species biomass (Conners et al., 2002). The EBS Tanner crab stock was declared overfished in 2011, and a subsequent update of the harvest strategy (Table 1) was meant to address the concept of a male terminal molt, as well as temporal and spatial differences in size at maturity between two State management districts (East and West), with the aim to increase fishery yield, reduce on-deck sorting time and discard of males, and avoid size-selective genetic effects (Zheng and Pengilly, 2011). This harvest strategy, subsequently referred to as the "harvest control rule" (HCR), led to higher exploitation rates than the previous HCR as expected, but the exploitation rate index (ERI) failed to match trends in MMB (Fig. 2), and the updated HCR led to several season closures because of failure to meet threshold levels of mature female biomass (MFB). Increasingly complex revisions to the HCR meant to improve Tanner crab management and allow for more aggressive harvest at high abundance levels inadvertently widened the divide between resource conservation and the economic performance of the fishery. The HCR was updated in March 2017 following a MFB-induced fishery closure in 2016, subsequent to a two-decade peak in catches in 2015, despite a MMB that led to an ABC of 20,490 tons (Bush et al., 2016). The update involved a reduction in the exploitation rate on males larger than 127 mm carapace width (CW) when the lower 95% confidence interval of the current year MFB estimate was less than 40% of the long-term average (ADF&G, 2017; Table 1; Figs 3 and 4). The 2017 HCR for EBS Tanner was arguably the most complicated HCR for any BSAI crab stock, and the additional complexities introduced in 2017 raised questions as to whether these changes were necessary and whether basing fishery closures on MFB was appropriate (Daly, 2018). A cooperative workshop, which included stakeholders, managers, and researchers occurred in December 2017 to evaluate Tanner crab management. The consensus recommendation of the Workshop was that a broad re-examination of the Tanner crab HCR using a management strategy evaluation (MSE) should be conducted, with any changes to the HCR occurring in concert with the BOF schedule.

Management strategy evaluation is the standard way to evaluate proposed alternative management strategies and can include stakeholder and manager input (Punt et al., 2016). MSE involves simulating the managed system under various conditions to provide information for decision-making using performance metrics. Performance metrics depend on the management objectives, and often include the probability of fishery closure or crash and expected catches, along with measures of resource conservation.

Here we provide a case study in the evaluation of candidate HCRs using MSE, informing decision-makers about the potential consequences of alternative HCRs tailored to the nature of the stock while also integrating industry stakeholders at all levels of the process. This MSE does not address size, sex, or season, but is related to the inclusion or exclusion of females in a control rule for male harvest given the uncertainties in the reproductive biology for Tanner crab. This MSE provides a framework to inform decision-makers and industry stakeholders in a transparent manner that captures and communicates projected population and fishery outcomes important to both groups, specifically the trade-offs associated with including female biomass in a HCR for a fishery that is focused on male-only exploitation. This study exemplifies multi-agency cooperative management for a 3-S stock, and the challenges associated with managing a stock with high levels of uncertainty about reproductive dynamics.

2. Methods

2.1 Overview

Meetings were held between stakeholders, state and federal scientists and managers, and university affiliates to summarize the current knowledge about Tanner crab, the assessment process, and the future goals for the fishery, specifically regarding the State HCR. An "*ad hoc bairdi* committee" was established by industry participants to communicate objectives as well as desired performance metrics. MSE for EBS Tanner crab, initiated through a collaboration between managers, scientists, and industry, and executed cooperatively, was considered the best way to identify and evaluate a suite of alternative HCRs. The overarching goal of this study was to frame "*... an approach to revise the bairdi harvest strategy that improves the economic outlook to the industry and acknowledges the importance of the bairdi reproductive capacity to conserve the stock*" (Goodman, 2018). The MSE evaluated fifteen HCRs, developed in collaboration with stakeholders, to identify a HCR that was simpler than the then-current 2017 HCR and most adequately achieved the conservation and economic objectives for the stock. The HCRs, which fundamentally determine the exploitation rate on males, ranged from a function based on female biomass alone to functions that did not incorporate females at all.

There are four critical components to an MSE (see Fig. 5 for a flowchart of the MSE process): (a) establishment of an operating model or set of operating models representative of the past and likely future dynamics of the managed resource, (b) a process for generating future data, (c) specification of an estimation method (or set of estimation methods) that produces parameter estimates given data simulated using the operating model, along with the HCR options that determine management actions given the output of the assessment (in combination, the data, an estimation method and a HCR are referred to as a 'strategy'), and (d) the performance metrics used to summarize the implications of each strategy (Punt et al., 2016). The methods for this MSE were reviewed by the *ad hoc bairdi* committee, with opportunities for stakeholder input on choice and interpretation of model outputs.

The MSE was based on the current federal assessment (TCSAM02 - Stockhausen, 2018), modified for MSE purposes. Each strategy was projected 100 times for 100 years to identify trends, and evaluate risks in terms of sustainability and economic metrics. While MSE usually involves a large number of simulations, this MSE was constrained by processing time (each replicate projection took ~6 hrs.) and storage capacity (8 GB for each replicate). Scenarios were run in parallel using Amazon web services' elastic compute cloud (Narula et al., 2015).

2.2 Operating model

The operating model represents the "true" population in the MSE. For this study it was built from the federal Tanner crab assessment model (Stockhausen, 2018), modified for MSE purposes, and was a two-sex size-structured single-species model that tracks crabs by maturity state (immature and mature), and shell condition (old and new shell) (see Supplementary Appendix S.II for the values for the parameters of the operating model). The estimation method is based on maximum likelihood, but with priors/penalties for some parameters, and fits to survey data (indices of abundance by sex, maturity state, and shell condition-specific size-composition) and fishery data (catch biomass, and size compositions for the directed and bycatch fisheries). The model represents crab in 32, 5 mm size classes from 25 to 185 mm CW. It includes mortality due to multiple fisheries: landed catches and discard mortality in the directed fishery, as well as discard mortality in several fisheries that capture Tanner crab as bycatch (the snow crab *Chionoecetes opilio* fishery, the red king crab fishery in Bristol Bay, and various groundfish fisheries; Stockhausen, 2018). The model year starts on July 1st when the annual NMFS survey occurs. Recruitment consists of immature crab smaller than 55 mm CW entering the population at that time. The population before the start of the fishing season, $N^1_{y,x,m,s,z}$ (see Table 2 for a list of symbols) is calculated as

$$N^1_{y,x,m,s,z} = N_{y,x,m,s,z}e^{-M_{x,m,z}\delta^F}, \tag{1}$$

where $N_{y,x,m,s,z}$ represents the number of crab of sex x, maturity state m (immature, mature), shell condition s (old, new), and size z, at the start of year y. Each combination of sex, maturity state, shell condition, and size will be denoted as a "partition" henceforth, $M_{x,m,z}$ represents natural mortality by partition[1], and δ^F is the proportion of the year until the fishery takes place. The numbers by size are updated to account for the fishery (modeled as a pulse):

$$N^2_{y,x,m,s,z} = N^1_{y,x,m,s,z}e^{-F^T_{y,x,z}}, \tag{2}$$

where $F^T_{y,x,z}$ is the fishing mortality due to all fisheries by partition during year y:

$$F^T_{y,x,z} = \sum_f F_{f,y,x,z} = \sum_f \tilde{F}_{f,y}\left(\Omega_{f,x,z} + [1 - \Omega_{f,x,z}]\lambda_f\right)\theta_{f,x,z}, \tag{3}$$

where $\tilde{F}_{f,y}$ is the capture rate of fully-selected animals in fishery f during year y, λ_f is the handling mortality for crab discarded by fishery f (0.321 for pot fisheries and 0.80 for groundfish trawl fisheries), $\theta_{f,x,z}$ is fishery selectivity by fishery, sex, and size, and $\Omega_{f,x,z}$ is retention probability by fishery, sex, and size, quantifying the proportion of crabs retained. Retention is zero for the bycatch fisheries and a logistic function of size for the directed fishery. The selectivity functions are asymptotic for females in all fisheries, as well as in the directed, groundfish, and red king crab fisheries for males. The selectivity function for males in the snow crab fishery is assumed to be a double logistic (i.e., "dome-shaped") function. Selectivity, natural mortality, and retention probability for all projection years are set to those for the last year of the assessment, given a lack of ability to forecast how and when selectivity might change in the future.

The future fishing mortality rates for non-directed fisheries are set to the estimated averages over the five years prior to the first simulated application of the strategies (2012-2017), while the TAC determines the fishing mortality rate for the directed fishery (set using the HCR being tested), subject to the total catch not exceeding the OFL. Molting and mating are assumed to occur on February 15th ($\delta^M = 0.625$ of the year), and the updated population numbers by size are given by:

$$N^3_{y,x,m,s,z} = N^2_{y,x,m,s,z}e^{-M_{x,m,z}(\delta^M - \delta^F)} \tag{4}$$

New shell (NS) crab are then crab that either molt to maturity (subscript MAT), or molt and remain immature (subscript IMM):

$$N^4_{y,x,MAT,NS,z} = \phi_{x,z}\sum_{i \le z} X_{x,z,z'}N^3_{y,x,IMM,NS,z'} \tag{5a}$$

$$N^4_{y,x,IMM,NS,z} = (1 - \phi_{x,z})\sum_{i \le z} X_{x,z,z'}N^3_{y,x,IMM,NS,z'}, \tag{5b}$$

[1]Natural mortality (M), fishery selectivity (Θ), and retention probability (Ω) depend on year in the assessment model. The MSE operating model does not allow for temporal variation in these parameters.

where ϕ is the probability by sex and size of a newly molted crab undergoing a terminal molt to maturity, and $X_{x,z,z'}$ represents the size transition matrix; that is, the probability of a crab of sex x and size z' molting to size z. The size transition matrix is calculated as:

$$X_{x,z,z'} = \left[\sum_{z'} [z - z']^{\alpha_{x,z'}-1} * e^{\frac{z-z'}{\beta_x}}\right]^{-1} [z - z']^{\alpha_{x,z'}-1} * e^{\frac{z-z'}{\beta_x}} \tag{6a}$$

$$\alpha_{x,z'} = \frac{[\bar{z}_{x,z'} - z']}{\beta_x} \tag{6b}$$

$$\bar{z}_{x,z'} = e^{\dot{a}_x} z'^{b_x} , \tag{6c}$$

where $[\bar{z}_{x,z'} - z']$ is the mean molt increment, $\bar{z}_{x,z'}$ is the mean size after molting from pre-molt size z', and $\dot{a}_x$, $b_{t,x}$, and β_x are model parameters. The mature crab that are terminally molted from the previous year transition to old shell (OS) crab, so the total number of mature old shell crab (there are no immature old shell crab) is defined as:

$$N^4_{y,x,MAT,OS,z} = N^3_{y,x,MAT,OS,z} + N^3_{y,x,MAT,NS,z} \tag{7}$$

Finally, the population by partition is calculated for the start of year y+1 accounting for the remaining portion of natural mortality and the addition of recruitment. Recruitment is determined as the product of total annual recruitment ($\dot{R}_y$), the proportion of the total recruitment by sex ($\ddot{R}_x$ = 0.5), and the proportion of the recruitment by sex that recruits to each size-class ($\dddot{R}_z$). The total recruitment is generated by randomly selecting from the estimates of recruitment for 1974-2017 from the stock assessment, which marks the period of the US-directed fishery and excludes the period of higher recruitment prior to 1974 and the 1975 establishment of the NMFS annual EBS survey (Supplementary Fig. S1).

$$N_{y+1,x,m,s,z} = \begin{cases} N^4_{y,x,IMM,NS,z} e^{-M_{x,IMM,z}(1-\delta^M)} + R_{y,x,z} & if \;\; m = IMM, s = NS \\ N^4_{y,x,m,s,z} e^{-M_{x,m,z}(1-\delta^M)} & otherwise \end{cases} \tag{8a}$$

$$R_{y,x,z} = \dot{R}_y \ddot{R}_x \dddot{R}_z \tag{8b}$$

$$\dddot{R}_z = \frac{(z+\frac{\delta z}{2}-z_{min})^{\frac{\partial}{\varphi}-1} e^{-\frac{z+\frac{\delta z}{2}-z_{min}}{\varphi}}}{\sum_z (z+\frac{\delta z}{2}-z_{min})^{\frac{\partial}{\varphi}-1} e^{-\frac{z+\frac{\delta z}{2}-z_{min}}{\varphi}}} , \tag{8c}$$

where ∂ and φ are location and shape parameters and δz is the size bin width.

The model-predicted retained and total catches are computed using the following equations:

$$C^{Ret}_y = \sum_m \sum_s \sum_z w_{MALE,z} \frac{\Omega_{f,x,z} F_{DIR,y,MALE,z}}{F^T{}_{y,MALE,z}} (1 - e^{-F^T{}_{y,MALE,z}}) N^1_{y,MALE,m,s,z} \tag{9a}$$

$$C^T_y = \sum_x \sum_m \sum_s \sum_z w_{x,z} N^1_{y,x,m,s,z} (1 - e^{-F^T_{y,x.z}}) , \tag{9b}$$

where C^{Ret}_y is landed catch biomass for the directed fishery during year y, C^T_y is the total removal during year y (both sexes and by all fisheries), $w_{x,z}$ is the weight for crab by sex and size, $F_{DIR,y,MALE,z}$ is the sex- and size-specific capture rate for the directed fishery and by partition, $F^T_{y,x,z}$ is the fishing mortality on Tanner crab of sex x due to all fisheries by partition (Eq 3), and $N^1{}_{y,x,m,s,z}$

is the abundance by partition just prior to the fishery (Eq 2). The fishing capture rate on males in the directed fishery during year y ($F_{DIR,y,MALE}$) is selected to minimize the sum of the squared difference between the TAC for year y and model-predicted retained catch for year y $\left(TAC_y - C_y^{Ret}\right)^2$, plus a penalty that prevents the total fishing mortality from all fisheries in year y (C_y^T) from exceeding the estimated OFL for that year (OFL_y). The penalty is zero if C_y^T is less than or equal to OFL_y, and is $100\left(C_y^T - OFL_y - 0.01\right)^2$ if C_y^T is greater than OFL_y.

2.2.1 Data generation

The data generated by the operating model for the projections match those for the actual assessment: (a) landings data for the directed fishery, (b) estimates of total catch in the directed fishery, and in the (non-directed) fisheries for snow crab, red king crab, and groundfish, (c) survey estimates of abundance by sex and maturity stage, (d) the size-composition of the landings in the directed fishery, (e) the size-composition of the total catch in the (non-directed) fisheries for snow crab, red king crab, and groundfish, and (f) growth increment data (see Stockhausen [2018] for details). No future growth increment data are generated.

Table 3 summarizes the structure of each data source that is available in the future (and whether data are available by sex, maturity stage, etc.), the sampling distribution for the data (lognormal for index data by maturity and sex, multinomial for size-composition, and normal for catch), and the level of precision of the data (determined by a CV or an effective sample size). The CVs and effective sample sizes are set to those from the actual assessment.

2.3 Estimation method

The estimation model (EM) is TCSAM02. The EM computes the OFL and ABC using the candidate HCRs (see below). The estimates from the EM are used to apply the HCRs, which lead to the TACs for the directed fishery that are then used to update the population in the operating model.

2.4 Harvest Control Rules

The State of Alaska provided candidate HCRs (Table 4) following meetings with stakeholder groups, which can be divided into three categories, (1) single-sex, (2) two sex, or (3) "for reference purposes only" (i.e., not considered viable for management purposes, but helpful for placing the other candidate HCRs in some context). Most of the HCRs were a function of the ratio of the mature biomass by sex to long term (1982-2017) averages (i.e., MMB_{ave} and MFB_{ave}),

$$MMB_y = \sum_s \sum_z w_{x,z} N^3_{y,MALE,MAT,s,z} \tag{10a}$$

$$MFB_y = \sum_s \sum_z w_{x,z} N^3_{y,FEM,MAT,s,z} \ , \tag{10b}$$

along with a threshold for opening the fishery (e.g., $MMB_y > 0.25MMB_{\text{ave}}$), a maximum exploitation rate (HCR-dependent), and a function that reduces exploitation rate when biomass estimates are below the long-term average. Some of the HCRs involved a constraint based on the mature component of the exploitable legal biomass (*ELM*, defined as crab from 127-182 mm CW inclusive):

$$ELM_y = \sum_{z=127}^{182} (N^3_{y,MALE,MAT,NS,z} + 0.4N^3_{y,MALE,MAT,OS,z}) w_{MALE,z} \ , \tag{11}$$

where 0.4 is the assumed directed fishery selectivity for old shell (OS) crab. The TAC was constrained not to exceed a pre-specified proportion (e.g., 0.3 and 0.5) of the *ELM*, to ensure that sufficient 127 mm+ CW crab would be available for mating in future years.

- HCR 1 (Female only): The exploitation rate on the exploitable mature male biomass for year y ($E_{\mathrm{MMB},y}$) increases from 0.05 when MFB_y equals $0.25MFB_{\mathrm{ave}}$ to 0.2 when MFB_y is equal to or exceeds MFB_{ave} (Fig. 6A). The TAC is constrained not to exceed $0.5ELM_y$.
- HCRs 2_1, 2_2, 2_3, and 2_4 (Male only): $E_{\mathrm{MMB},y}$ increases from 0.05 when MMB_y equals $0.25MMB_{\mathrm{ave}}$ to x_i when MMB_y is equal to or exceeds MMB_{ave} where x_i represents various maximum exploitation rates (x_i=0.1, 0.15, 0.2, and 0.225) (Fig. 6B). The TAC is constrained not to exceed $0.5ELM_y$.
- HCR 3 (ABC): The TAC equals the portion of the ABC that consists of males greater than 127 mm CW.
- HCR4 (Female "Dimmer")
  - HCR 4_1*:* $E_{\mathrm{MMB},y}$ depends on both MMB/MMB_{ave} and MFB/MFB_{ave}. $E_{\mathrm{MMB},y}$ increases from 0.05 when $MMB_y = 0.25MMB_{\mathrm{ave}}$ to a maximum of 0.2 based on ratios of male and female biomass to their respective average ratios. The female ratio determines the maximum exploitation rate (the "dimmer"): a linear increase as a function of MFB/MFB_{ave} from 0.05 when $MFB \leq 0.25MFB_{ave}$ to 0.20 when $MFB \geq MFB_{ave}$, and the male ratio determines the exploitation rate within the female-determined range (Fig. 6C). The maximum exploitation rate is set when MMB and MFB both exceed their long-term averages. The TAC is constrained not to exceed $0.5ELM_y$.
  - HCR 4_2: same as HCR 4_1, except that $E_{\mathrm{MMB},y}$ increases from 0.1 when $MMB_y = 0.25MMB_{\mathrm{ave}}$ to 0.2 when $MFB \geq MFB_{ave}$ (Fig. 6D).
  - HCR 4_3: same as HCR 4_1, except that $E_{\mathrm{MMB},y}$ increases from 0.1 when $MMB_y = 0.25MMB_{\mathrm{ave}}$ to 0.225 when $MFB \geq MFB_{ave}$ (Fig. 6E).
  - HCR 4_4: same as HCR 4_3, except the TAC is constrained not to exceed $0.3ELM_y$. (Fig. 6E).
- HCR 5 (Blocked Female "Dimmer")*:* the maximum value for $E_{\mathrm{MMB},y}$ depends on blocked ranges of $MFB_y/MFB_{\mathrm{ave.}}$ The maximum $E_{\mathrm{MMB},y}$ starts at 0.05 if $MFB_y/MFB_{\mathrm{ave.}} < 0.3$ and increases to 0.1 when $0.3 < MFB_y/MFB_{\mathrm{ave.}} < 0.5$, to 0.15 when $0.5 < MFB/MFB_{\mathrm{ave.}} < 0.7$, and to 0.2 when $MFB/MFB_{\mathrm{ave.}} > 0.7$ (Fig. 6F) depending on $MMB/MMB_{\mathrm{ave.}}$ The TAC is constrained not to exceed $0.5ELM_y$.
- HCR 6 (ELM): The TAC is set based on ELM, $TAC_y = zELM_y$. There are three variants for z*:* 0.3 (HCR 6_3), 0.4 (HCR 6_4), or 0.5 (HCR 6_5) of ELM_y.
- HCR 7 (Status Quo): $E_{\mathrm{MMB},y}$ is set using a combination of the HCRs from 2011 and 2017. Specifically, the fishery is closed if the MMB is less than 25% of its long-term average, or MFB is less than 40% of its long-term average, and the TAC is calculated using the following equation if fishery is open:

$$TAC = 0.9\, C_{MSY}\, max\left(\frac{MMB}{MMB_{ave}}, 1\right), \tag{12}$$

  where C_{MSY} is the catch biomass resulting from fishing at $F_{35\%}$ on the estimated MMB at the estimated mean time of mating. Unlike the 2011 and 2017 HCRs, MFB_{ave} and MMB_{ave} are defined over 1982-2017 for consistency with the other HCRs. The TAC is half the value from Eq 12 if the fishery was closed in the previous year.

2.5 Objectives and performance metrics

The objectives were defined by the *ad hoc bairdi* committee and the ADF&G to evaluate the effects of including female biomass in the HCR and to maximize exploitation while avoiding fishery closures. Objectives and corresponding performance metrics are split into conservation and economic metrics (Table 5). It was recognized that all of the objectives could not be achieved simultaneously. For example, the risk of overexploitation would be greater if high weight was placed on stability of harvest or on high short-term catches (especially during periods of low abundance).

The conservation performance metrics focus on satisfying pre-specified federal management objectives. These metrics are expressed in terms of the probability of MMB exceeding biological reference points and include:

- Pr(MMB<MSST): the probability of MMB being below the minimum stock size threshold (MSST, the threshold for being "overfished" = $0.5B_{\mathrm{MSY}}$ with $B_{35\%}$, [$B_{35\%}$ is 35% of the expected unfished MMB], being the proxy for B_{MSY});
- Pr(C^T >OFL), the probability of total catch mortality (Eq 9b) exceeding the operating model (i.e., true) OFL, representing overfishing;
- Pr(C^T >ABC). the probability of total catch mortality exceeding the operating model (i.e., true) ABC, representing being in the "danger zone" with a risk of approaching overfishing;
- Pr(MMB<B_{MSY}), the probability of MMB<B_{MSY} ;
- MMB Median: the median (over simulations and years) MMB was evaluated as an indicator of the effect of the HCR on long-term male biomass levels; and
- MMB/B_{MSY}: the median (over simulations, n_s and years, n_y) ratio of MMB to $B_{35\%}$.

The absence of Tanner crab during closures can have a strong influence on markets. There are supply and price effects (Nichols et al., 2021), but the performance metrics were designed to find a balance between keeping Tanner crab products available more consistently and some catch volumes. The are no explicit economic metrics dependent on gross value, and implicit assumptions about fishery performance mostly relied on seasons being open given the history of frequent closures. The specific metrics considered were:

- Pr(Closure): probability that the fishery is closed;
- Mean TAC: the median (over simulations and years) of the annual TACs;
- TAC Variability: average annual variation (AAV; over years and simulations in TAC:

$$\overline{AAV} = \frac{\sum_y \sum_s \left|\frac{TAC_{y,s} - TAC_{y+1,s}}{TAC_{y,s}}\right|}{n_y n_s}, \tag{13}$$

  where $TAC_{y,s}$ is the TAC for year y and simulation s;
- Pr(TAC > 5/10/15 million lb.): the probability of the TAC exceeding specific catch limits was requested by industry stakeholders: 5, 10, and 20 million lb. (equivalent to 2,268, 4,536, and 9,072 metric tons, respectively) - stakeholders and managers wished for an average TAC that was above 5 million lb. on average, but not above 20 million lb. to avoid imposing too much pressure on the fishery over the long term (TAC allocation is presented by ADF&G in millions of lb. and this unit was used for clarity when presenting to stakeholders) ; and

- Pr(MMB<Ave): the probability that MMB is below the long-term average, MMB_{ave}, indicating that the exploitation rate is lower than the maximum possible based on male biomass given HCRs with a sloping control rule.

Probabilities were calculated as the number of the total simulated years that were either above or below the given metric after excluding the first ten years (9,000 total years of model output). The first ten years of results were omitted so that the performance metrics were based on the years once the effects of the initial conditions on the model outputs were largely eliminated.

To evaluate the combination of conservation and economic objectives, trade-offs between the highest priority economic metric for stakeholders and ADF&G, mean TACs (Table 5), were compared to conservation performance metrics identified by all cooperative bodies, Pr(MMB<B_{MSY}), Pr(C^T>ABC), and Pr(C^T >OFL). Other metrics considered were median and 90% intervals for TAC, OFL, MFB, ELM biomass, MMB catch, MMB discards, MFB discards, and recruitment trends, as well as comparisons of estimated TAC ratios to OFL and ABC (Supplementary Appendix S.III, Fig. A3.1–A3.30)[2].

3. Results

3.1 Overview

The following sections compare the fifteen HCRs in terms of their ability to satisfy the conservation and economic objectives separately and then highlight some of the trade-offs among these two sets of objectives. The initial stabilization period of ten years that was excluded from the summary statistics is exemplified in Fig. 7A, which depicts the 100-year projection period of median TAC for all HCRs.

3.2 Conservation metrics

All of the evaluated strategies had a <1% probability of the stock being in an overfished state over years and simulations (i.e., Pr(MMB<MSST); Table 6). The probability of total catch mortality exceeding the OFL (Table 6; Fig. 7B), and consequently the stock experiencing overfishing, was greater than 0.1 for HCR 7 and greater than or equal to ~0.3 for HCRs 3, 6_4, and 6_5. The probability of MMB falling below B_{MSY} was less than 0.1 for all HCRs (maximum 0.085 for HCR 6_5; minimum 0.004 for HCR 2_1) (Table 6). Median MMB was highest for HCRs 2_1 and 5 (Fig. 7C) because these strategies led to the lowest fishing mortalities on average. MFB was not sensitive to the choice of strategy (Fig. 7D), which was expected given there was little fishing pressure on females (only discard in the pot fisheries, and fishing by the groundfish fishery) and simulated recruitment was independent of MMB and MFB. MMB was greater than twice B_{MSY} for all but HCRs 3, 6_4, and 6_5, although MMB/B_{MSY} still exceeded 1.8 for these strategies.

3.3 Economic metrics

The probability of fishery closure was less than 1% for all strategies except for HCR 7, the status quo rule, for which closure probability was <2%. Most of the strategies led to mean TACs between 7,000 and 8,000 t. The mean TAC was the lowest for HCRs 2_1 and 5 (5,200 t and 5,600 t, respectively), and highest for HCRs 6_5 and 3 (10,700 t and 9,900 t, respectively). Generally, strategies led to a mean annual TAC variability (AAV, Eq 13) of ~0.26 (Table 7; Fig. 8), with HCR 2_1 having the lowest TAC variability (0.18) and HCR 7 having the greatest (0.47) (Fig. 8B-C).

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[2] Note that the median landed catch trajectory is not always equal to the TAC trajectory for HCRs that involve higher exploitation rates because this would have led to total catches in excess of the OFL (e.g., Figs. A3.12, A3.26, A3.28).

All HCRs except 4_1 led to a probability of the TAC exceeding 5 million lb. of 0.9 or greater. This probability was greater than 0.99 for HCRs 3, 6_30, 6_40, and 6_50; it was lowest for HCRs 4_1, 5, and 7. The qualitative ranking of the HCRs was similar for the probability of the TAC exceeding 10 million and 20 million lb., but the probabilities were lower (Table 7).

The final economic metric, the probability of MMB falling below the long-term average, and hence exploitation rate falling on the slope of the HCR, was greater or equal to 0.5 for HCRs 3, 6_50, and 6_4. This probability was lowest for HCRs 2_1 and 2_2 (0.205 and 0.310 respectively). The probability ranged between 0.30-0.40 for the remaining strategies.

3.4 Trade-offs

Trade-offs are shown in Fig. 9 where mean TAC is plotted against the conservation metrics defined by ADF&G; Pr(MMB<B_{MSY}) (Fig. 9A), Pr(C^{T}>OFL) (Fig. 9B), Pr(C^{T}>ABC) (Fig. 9C), and TAC variation (Fig. 9D). ADF&G and stakeholders identified mean annual TAC variability as a metric summarizing stability in a historically highly variable fishery. Generally, HCRs that fall in the upper left-hand quadrants of Figs. 9A-D achieve the ideal performance (low risk or variability and highest catches), while HCRs in the lower right quadrant perform poorly in terms of catches, variability, and risk. As expected, the results in Figs 9A-D highlight a trade-off between risk and mean TACs. The ADF&G goals include minimizing the probability of total catch mortality exceeding the OFL, and that there should be less than a 0.5 probability of total catch mortality exceeding ABC.

HCRs 3, 6_4, and 6_5 all resulted in high mean TACs, but also had a higher probability of falling below B_{MSY}, a higher probability of overfishing (exceeding OFL), and a higher probability of exceeding ABC and approaching overfishing than the other strategies. These three HCRs had mean annual TAC variability less than 0.3, which placed them in the upper left-hand quadrant, along with a cluster of other strategies. In addition, these three HCRs had average TACs greater than 20 million lb., although the TAC was not always landed because doing so would have led to the total catch (which includes discards) exceeding the OFLs (i.e., the total catch, including discards would exceed the OFL). All remaining scenarios had average TACs that were above 10 million lb. (Fig. 8).

HCRs 2_1, 2_2, and 5 had lower TACs and lower risk of exceeding conservation thresholds (Figs. 9A-C). When considering TAC variability, HCR 5 had a low average TAC and relatively high TAC variability. HCR 7, the status quo rule, had a higher average TAC and a lower conservation risk, except for TAC variability, where it exhibited the greatest interannual variability.

The remaining rules (HCRs 1, 2_3, 2_4, 4_1, 4_2, 4_3, 4_4, and 6_3) performed similarly and were clustered in the upper left-hand quadrant for all conservation performance metrics. All HCRs, except for 6_3, were based on either a single-sex, or a female "dimmer" variant.

3.5. Selection of HCRs

3.5.1 Initial strategy elimination

The ADF&G ranked the candidate HCRs based on the weighted conservation and economic metrics, and input from stakeholders. They eliminated some strategies based on the stated objectives. HCRs 3, 6_4, and 6_5 had higher risk, maximizing TACs at the expense of conservation performance which, in some simulations, led to total catches potentially exceeding the (estimated) OFL. These three HCRs were consequently removed from further consideration. The least risky HCRs in terms of conservation were 2_1, 2_2, and 5, and while they were sufficiently cautious, they performed relatively poorly in terms of the economic objectives and were also eliminated from further consideration.

The remaining nine HCRs had similar mean TACs and values for the other performance metrics, but differed in how females were treated, and the upper and lower bounds for exploitation rate of males. HCR 1, the female-only control rule, led to a mean TAC in the range of other remaining HCRs, low TAC variability, and a low risk of the stock being overfished or experiencing overfishing. However, a HCR for a male-only fishery based only on MFB was not an option highly regarded by stakeholders, especially given the recent fishery closures based on MFB relative to its long-term average. The variants of HCR 4, with different maximum male exploitation ranges (5–20%, 10–20%, and 10–22.5%) and caps on ELM all performed well in terms of the economic and conservation metrics. However, stakeholders raised concern regarding a policy with a 30% ELM cap (40% lower than the historical ELM caps), and HCRs 4_4 and 6_3 were removed from consideration. This left two male-only HCRs (2_3 and 2_4), and three female "dimmer" rules (4_1, 4_2, and 4_3) that all had similar mean TACs, risks of overfishing, and interannual TAC variability.

3.5.2 Final selection

The next step in the selection process considered whether reproductive buffers should be included in the final strategy or to move to a male-only HCR. While HCRs 2_3, 2_4, 4_1, 4_2, and 4_3 all had similar values for the performance metrics, given the limited understanding and ability to quantify reproductive dynamics, ADF&G noted that male-only control rules would be inconsistent with the BOF policy on Tanner crab management (ADF&G, 1990[3]) and HCRs 2_3, and 2_4 were removed from consideration. Initial discussions with stakeholders had reflected some support for male-only control rules. However, the decision to bring the suite of HCR4 strategies (4_1, 4_2, and 4_3, “female dimmer” rules) forward for presentation to the BOF (the decision-making body) was generally supported both by the ADF&G and by industry. In addition to the MSE results, the results of a simple retrospective analysis of what TACs would have been under each of the HCR 4 strategies (Fig. 10) was provided to the BOF. Based on that analysis, any of the presented strategies would have resulted in a substantial increase in TAC compared to the existing strategy. When considering the increase in catch magnitude given the cyclic nature of the Tanner crab population dynamics, uncertainty associated with the model, retrospective analysis, and the similarity in performance metrics the BOF adopted HCR 4_1 (Daly et al., 2020) with threshold year averages updated to 1982-2018, noting that this rule slightly favored conservation over economic metrics compared to the alternatives.

[3] Policy 2 states “Routinely monitor crab resources to provide information on abundance of females as well as prerecruit, recruit, and postrecruit males. This is necessary to detect changes in the population which may require adjustments in management to prevent irreversible damage to the reproductive potential of each stock and to better achieve the benefits listed above. Harvests must be conducted in a conservative manner in the absence of adequate information on stocks.” Policy 6 states “Establish management measures in each fishing area based on the best available information. Stock and fishery characteristics, as well as available data, vary from area to area within Alaska. Actual management practices in each area will vary accordingly.” Excluding female information does not use “the best available information” in each area (Policy 6), prevents the ability to “detect changes” in this portion of the population (Policy 2), and is inconsistent with an attempt to prevent “irreversible damage to the reproductive potential of each stock” (Policy 2). Policy 2 further directs ADF&G to implement a harvest policy in a “conservative manner in the in the absence of adequate information on stocks”; thus, failure to consider mature females implies a more conservative harvest strategy is appropriate.

4. Discussion

We demonstrated that MSE can provide a framework in which managers and stakeholders can evaluate trades-offs between conservation and economic objectives given biological and environmental uncertainty to select a HCR. MSE has been used for this purpose for several other fisheries (Punt et al., 2016). The fifteen potential State HCRs evaluated arose from extensive discussion and deliberation among Tanner crab stakeholders and managers, and the MSE performance metrics allowed for a process where individual HCR options could be eliminated for failing to satisfy conservation or economic goals. While the MSE did not provide a clear single policy choice, there was general alignment between managers and stakeholders preferences for "two sex" HCRs.

4.1 Sex-based reproduction buffers

Management of Bering Sea Tanner crab accounted for females in previous State harvest strategies, but in ways that did not achieve economic goals and to the extent that stakeholders initially called for the removal of female consideration from the HCR. The discussion over the inclusion of reproductive buffers relied on knowledge of crab reproductive dynamics, ideally quantified using a stock-recruit (S-R) relationship, which predicts recruitment given the amount of sexually mature adults and is usually defined by either a dome-shaped (Ricker, 1954) or asymptotic (Beverton and Holt, 1957) function. However, crab stocks, including EBS Tanner crab, generally do not have a well-defined S-R relationship due to difficulty defining reproductive stock size and accounting for environmental factors impacting survival at the early life-history stages. Tanner crab recruitment is highly erratic with no clear relationship to the abundance of mature adults (Zheng and Kruse, 2003). BSAI crab assessments use MMB as a proxy for reproductive capacity, although data on gravid female clutch health and fullness are recorded during the annual NMFS summer survey for all commercial crab species as alternative indices of reproductive potential (e.g., Webb et al., 2016). Conservation buffers applied in years with low MFB were designed to ensure sperm availability to females, and to optimize chances of mating for future mature female recruits. There was evidence of a declining trend in clutch fullness for Tanner crab from 1994-2000; this, however, reversed in 2001 (Orensanz et al., 2005). While there has been no indication of failed fertilization in female Tanner crab in the EBS in recent years, negative impacts of a male-only fishery on the reproductive potential of a population are not unprecedented for Alaska crab stocks. For example, in southeast Alaska, stored sperm cell counts in female Tanner crab are negatively correlated with fishery exploitation rates and high levels of sperm reserves were associated with a high ratio of large old-shell males to multiparous females (Webb and Bednarski, 2010), signaling that male-only harvest may decrease levels of stored sperm available for fertilization of subsequent clutches.

For Canadian snow crab stocks, large-male-only fisheries can impact mating dynamics via shifts in sex ratios, sperm reserves, competition among males for mating opportunities, and female mate choice (Sainte-Marie et al., 2008) suggesting the potential for instability of reproductive potential with increased fishing pressure. Fishery removals of male crab in their prime reproductive condition (i.e., large, intact, mature) promotes greater reproductive participation by individuals with less reproductive potential such as adolescent or senescing males (Sainte-Marie et al., 2008). Extended periods of low recruitment (resulting in a population comprised mostly of old shell mature males and females) and low mature abundance may result in conditions where there are insufficient males to fertilize all females (Elner and Beninger, 1995), especially in populations with patchy distributions across large spatial areas (such as the eastern Bering Sea) where encounter rates could be reduced. Small mature males have less reproductive success with multiparous females than large mature males (Elner and Beninger, 1995), thus conservation of large mature males is needed to promote the opportunity to fertilize multiparous females and incoming primiparous female recruits because the duration of low abundance and the timing of mature female recruitment is unknown. In addition, the relative reproductive importance of large males increases during periods of low mature female abundance because they are more effective at protecting vulnerable soft-shell females during mating relative to small males (Donaldson and Adams, 1989; Rondeau and Sainte-Marie, 2001). Finally, because female Tanner crab mature more quickly and at smaller sizes than males (Donaldson et al., 1981), trends in mature male biomass can lag those in females by one to two years. A high proportion of MMB to MFB during periods of low mature female relative abundance suggests that a downward trend in MMB is imminent, thus a reduced exploitation rate prior to a decline in MMB is deemed a proactive approach to dampen fishery removals during periods of approaching conservation concern.

All State BSAI crab harvest strategies include some consideration of mature females for stocks for which there is reliable data on mature female abundance given the complexity of mating dynamics for Bering Sea crab stocks and the importance of mature females for crab reproductive potential. For example, Bristol Bay red king crab is largely considered to be the most studied BSAI crab stock and employs a stair-step harvest strategy that reduces the exploitation rate on mature male abundance based on mature female abundance and biomass thresholds (Zheng et al., 1997). In Canada, snow crab is managed for exploitable biomass (males ≥95 mm CW). While this approach does not incorporate consideration of spawning stock biomass, it is believed that existing management and fishing practices (e.g., gear selectivity) sufficiently protects females from fishery mortality (Mullowney et al., 2018). Nevertheless, concerns about sperm limitation have led to recent modifications in Canadian snow crab management including the consideration of metrics (female clutch fullness, fishery CPUE, and fishery discards) aimed to protect stock reproductive capacity and minimize bycatch mortality (Mullowney et al., 2018). In contrast, Pacific West Coast Dungeness crab *Cancer magister* (also a 3S fishery) are not surveyed, have no formal stock assessment with no set quota, and generally follow punctuated early season landing cycles with an end to seasonal fishing coincident to a strong decline in CPUEs (Richardson et al., 2020). In both cases these stocks exhibit cyclic biomass trends under different management measures suggesting population-level responses to fishery mortality likely depend on the magnitude of removals and species-specific life history traits. Bering Sea Tanner crab management is meant to safeguard the stock reproductive capacity to given biological uncertainties in mating dynamics and recruitment mechanisms.

4.2 MSE limitations

HCR 7 acted as a proxy for the status-quo, as previously implemented, HCR in the MSE. While the HCR performed well in terms of economic and conservation objectives, it also had a low chance of fishery closures, which is not reflective of reality based on the known frequency of season closures under status quo. Further, the actual implementation of the status-quo strategy allowed ADF&G flexibility when setting the TAC, including accounting for qualitative and quantitative aspects of survey uncertainty. These aspects could not be captured within HCR 7 as implemented in the MSE because they are not specified precisely. The status quo rule was originally designed to allow high levels of exploitation when the stock was healthy, but with conservation buffers that would close the fishery if identified thresholds were not met. While the MSE was able to generally capture the cyclic nature of population dynamics, MFB was relatively stable (Supplementary Appendix S.III Fig. A3.29), and thus did not drop below closure thresholds, resulting in better HCR 7 performance in the MSE than in reality, and less contrast to other HCRs than anticipated.

The operating model does not account for the uncertainty about Tanner crab spawning dynamics. The MSE used the federally approved assessment model as the foundation for the operating model but given the lack of a S-R relationship, future recruitment was generated by resampling from historical estimates of recruitment (excluding the period of high recruitment prior to 1974, when recruitment estimates were informed only by retained catch). This implies that (hypothetically) there should be recruitment even in the absence of females, but the MFB does not drop to low levels for the HCRs considered in this paper (Supplementary Appendix S.III). Recruitment generation also ignored temporal autocorrelation, for which there is some evidence (Supplementary Fig. S1). Inclusion of such autocorrelation could potentially have led to higher probabilities of fishery closures and the stock being in an overfished state. Furthermore, there was no parameter uncertainty within the operating model, which reduced uncertainty in model outputs (Francis and Shotten, 1997) and no implementation error was considered. Only one operating model was used in this study, as the federally approved stock assessment (Stockhausen, 2018) was preferred by ADF&G.

4.3 Cooperative engagement and conclusions

MSEs are based on understanding uncertainties and modeling limitations and are an effective way to compare HCRs in a simulated setting. Cooperative efforts involving managers, scientists, and industry representatives ensure that MSE metrics important to all parties are considered during the decision-making process and improves manager and harvester relationships and trust. This is especially critical when faced with controversial and potentially polarizing concepts such as whether to include females in the HCR for a male-only fishery that minimally directly impacts females.

This MSE was proposed following a challenging time between the crab industry and managers, and managers decided that the HCR for Tanner crab needed to be re-evaluated. The *bairdi* workshop provided a "reset" for the relationship between the industry and State managers, and a platform where industry concerns and ideas could be directly included in an evaluation of HCRs to better address both industry and State management objectives. The MSE aimed to explore how HCRs with, and without, female factors would perform, and decision-makers were faced with choosing between a male-only HCR, and a two-sex HCR. There was hesitancy by industry representatives to any inclusion of females, as this was seen as a hurdle to fishing and not as a conservation metric, especially given the performance of previous HCRs. The use of females to determine the maximum exploitation rate, as opposed to an on/off switch, was eventually more acceptable to industry. Moreover, the similar performance of the male-only versus the two-sex HCRs using females to scale maximum exploitation instead of closing the fishery helped with acceptance of reproductive conservation buffers as part of the selected HCR.

Based on the workshop, MSE development and progress, comprehensive discussions, and newly built trust, this cooperative effort was vital in addressing previous industry frustrations. It established new relationships and ultimately made possible the adoption of a HCR inclusive of both sexes in a less restrictive manner with a more unified body of supporters. This process represented a way to select a HCR that would improve fishery stability and satisfy stakeholders, while accounting for conservation metrics critical to State of Alaska management.

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Table 1: Historical harvest control rules as part of ADF&G TAC setting, and changes over the last two harvest strategy updates.

Metric	1999	2011	2017
Female Threshold	9,525 metric tons (females ≥ 79 mm CW, east of 173° W)	0.40 of 1975-2010 average (females ≥ 80- or 85-mm CW, east of 173° W)	0.40 of 1982-2016 average ("actual" maturity, entire EBS surveyed area)
East/West line	168° W	166° W	166° W
Male Threshold	0.25 MMB_{ave}	0.25 MMB_{ave}	0.25 MMB_{ave} if error band above threshold; 1.0 MMB_{ave} if threshold within error band
Male exploitation	Mature males (1.0 newshell + 0.15 oldshell): Stairstep: 0.0 when females < 9,525 metric tons, 0.10 when females ≥ 9,525 metric tons and <20,411 metric tons, 0.20 when females are ≥ 20,411 metric tons	(F_{MSY} x exploited males) x (MMB/MMB_{ave} x 0.9)	(F_{MSY} x exploited males) x(MMB/MMB_{ave} x 0.9) if error band above threshold; (F_{MSY} x exploited males) x (MMB/MMB_{ave} -1) if threshold is within error band
Definition of "exploited legal males"	1.0 newshell + 0.32 oldshell legal males	East: males ≥ 139 mm CW x fishery selectivity; West: males ≥ 127 mm CW x fishery selectivity	East: males ≥ 127 mm CW x fishery selectivity; West: males ≥ 127 mm CW x fishery selectivity
Legal harvest cap	0.5 of exploited legal males	0.5 of exploited legal males	0.5 of exploited legal males
Female 1/2 TAC penalty	Reduce TACs to half of computed value if previous year failed to meet thresholds	Reduce TACs to half of computed value if previous year failed to meet thresholds	Reduce TACs to half of computed value if previous year error band was below threshold

Table 2: Acronyms, parameters, and variables. The subscripts include maximum sustainable yield (MSY), fishery (*f*), year (*y*), sex (*x*), maturity (*m*), size (*z*), and pre-molt size (*z'*). For simplicity, the "*y*" subscripts are omitted from quantities that are time-varying in the past, but time-invariant in the future.

Acronyms	**Meaning**	**Subscript(s)**
AAR	Mean Annual TAC variability	
ABC	Allowable Biological Catch	
ADF&G	Alaska Department of Fish and Game	
B_{MSY}	MMB corresponding to maximum sustainable yield, approximated by 35% of unfished MMB	
BSAI	Bering Sea Aleutian Islands	
C	Catch Biomass	MSY
C^{Ret}	Catch Retained	y
C^{T}	Catch Total	y
CW	Carapace Width	
EBS	Eastern Bering Sea	
ELM	Exploitable Legal Males	z
FMP	Fishery Management Plan	
F_{MSY}	Fishing Mortality corresponding to maximum sustainable yield, approximated by the *F* that reduces spawning biomass per-recruit of 65%	
HCR	Harvest Control Rule	
MFB	Mature Female Biomass	
$\mathrm{MFB}_{\mathrm{ave}}$	Long Term Average Mature Female Biomass	
MMB	Mature Male Biomass	y
$\mathrm{MMB}_{\mathrm{ave}}$	Long Term Average Mature Male Biomass	
MSE	Management Strategy Evaluation	
NPFMC	North Pacific Fishery Management Council	
NMFS	National Marine Fisheries Service	
OFL	Overfishing level	
TAC	Total Allowable Catch	y
Variables		
E	Exploitation rate on mature male biomass	y
F	Fishing Mortality	f, y,x,z
$\tilde{F}$	Fully-selected fishing mortality	f,y
F^{T}	Total fishing mortality due to all fisheries	y,x,z
M	Natural Mortality	x,m,z
N^{x}	Population, where superscript X is the calculation phase	y,x,m,s,z
$\acute{R}$	Recruitment	y,x,z
Parameters		
$\dot{\alpha}$, b, and β	Arithmetic-scale parameters	x
α	Mean molt increment scaled by β	x,z'
∂ and φ	Natural log-scale location and shape parameters	
δ^F	Fraction of the year when the fishery occurs	
δ^M	Fraction of the year when molting and mating occurs	
δz	Size bin width	z
Λ	Handling mortality	f
Θ	Fishery capture rate	f,x,z
Ω	Retention function quantifying the proportion of crabs retained	f,x,z
Φ	Probability of a newly molted crab undergoing terminal molt to maturity	x,z
w	Weight	x,z
χ	Size transition matrix	x, z, z'
$\bar{z}$	Mean size after molting	x,z'

Table 3: Summary of how the projected data are generated.

Data type	Partition	Sampling distribution	Abundance CV	Effective sample size
Survey index	Immature Males	Lognormal	0.1627	--
	Mature Males	Lognormal	0.0911	--
	Immature Females	Lognormal	0.1690	--
	Mature Females	Lognormal	0.2006	--
Survey size-composition	Sex, maturity, shell condition, size	Multinomial	--	100
Directed retained catch	Males	Normal	0.05	--
Directed retained size-composition	Males, shell condition	Multinomial	--	100
Directed total catch	Males	Normal	0.2	--
	Females	Normal	0.2	--
Directed total size-composition	Sex, maturity, (shell condition for males)	Multinomial	--	100
Snow crab total catch	Sex	Normal	0.2	--
Snow crab size-composition	Sex (shell condition for males)	Multinomial	--	100
Red king crab total catch	Sex	Normal	0.2	--
Red king crab size-composition	Sex (shell condition for males)	Multinomial	--	100
Groundfish total catch	None	Normal	0.2	--
Groundfish size-composition	Sex	Multinomial	--	100

Table 4: HCRs tested, with a description of the rule, whether the exploitation rate on mature males is pre-specified or depends on biomass ratios ("ramp"), the lowest non-zero exploitation rate for "ramp" exploitation, the maximum exploitation rate, and any caps on the TAC. All HCRs close the fishery if mature male biomass is less than 0.25MMB_{ave}, except HCR1, which closes the fishery if mature female biomass is less than 0.25MFB_{ave}.

Policy	Description	Fixed vs. "Ramp" exploitation rate	Lowest Non-zero exploitation rate	Maximum exploitation Rate	Max TAC
HCR1	Female Only	Ramp	0.05	0.20	0.5 ELM
HCR2_1	Male Only	Ramp	0.05	0.1	0.5 ELM
HCR_2	Male only	Ramp	0.05	0.15	0.5 ELM
HCR2_3	Male only	Ramp	0.05	0.2	0.5 ELM
HCR2_4	Male only	Ramp	0.05	0.225	0.5 ELM
HCR3	TAC=$ABC_{127mm+males}$	Ramp (F_{MSY})	NA	NA	NA
HCR4_1	Female "Dimmer"	Ramp	0.05	0.22	0.5 ELM
HCR4_2	Female "Dimmer"	Ramp	0.1	0.2	0.5 ELM
HCR4_3	Female "Dimmer"	Ramp	0.1	0.225	0.5 ELM
HCR4_4	Female "Dimmer"	Ramp	0.1	0.225	0.3 ELM
HCR5	Female Blocks	Stairstep Fixed	0.05	0.2	0.5 ELM
HCR6_3	ELM 30%	Fixed	NA	NA	0.3 ELM
HCR6_4	ELM 40%	Fixed	NA	NA	0.4 ELM
HCR6_5	ELM50%	Fixed	NA	NA	0.5 ELM
HCR7	Status Quo	Ramp (F_{MSY})	NA	NA	NA

Table 5: Objectives, performance metrics, definitions, and the stakeholder groups most interested in the metrics (S: state of Alaska (ADF&G); F: the federal government (NMFS); I: the crab industry).

Objective	Performance metric	Meaning	Cooperative body interest
Conservation	Pr(MMB<MSST)	Probability of the stock being in an overfished state	S,F,I
Conservation	Pr(C^T >OFL)	Probability of overfishing occurring	S,F,I
Conservation	Pr(C^T >ABC)	Probability of getting close to overfishing	S,F,I
Conservation	Pr(MMB<B_{MSY})	Probability of MMB falling below B_{MSY}	S,F,I
Conservation	Median MMB	Median value over all years and simulations in 1000's of tons of MMB	S, I
Conservation	MMB/B_{MSY}	Ratio MMB to B_{MSY}	S, F
Economic	Pr(Closure)	Probability of fishery closure	S,F,I
Economic	Mean TAC	Average TAC	S, I
Economic	TAC Variation	Interannual variability in TACs	S, I
Economic	Pr(TAC>5m lbs)	Probability of TAC greater than 5 m lbs	I
Economic	Pr(TAC>10m lbs)	Probability of TAC greater than 10 m lbs	I
Economic	Pr(TAC>20m lbs)	Probability of TAC greater than 20 m lbs	I
Economic	Pr(MMB<Ave)	Probability of exploitation rate less than the maximum	S, I

Table 6: The values for the conservation performance metrics. The shading represents relative performance, with darker colors indicating poorer performance. The + indicates column highs and the – column lows (omitted for columns with multiple zero values).

	Overfished Pr(MMB<MSST)		Overfishing Pr(C^T >OFL)		Danger Zone Pr(C^T >ABC)		Below B_{MSY} Pr(MMB<B_{MSY})		MMB Median 1000s Tons		MMB/B_{MSY}	
HCR1	0.000		0.048		0.145		0.016		65.117		2.127	
HCR2_1	0.000		0.000	-	0.000	-	0.004	-	75.158		2.455	
HCR2_2	0.000		0.002		0.027		0.007		69.905		2.283	
HCR2_3	0.000		0.044		0.134		0.014		66.134		2.157	
HCR2_4	0.000		0.074		0.182		0.017		64.250		2.130	
HCR3	0.000		0.372		0.718	+	0.056		53.725	-	1.808	-
HCR4_1	0.000		0.035		0.109		0.007		67.144		2.203	
HCR4_2	0.000		0.042		0.130		0.017		65.533		2.150	
HCR4_3	0.000		0.076		0.179		0.019		64.022		2.123	
HCR4_4	0.000		0.035		0.123		0.017		66.479		2.168	
HCR5	0.000		0.031		0.080		0.007		75.200	+	2.531	+
HCR6_3	0.000		0.065		0.192		0.035		64.535		2.140	
HCR6_4	0.000		0.299		0.514		0.062		58.370		1.955	
HCR6_5	0.000	+	0.467	+	0.688		0.085	+	54.330		1.814	
HCR7	0.000		0.140		0.235		0.016		63.212		2.133	

Table 7: The values of the economic metrics. The shading represents relative performance, with darker colors indicating poorer performance within each column. The + indicates column highs and the – column lows (omitted for columns with multiple zero values).

HCR	Pr(Closure)	Mean TAC	TAC Variability	Pr(TAC > 5 m lbs)	Pr(TAC > 10 m lbs)	Pr(TAC > 20 m lbs)	Pr(MMB<Ave)
HCR1	0.000	7.661	0.220	0.954	0.711	0.311	0.357
HCR2_1	0.000	5.610	0.182 -	0.926	0.574	0.110	0.225 -
HCR2_2	0.000	6.746	0.230	0.939	0.641	0.232	0.287
HCR2_3	0.000	7.578	0.280	0.945	0.676	0.303	0.337
HCR2_4	0.000	7.785	0.298	0.945	0.684	0.306	0.364
HCR3	0.000	9.917	0.241	0.994	0.873	0.465	0.551 +
HCR4_1	0.000	7.203	0.287	0.894 -	0.603	0.300	0.304
HCR4_2	0.000	7.495	0.249	0.973	0.681	0.293	0.347
HCR4_3	0.000	7.844	0.265	0.971	0.686	0.310	0.369
HCR4_4	0.000	7.533	0.267	0.975	0.705	0.275	0.342
HCR5	0.000	5.175 -	0.383	0.916	0.482 -	0.089 -	0.304
HCR6_3	0.000	7.671	0.245	0.992	0.773	0.260	0.379
HCR6_4	0.000	9.069	0.270	0.996	0.856	0.365	0.490
HCR6_5	0.000	10.714 +	0.280	0.999 +	0.925 +	0.486 +	0.551
HCR7	0.015 +	8.147	0.474 +	0.921	0.633	0.278	0.385

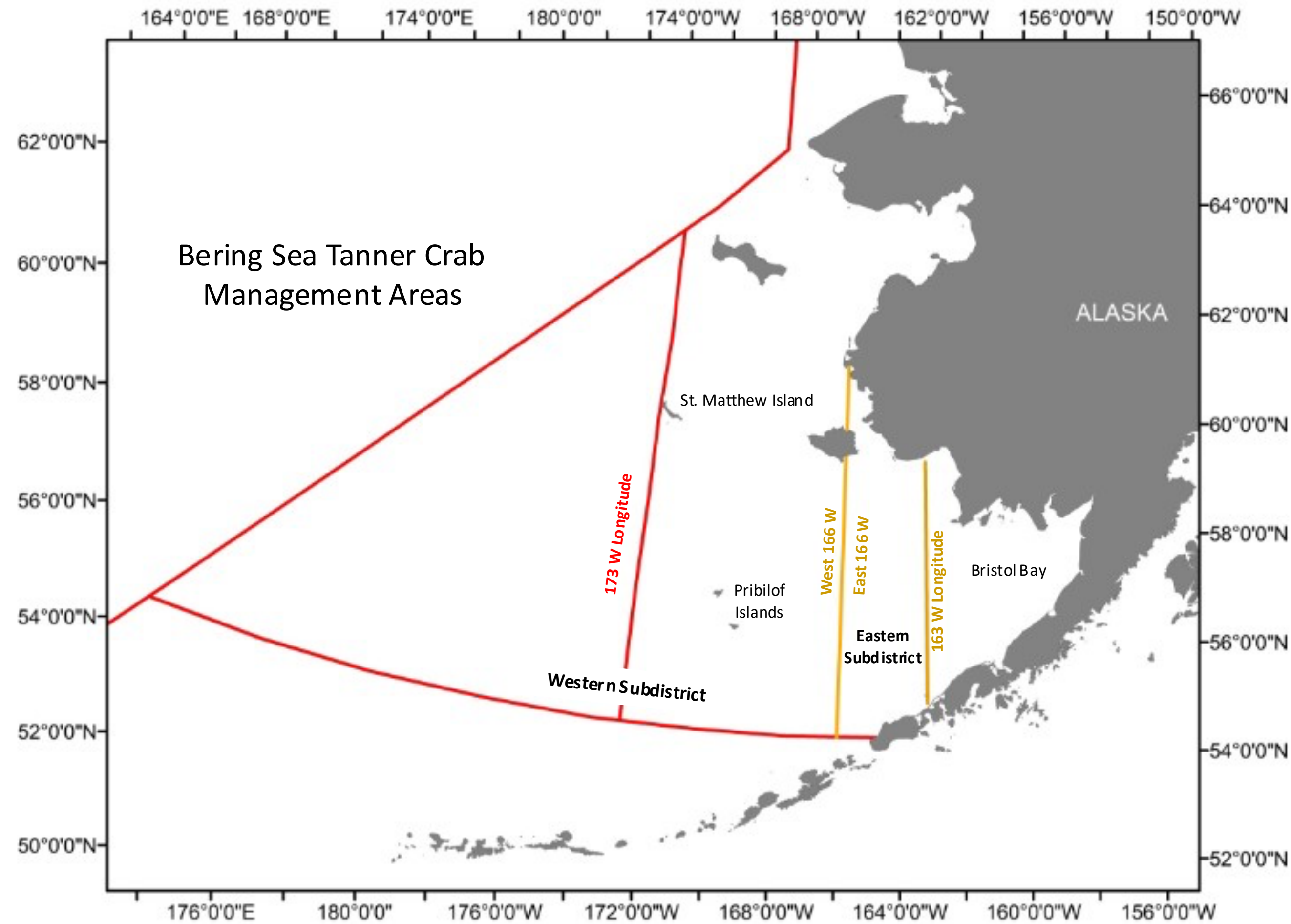

Figure 1: Bering Sea ADF&G district boundaries, where the western Bering Sea Tanner crab district is west of 166° W and the eastern district is east of 166° W to 163° W.

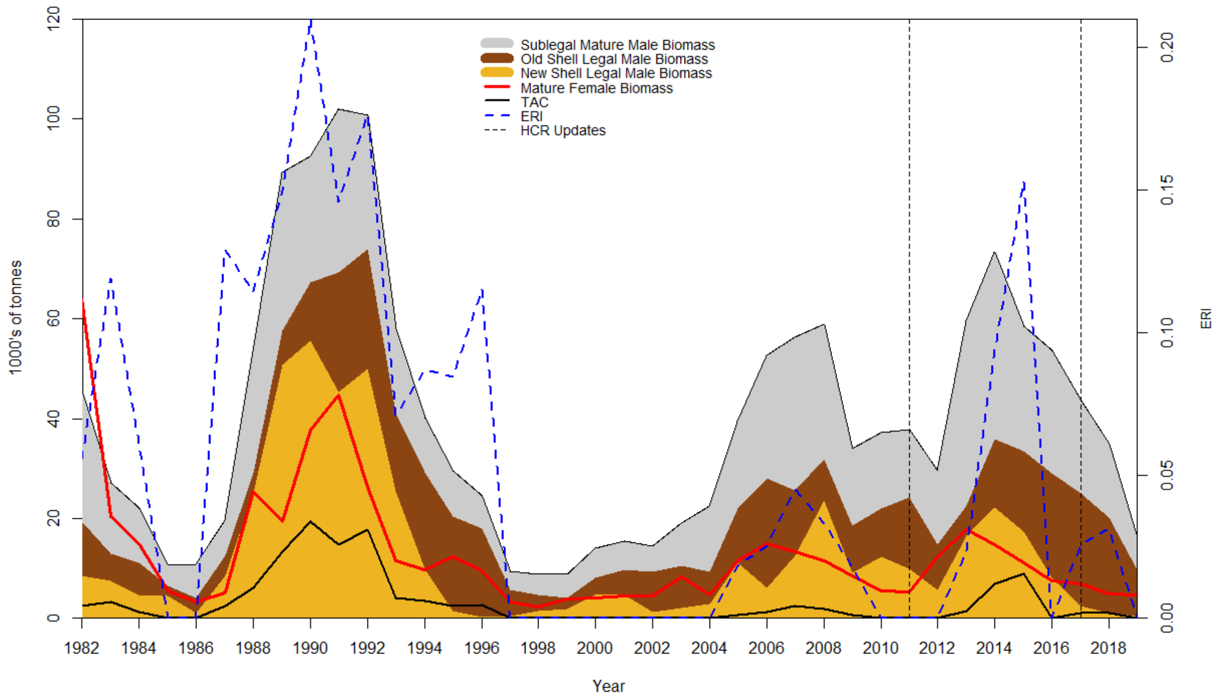

Figure 2: Tanner crab biomass by category based on surveys: sublegal MMB (CW less than 127 mm; grey), old shell legal MMB (brown), new shell legal MMB (gold), MFB (red line), TAC (black line), and the exploitation rate index (ERI; blue line), 1982 to 2019. Survey methods prior to 1982 varied in spatial coverage and gear configuration (Stauffer, 2004). State harvest strategy updates occurred in 2011 and 2017 and are indicated by the dashed vertical lines.

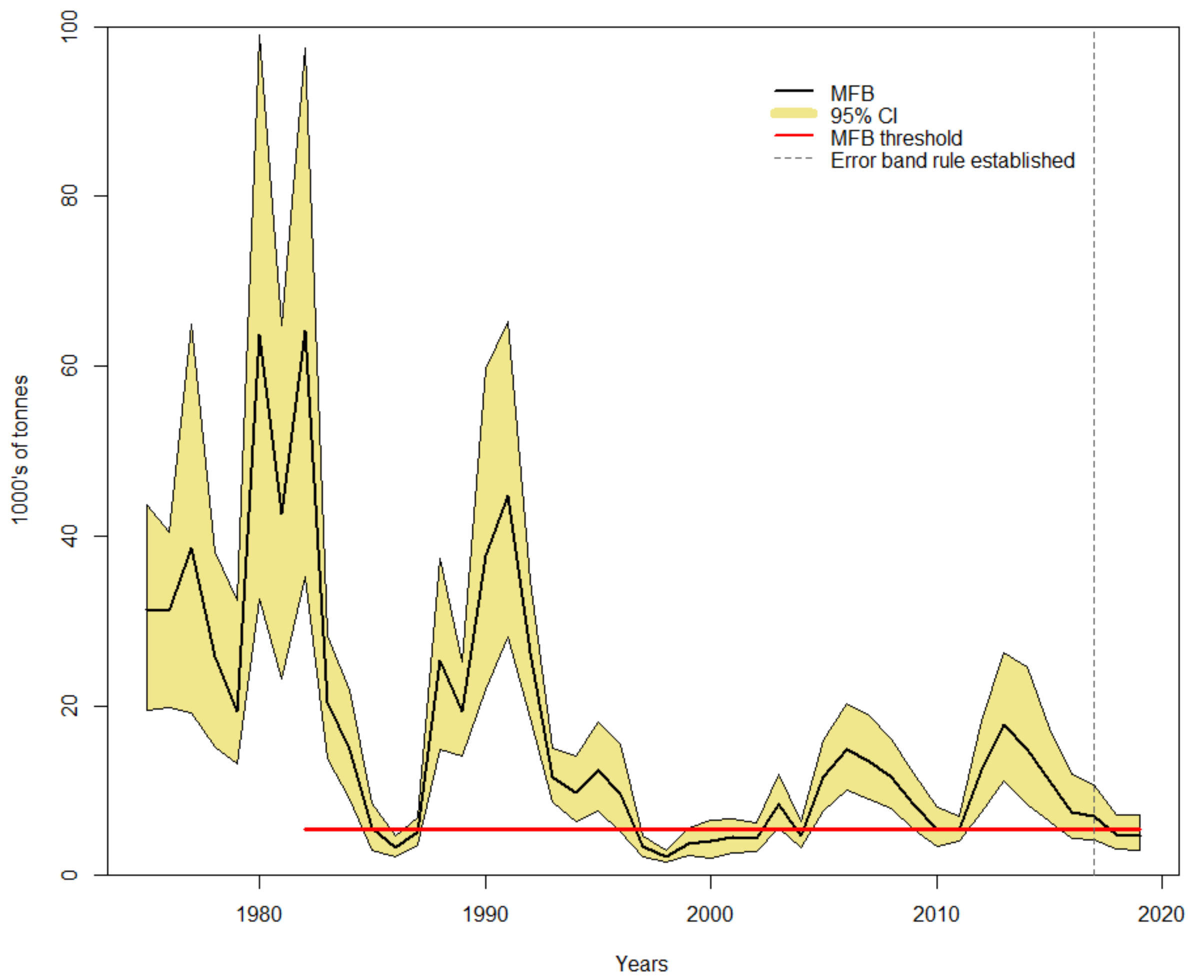

Figure 3: Error band rule, established in 2017 (dashed line) where MFB from NMFS survey estimates and 95% confidence intervals (bootstrapped with 5,000 replicates) are depicted with the MFB threshold. The fishery is closed if the estimate of MFB falls below the threshold (e.g., 1997–1999), there is reduced harvest if the 95% confidence interval encompasses the threshold (e.g., 2017–2019), and there is no penalty on male harvest from females if the upper 95% confidence interval is greater than the threshold.

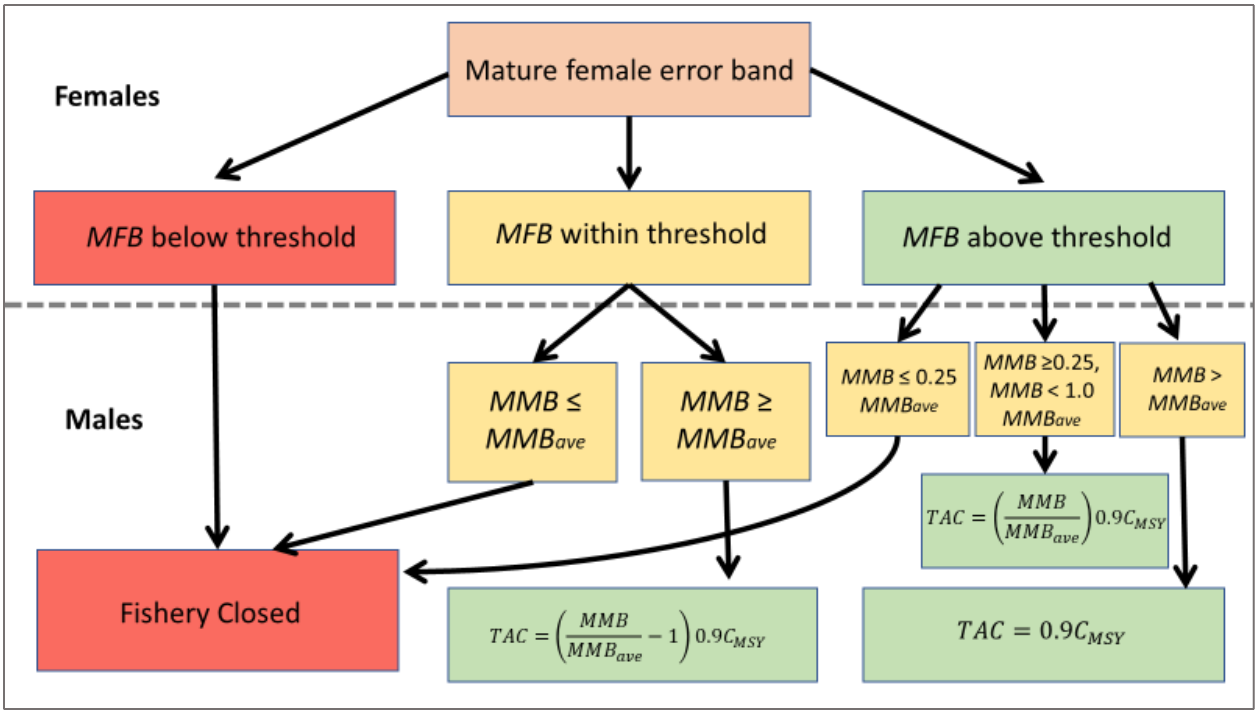

Figure 4: Flow chart showing how the female error band rule (Fig. 3) scales harvest. The error band is determined by bootstrapping MFB survey data to establish a 95% confidence interval. This error band is then compared to the female threshold of $0.4MFB_{ave}$. The fishery is closed if the error band is fully below the threshold. Males are evaluated to determine which equation sets the TAC if the error band encompasses the threshold or is above the threshold.

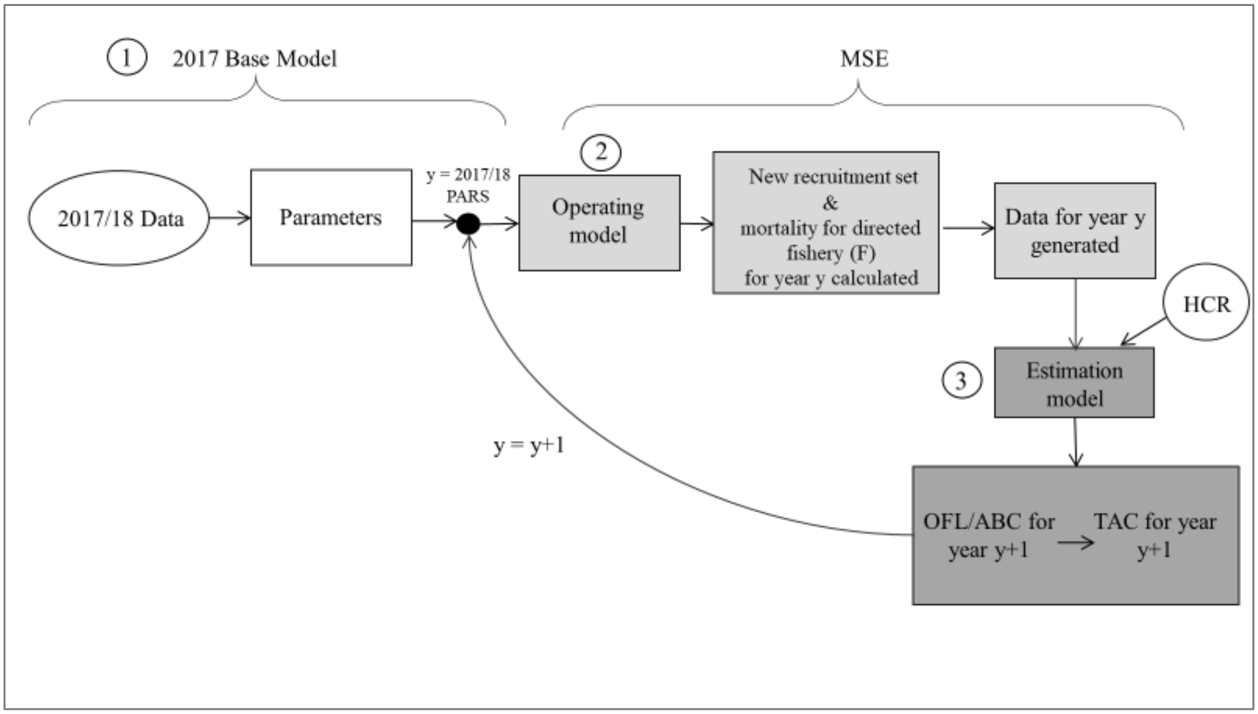

Figure 5: Flow chart of the MSE process, where the parameters of the operating model are set based on the 2017 stock assessment (1). The operating model (2) generates recruitment, calculates the fishing mortality rate for the year and generates survey data, which are provided to the estimation method (3). The HCR is used to compute the TAC for the directed fishery, which is then used to update the population dynamics in the operating model. This cycle is repeated for 100 years.

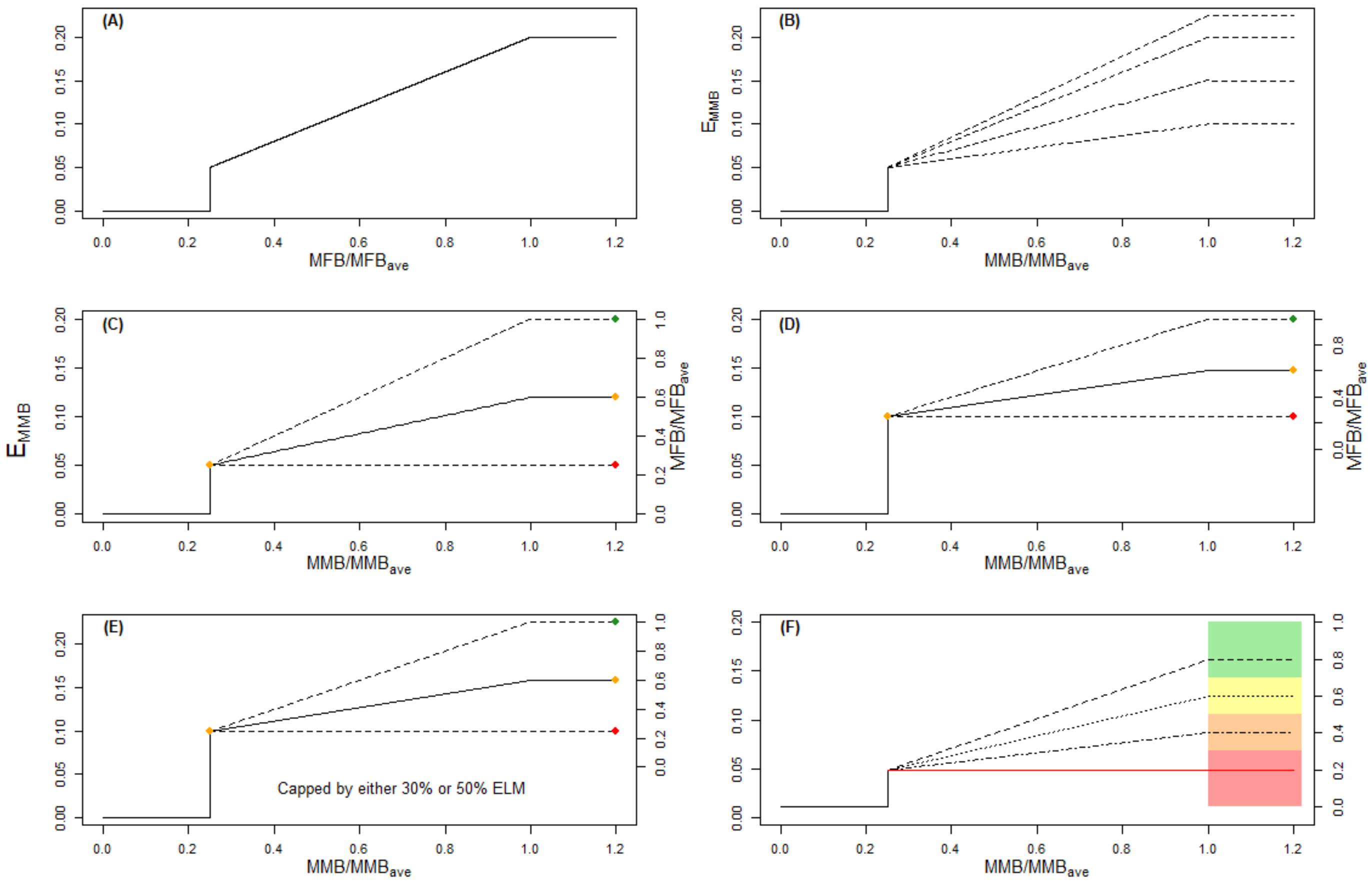

Figure 6. Ten of the HCR options—the female only HCR1 (A), the male only HCR2_1, HCR2_2, HCR2_3, and HCR2_4 (B), the female dimmer HCR4_1 (C), HCR4_2 (D), HCR4_3 and HCR4_4 (E) and the female blocked dimmer HCR5 (F).

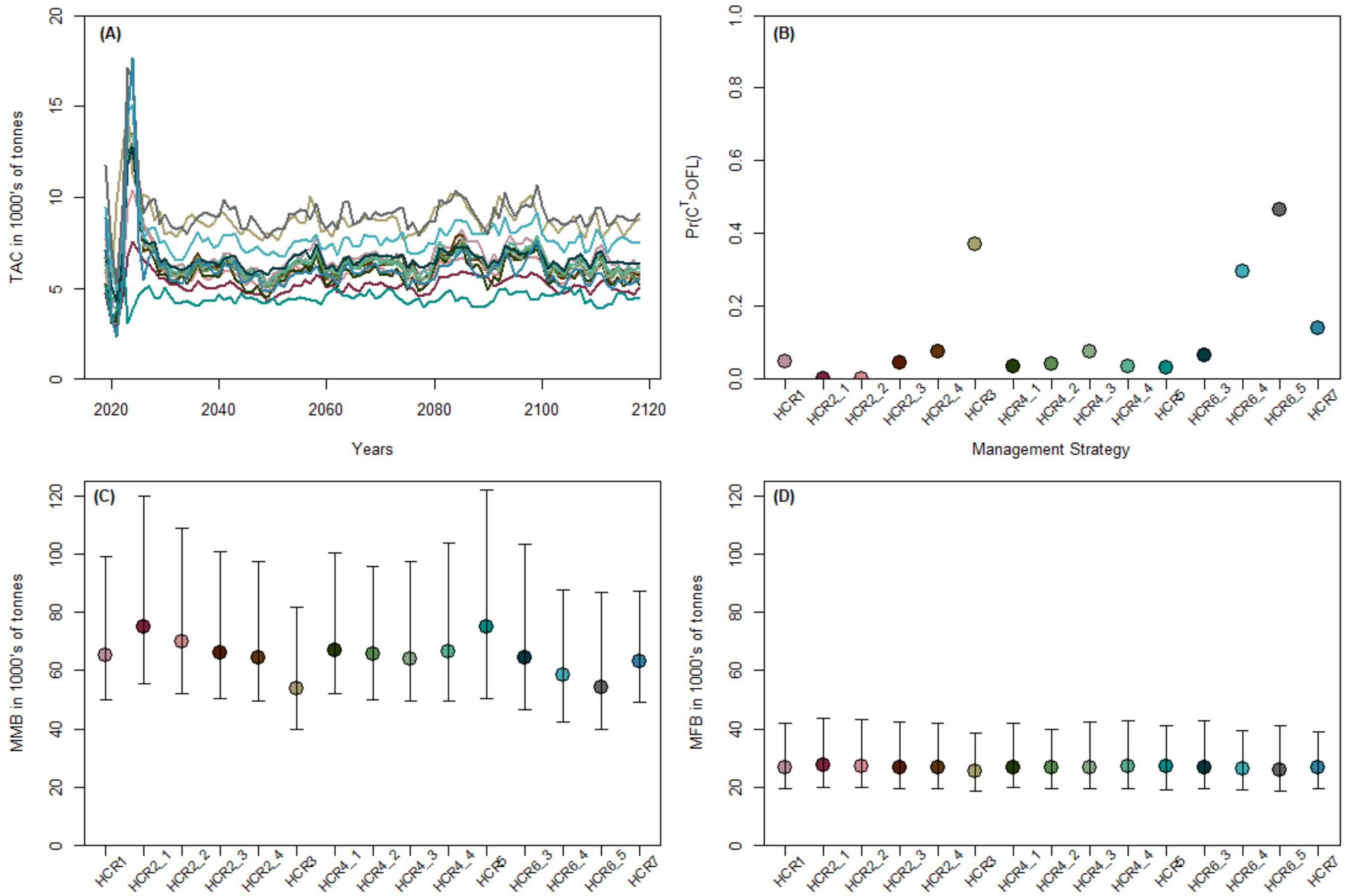

Figure 7: Median TAC over time by HCR (A). HCRs are color coded to match panels B-D. Note the initialization period that occurs within the first 10 years of projection. Other panels show the probability of total catch mortality exceeding the OFL (B), MMB (median and 90% intervals) (C), and MFB (median and 90% intervals) (D).

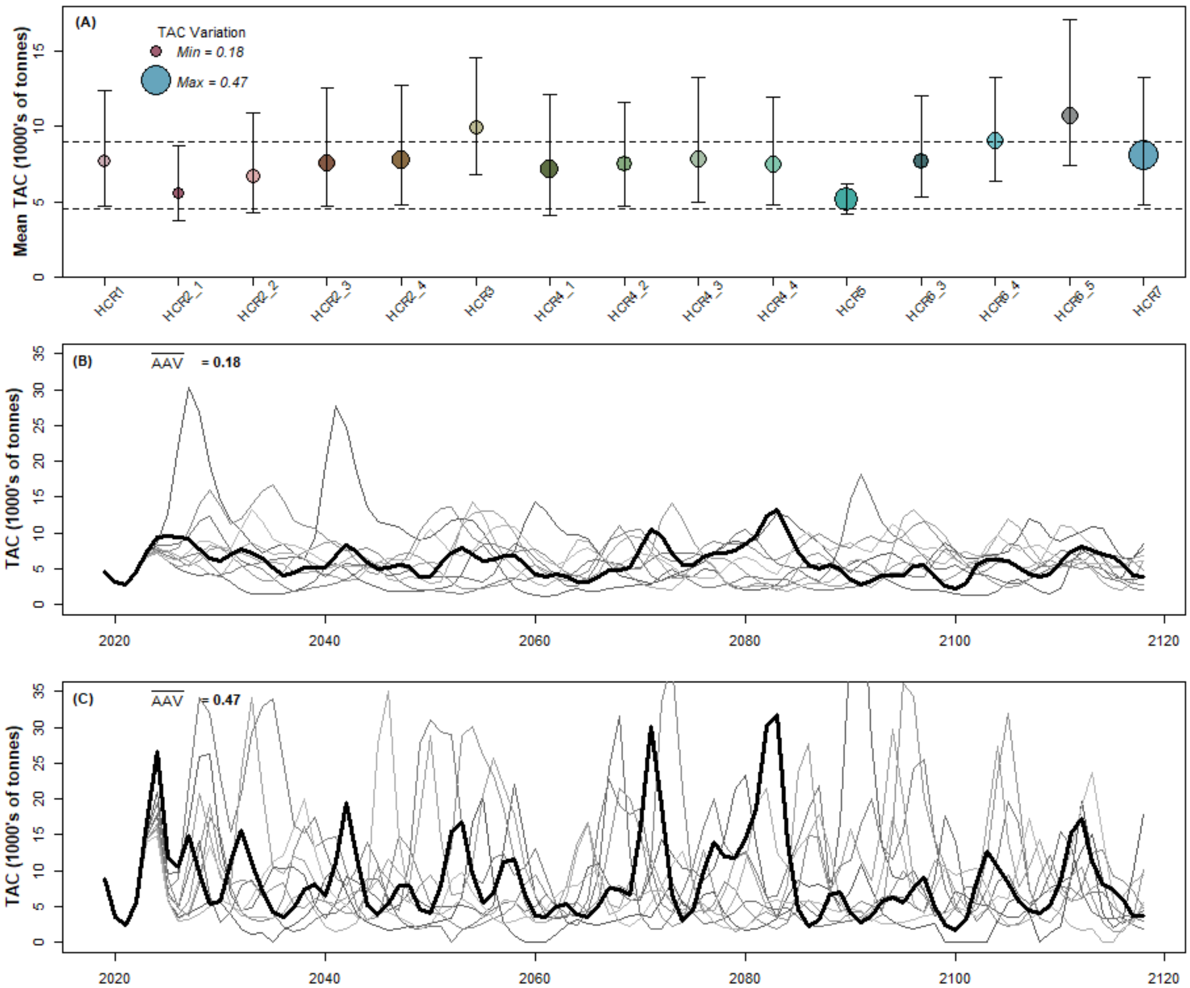

Figure 8: Panel A shows the mean TAC (and 90% intervals) for the 15 HCR options where the bubble size is the extent of TAC variation. The dotted lines represent 10 and 20 million lbs., values that were desirable to industry stakeholders. Panels B and C show the difference in annual average TAC variability (AAV) between the HCR with the lowest TAC variability (HCR2_1; B), and that with highest TAC variability (HCR7; C). Each plot has 10 example trajectories of TAC, with one simulation bolded for clarity.

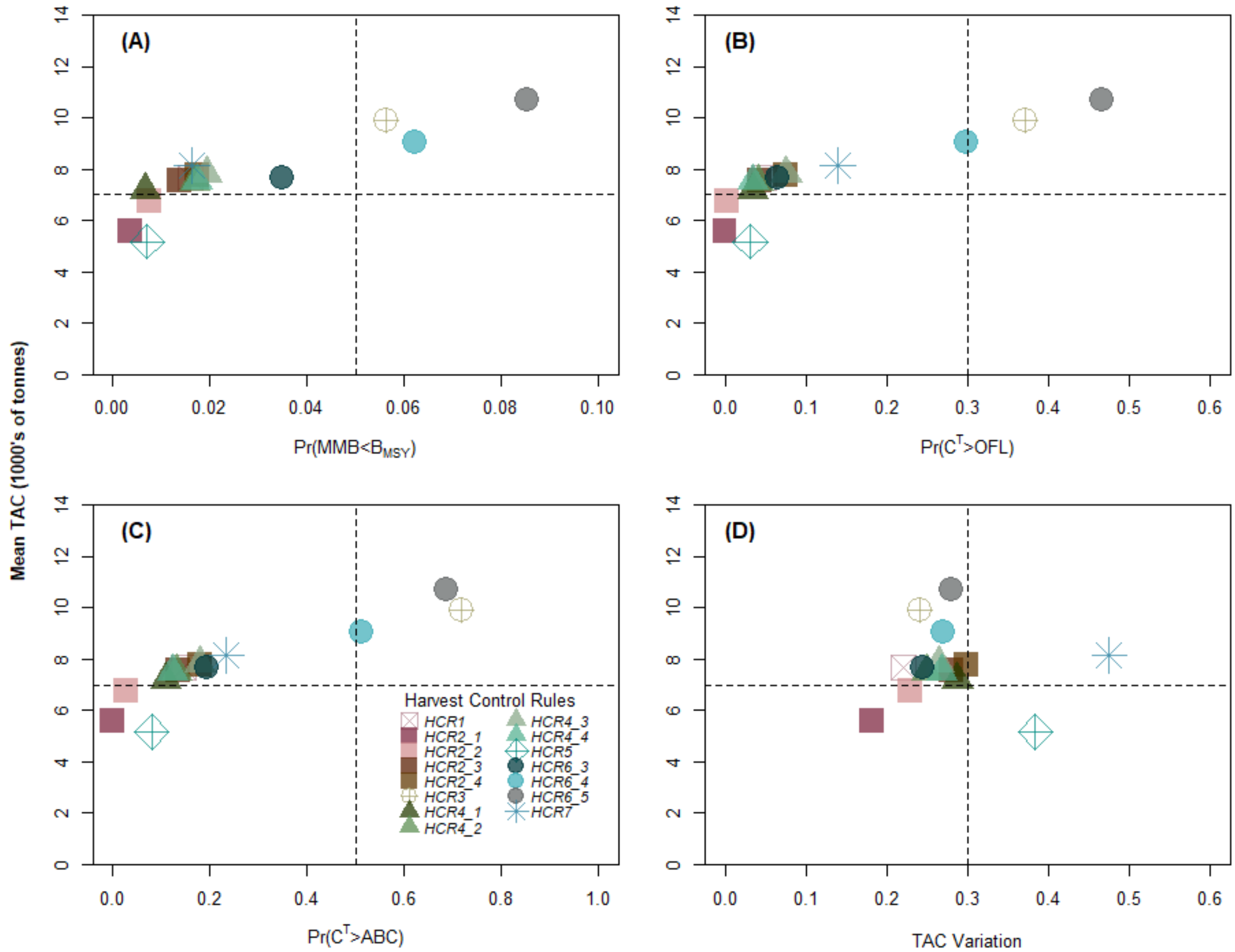

Figure 9: Panels A-D show mean TAC plotted against the probability of MMB falling below B_{MSY} (A), probability of overfishing (B), the probability of approaching overfishing (C), and TAC variation (D).

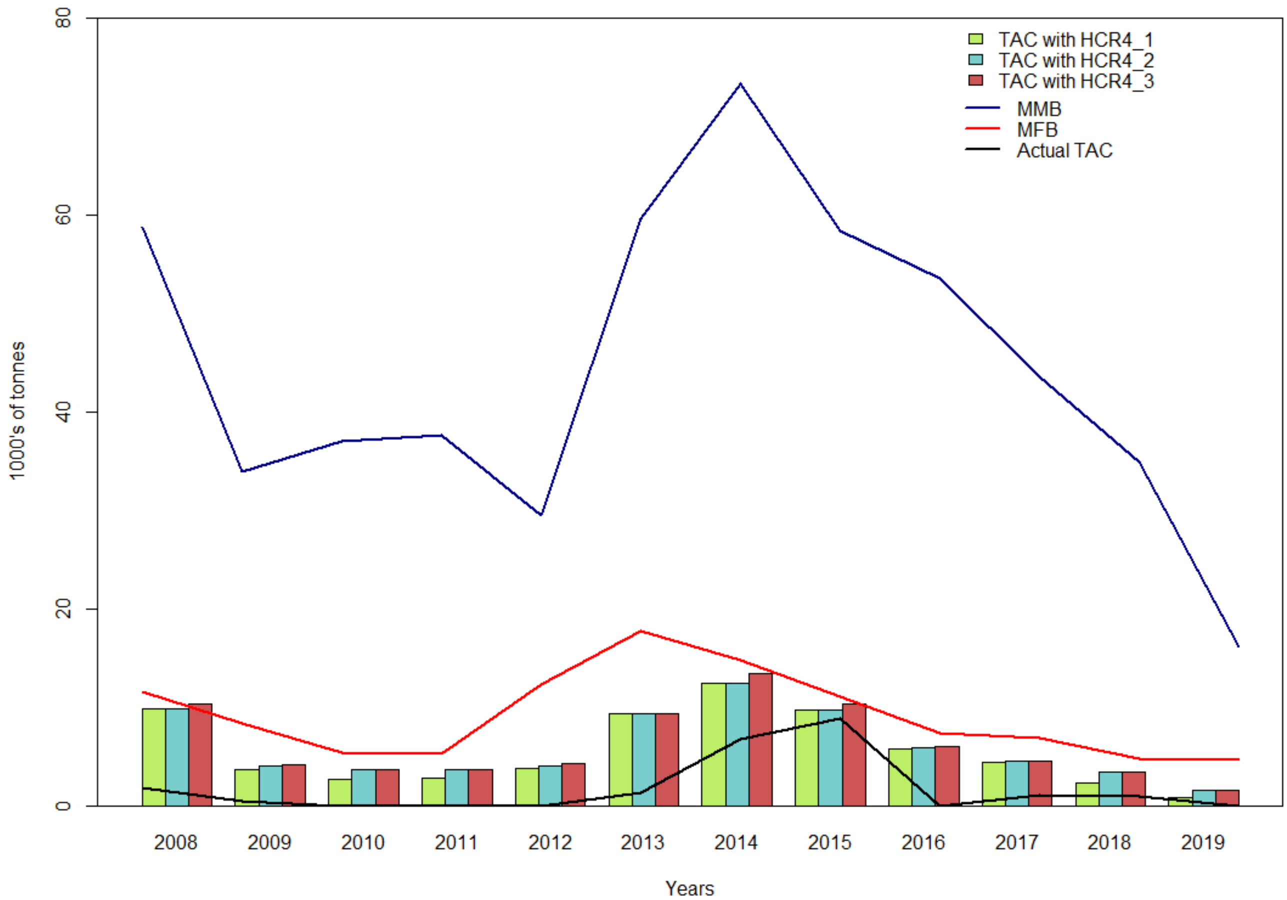

Figure 10: Historical MMB, MFB, and TAC values. The bars represent what the TACs would have been given the biomass estimates for the year concerned for HCR4_1, HCR4_2, and HCR4_3. Note that there is no feedback between the TAC implied by the HCR for one year and the biomass for the next year in this plot.

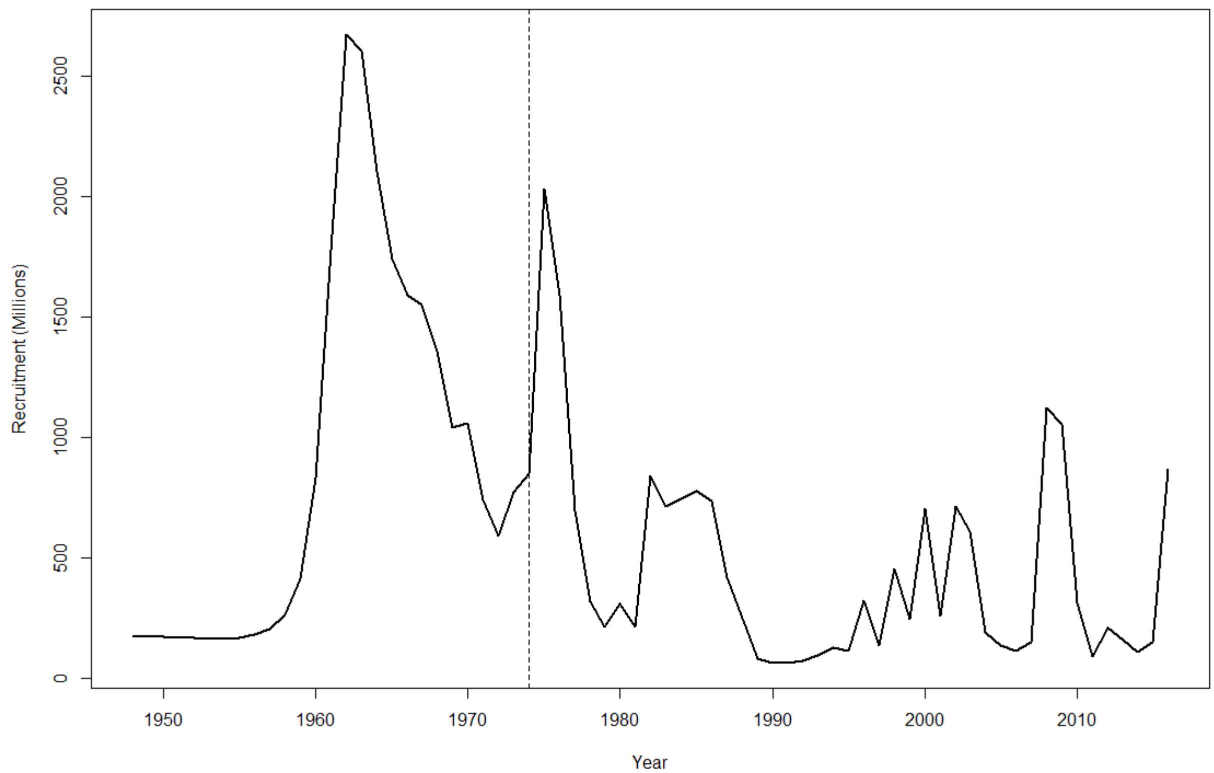

Figure S1. Time-trajectory of estimated recruitment of Tanner crab from TCSAM02 version 17AMu (Stockhausen, 2018).

Appendix S.I: Overfishing Limit (OFL) and Allowable Biological Catch (ABC)

When an assessment model is being developed withing the NPFMC structure, species are assigned to a tier (1-5), representing the amount of information available for the species in question. Tiers 1-3 represent the most data-rich stocks with reliable biomass estimates, an understanding of the biomass corresponding to maximum sustainable yield or a valid proxy (B_{MSY}), and essential life history information. Tier 4 stocks do not have life history information, and tier 5 stocks are data deficient. The Tanner crab fishery was upgraded to become a Tier 3 fishery in 2009, with a stock assessment accepted in 2012. If overfishing occurred or the stock is overfished, section 304(e)(3)(A) of the Magnuson-Stevens Act, as amended, requires the NPFMC to immediately end overfishing and rebuild affected stocks.

The Tier 3 HCR involves using $F_{35\%}$ and $B_{35\%}$ as proxies for F_{MSY} and B_{MSY}. The fishing

	Stock Status	F_{OFL}	ABC Control Rule
(a)	$\frac{B}{B_{35\%*}} > 1$	$F_{OFL} = F_{35\%}*$	
(b)	$\beta < \frac{B}{B_{35\%*}} \leq 1$	$F_{OFL} = F^{*}_{35\%} \frac{\frac{B}{B^{*}_{35\%}} - \alpha}{1 - \alpha}$	$ABC \leq (1-b) * OFL$
(c)	$\frac{B}{B_{35\%*}} \leq \beta$	$Directed\ fishery\ F = 0\,;\ F_{OFL} \leq F_{MSY}\ \dagger$	

**35% is the default percentage unless otherwise specified by the science and statistical committee as part of the NPFMC.*

† $An\ F_{OFL} \leq F_{MSY}$ *will be determined in the development of a rebuilding plan for an overfished stock*

v is a buffer

mortality used to set the OFL (F_{OFL}) is computed using the formula

Within the MSE, calculation of the OFL and ABC require an assumption regarding future fishing mortality due to the snow crab fishery, the groundfish fishery and the fishery for red king crab in Bristol Bay. These were taken to be the average fishing mortalities for the most recent five years.

Appendix S.II: Operating model parameter values

Table A2.1: Operating model parameter values from the 2017 assessment base model. Mean size at 50% or 95% selectivity or retention are designated by z50 or z95, with z95-z50 representing the size difference. Fisheries are designated by acronyms in the table, e.g., Tanner crab fishery (TCF), snow crab fishery (SCF), red king crab fishery (RKF), and groundfish fishery (GF).

Process	Name	Label	Index	Value
	pGrA[1]	Mean growth coefficient 'a' for males		33.09
	pGrA[2]	Mean growth coefficient 'a' for females		34.46
Growth	pGrB[1]	Mean growth coefficient 'b' for males		166.96
	pGrB[2]	Mean growth coefficient 'b' for females		115.10
	pGrBeta[1]	Growth transition matrix scale factor for both sexes		0.81
	pDM1[1]	Multiplier for immature crab		1.00
	pDM1[2]	Multiplier for mature males		1.15
Natural Mortality	pDM1[3]	Multiplier for mature females		1.39
	pDM2[1]	1980-1984 multiplier for mature females		2.59
	pDM2[2]	1980-1984 multiplier for mature males		1.31
	pM[1]	Base ln-scale M		-1.47
	pLnR[1]	Log mean recruitment: Historical recruitment period		5.66
	pLnR[2]	Log mean recruitment: Recent recruitment period		5.14
Recruitment	pRa[1]	Size-at-recruitment parameter a		2.44
	pRb[1]	Size-at-recruitment parameter b		1.39
	pRCV[1]	Recruitment cv's (log)		-0.69
	pRX[1]	Logit fraction males at recruitment		0.00
Recruitment	pDevsLnR [1]	Recruitment deviations (1949-1974)	1949	-1.41
			1950	-1.41
			1951	-1.41
			1952	-1.41
			1953	-1.39
			1954	-1.37
			1955	-1.34
			1956	-1.28
			1957	-1.19
			1958	-1.05
			1959	-0.82
			1960	-0.44
			1961	0.17
			1962	0.97
			1963	1.63
			1964	1.80
			1965	1.62
			1966	1.37
			1967	1.21
			1968	1.19
			1969	1.25
			1970	1.23

Table A2.1 (continued).

Process	Name	Label	Index	Value
Recruitment	pDevsLnR [1]	Recruitment deviations (1949-1974)	1971	1.08
			1972	0.67
			1973	0.25
			1974	0.10
Recruitment	pDevsLnR [2]	Recruitment deviations (1975-2018)	1975	1.33
			1976	2.00
			1977	1.74
			1978	0.91
			1979	0.06
			1980	-0.44
			1981	0.06
			1982	-0.52
			1983	1.07
			1984	0.87
			1985	1.17
			1986	1.13
			1987	1.13
			1988	0.74
			1989	0.00
			1990	-1.18
			1991	-1.40
			1992	-1.53
			1993	-1.53
			1994	-1.26
			1995	-1.00
			1996	-1.08
			1997	-0.01
			1998	-0.92
			1999	0.29
			2000	-0.37
			2001	0.82
			2002	-0.32
			2003	0.78
			2004	0.75
			2005	-0.56
			2006	-0.83
			2007	-1.08
			2008	-0.65
			2009	1.22
			2010	1.08
			2011	0.17
			2012	-1.43

Table A2.1 (continued).

Process	Name	Label	Index	Value
Recruitment	pDevsLnR [2]	Recruitment deviations (1975-2018)	2013	-0.45
			2014	-0.83
			2015	-1.24
			2016	-0.89
			2017	0.96
			2018	1.24
Molt to maturity	pLgtPrM2M[1]		27	-12.03
		logit-scale parameters for Pr(molt-to-maturity | size) for males by 5mm size class (27-182mm)	32	-10.85
			37	-9.66
			42	-8.48
			47	-7.31
			52	-6.16
			57	-5.11
			62	-4.49
			67	-4.10
			72	-3.46
			77	-2.93
			82	-2.50
			87	-2.03
			92	-1.44
			97	-0.95
			102	-0.68
			107	-0.53
			112	-0.06
			117	0.56
			122	1.44
			127	2.81
			132	5.06
			137	7.20
			142	9.01
			147	10.50
			152	11.69
			157	12.63
			162	13.36
			167	13.91
			172	14.35
			177	14.69
			182	15.00

Table A2.1 (continued).

Process	Name	Label	Index	Value
Molt to maturity	pLgtPrM2M[2]	logit-scale parameters for Pr(molt-to-maturity | size) for females by 5mm size class (27-102mm)	27	-15.00
			32	-13.77
			37	-12.48
			42	-11.09
			47	-9.53
			52	-7.76
			57	-5.75
			62	-3.58
			67	-1.77
			72	-0.43
			77	0.31
			82	0.59
			87	1.28
			92	2.58
			97	4.03
			102	5.52
Selectivity and Retention	pS1[1]	Mean size at 50% (z50) selectivity in NMFS survey (males, pre-1982)		52.44
	pS1[2]	z50 selectivity in NMFS survey (males, 1982+)		34.26
	pS1[3]	z50 selectivity in NMFS survey (females, pre-1982)		56.41
	pS1[4]	z50 selectivity in NMFS survey (females, 1982+)		-35.49
	pS1[5]	z50 retention in Tanner crab fishery (TCF) (pre-1991)		138.04
	pS1[6]	z50 retention in TCF (1991-1996)		137.48
	pS1[8]	ln(z50) for TCF selectivity (males)		4.86
	pS1[9]	z50 for TCF selectivity (females)		96.44
	pS1[10]	Ascending z50 for snow crab fishery (SCF) selectivity (males, pre-1997)		87.65
	pS1[11]	Ascending z50 for SCF selectivity (males, 1997-2004)		95.65
	pS1[12]	Ascending z50 for SCF selectivity (males, 2005+)		105.45
	pS1[13]	Ascending z50 for SCF selectivity (females, pre-1997)		70.33
	pS1[14]	Ascending z50 for SCF selectivity (females, 1997-2004)		76.37
	pS1[15]	Ascending z50 for SCF selectivity (females, 2005+)		84.94
	pS1[16]	z50 for groundfish (GF) all gear selectivity (males, pre-1987)		55.07
	pS1[17]	z50 for GF all gear selectivity (males, 1987-1996)		59.01
	pS1[18]	z50 for GF all gear selectivity (males, 1997+)		80.71
	pS1[19]	z50 for GF all gear selectivity (males, pre-1987)		41.21
	pS1[20]	z50 for GF all gear selectivity (males, 1987-1996)		40.00
	pS1[21]	z50 for GF all gear selectivity (males, 1997+)		76.23

Table A2.1 (continued).

Process	Name	Label	Index	Value
Selectivity and Retention	pS1[22]	Mean size at 95% (z95) selectivity in red king crab fishery (RKF)(males, pre-1997)		157.78
	pS1[23]	z95 for RKF selectivity (males, 1997-2004)		180.00
	pS1[24]	z95 for RKF selectivity (males, 2005+)		180.00
	pS1[25]	z95 for RKF selectivity (females, pre-1997)		121.87
	pS1[26]	z95 for RKF selectivity (females, 1997-2004)		122.10
	pS1[27]	z95 for RKF selectivity (females, 2005+)		140.00
	pS1[28]	z50 for TCF retention (2005-2009)		138.80
	pS1[29]	z50 for TCF retention (2013+)		125.23
Selectivity and Retention	pDevsS1[1]	ln(z50 devs) for selectivity (males, 1991+)	1991	0.04
			1992	0.12
			1993	0.11
			1994	0.09
			1995	0.00
			1996	0.13
			2005	-0.08
			2006	-0.09
			2007	-0.12
			2008	0.02
			2009	0.19
			2013	-0.04
			2014	-0.10
			2015	-0.14
			2017	-0.13
Selectivity and Retention	pS2[1]	z95-z50 for NMFS survey selectivity (males, pre-1982)		23.61
	pS2[2]	z95-z50 for NMFS survey selectivity (males, 1982+)		75.23
	pS2[3]	z95-z50 for NMFS survey selectivity (females, pre-1982)		40.09
	pS2[4]	z95-z50 for NMFS survey selectivity (females, 1982+)		100.00
	pS2[5]	Slope for TCF retention (pre-1991)		0.69
	pS2[6]	Slope for TCF retention (1997+)		0.95
	pS2[7]	Slope for TCF selectivity (males, pre-1997)		0.12
	pS2[8]	Slope for TCF selectivity (males, 1997+)		0.16
	pS2[9]	Slope for TCF selectivity (females)		0.19
	pS2[10]	Ascending slope for SCF selectivity (males, pre-1997)		0.38
	pS2[11]	Ascending slope for SCF selectivity (males, 1997-2004)		0.21

844 Table A2.1 (continued).

Process	Name	Label	Index	Value
Selectivity and Retention	pS2[12]	Ascending slope for SCF selectivity (males, 2005+)		0.18
	pS2[13]	Slope for SCF selectivity (females, pre-1997)		0.22
	pS2[14]	Slope for SCF selectivity (females, 1997-2004)		0.26
	pS2[15]	Slope for SCF selectivity (females, 2005+)		0.16
	pS2[16]	Slope for GF all gear selectivity (males, pre-1987)		0.10
	pS2[17]	Slope for GF all gear selectivity (males, 1987-1996)		0.06
	pS2[18]	Slope for GF all gear selectivity (males, 1997+)		0.07
	pS2[19]	Slope for GF all gear selectivity (females, pre-1987)		0.14
	pS2[20]	Slope for GF all gear selectivity (females, 1987-1996)		0.19
	pS2[21]	Slope for GF all gear selectivity (females, 1997+)		0.07
	pS2[22]	ln(z95-z50) for RKF selectivity (males, pre-1997)		3.07
	pS2[23]	ln(z95-z50) for RKF selectivity (males, 1997-2004)		3.55
	pS2[24]	ln(z95-z50) for RKF selectivity (males, 2005+)		3.52
	pS2[25]	ln(z95-z50) for RKF selectivity (males, pre-1997)		2.79
	pS2[26]	ln(z95-z50) for RKF selectivity (males, 1997-2004)		2.86
	pS2[27]	ln(z95-z50) for RKF selectivity (males, 2005+)		2.98
	pS2[28]	Slope for TCF retention (2005-2009)		0.86
	pS2[29]	Slope for TCF retention (2013+)		0.56
	pDevsS2[1]	Devs to 2nd input to selectivity function		0.00
	pS3[1]	ln(dz50-az50) for SCF selectivity (males, pre-1997)		3.96
	pS3[2]	ln(dz50-az50) for SCF selectivity (males, 1997-2004)		3.72
	pS3[3]	ln(dz50-az50) for SCF selectivity (males, 2005+)		3.45
	pS4[1]	Descending slope for SCF selectivity (males, pre-1997)		0.50
	pS4[2]	Descending slope for SCF selectivity (males, 1997-2004)		0.13
	pS4[3]	Descending slope for SCF selectivity (males, 2005+)		0.18
	pDevsS4[1]	Devs to 4th input to selectivity function		0.00
	pS5	Number of bounded parameters		0.00
	pDevsS5[1]	Devs to 5th input to selectivity function		0.00
	pS6	Number of bounded parameters		0.00
	pvNPSel[1]	Logit-scale parameter vectors for non-parametric smooth selectivity		0.00
Handling Mortality	pHM[1]	Handling mortality for pot fisheries		0.321
	pHM[2]	Handling mortality for groundfish trawl fisheries		0.80

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Table A2.1 (continued).

Process	Name	Label	Index	Value
Capture	pLnC[1]	TCF: base capture rate, pre-1965 (=0.05)		-3.00
	pLnC[2]	TCF: base capture rate, 1965+		-1.42
	pLnC[3]	SCF: base capture rate, pre-1978 (=0.01)		-4.61
	pLnC[4]	SCF: base capture rate, 1992+		-2.86
	pLnC[6]	GTF: base capture rate, all years		-4.41
	pLnC[7]	RKF: base capture rate, pre-1953 (=0.02)		-3.91
	pLnC[8]	RKF: base capture rate, 1992+		-4.01
	pDC1[1]	ln-scale capture rate offset 1		0.00
	pDC2[1]	TCF: female offset		-2.35
	pDC2[2]	SCF: female offset		-1.75
	pDC2[3]	GTF: female offset		-0.96
	pDC2[4]	RKF: female offset		-0.83
	pDC3[1]	ln-scale capture rate offset 3		0.00
	pDC4[1]	ln-scale capture rate offset 4		0.00
Capture	pDevsLnC[1]	ln-scale annual capture rate devs	1965	-0.55
		TCF: 1965-1984, 1987-1996, 2005-2009, 2013-2015, 2017	1966	-0.77
			1967	0.45
			1968	0.29
			1969	0.47
			1970	0.33
			1971	0.14
			1972	-0.03
			1973	-0.28
			1974	-0.09
			1975	0.13
			1976	0.91
			1977	1.71
			1978	2.04
			1979	2.82
			1980	2.02
			1981	0.21
			1982	-0.79
			1983	-1.80
			1984	-0.78
			1987	-1.34
			1988	-0.53
			1989	0.67
			1990	1.35
			1991	1.35
			1992	2.05

Table A2.1 (continued).

Process	Name	Label	Index	Value
Capture	pDevsLnC[1]	ln-scale annual capture rate devs	1993	1.44
		TCF: 1965-1984, 1987-1996, 2005-2009, 2013-2015-2017	1994	0.93
			1995	0.34
			1996	0.05
			2005	-2.09
			2006	-1.49
			2007	-1.47
			2008	-1.83
			2009	-1.20
			2013	-1.82
			2014	-0.62
			2015	-0.36
			2017	-1.86
Capture	pDevsLnC[2]	ln-scale annual capture rate devs	1992	1.94
		SCF: 1992+	1993	1.64
			1994	1.24
			1995	1.17
			1996	-0.27
			1997	0.78
			1998	1.00
			1999	-0.04
			2000	-0.98
			2001	-0.83
			2002	-0.61
			2003	-1.31
			2004	-1.65
			2005	-0.54
			2006	-0.25
			2007	-0.14
			2008	-0.73
			2009	-0.50
			2010	-0.33
			2011	0.26
			2012	-0.39
			2013	-0.27
			2014	0.65
			2015	0.42
			2016	0.20
			2017	-0.46
Capture	pDevsLnC[3]	ln-scale annual capture rate devs	1973	1.31
		GF all gear: 1973+	1974	1.70

Table A2.1 (continued).

Process	Name	Label	Index	Value
Capture	pDevsLnC[3]	ln-scale annual capture rate devs	1975	0.86
		GF all gear: 1973+	1976	0.32
			1977	0.01
			1978	-0.25
			1979	0.37
			1980	-0.01
			1981	-0.20
			1982	-0.97
			1983	-0.42
			1984	-0.20
			1985	-0.62
			1986	-0.46
			1987	-0.66
			1988	-1.07
			1989	-0.87
			1990	-0.53
			1991	0.57
			1992	0.87
			1993	0.70
			1994	1.17
			1995	1.15
			1996	1.44
			1997	1.42
			1998	1.19
			1999	0.74
			2000	0.82
			2001	1.13
			2002	0.46
			2003	-0.16
			2004	0.00
			2005	-0.25
			2006	-0.23
			2007	-0.34
			2008	-0.59
			2009	-0.78
			2010	-0.90
			2011	-0.91
			2012	-1.07
			2013	-0.94
			2014	-0.91
			2015	-0.95
			2016	-0.89

Table A2.1 (continued).

Process	Name	Label	Index	Value
Capture	pDevsLnC[3]	ln-scale annual capture rate devs GF all gear: 1973+	2017	-1.02
Capture	pDevsLnC[4]	ln-scale annual capture rate devs	1992	0.84
		RKF: 1992+	1993	2.22
			1994	-0.04
			1995	0.01
			1996	-0.01
			1997	-0.03
			1998	-0.04
			1999	-0.05
			2000	-0.06
			2001	-0.08
			2002	-0.13
			2003	-0.16
			2004	-0.22
			2005	-0.23
			2006	-0.13
			2007	-0.24
			2008	-0.28
			2009	-0.24
			2010	-0.20
			2011	-0.19
			2012	-0.14
			2013	-0.23
			2014	-0.22
			2015	-0.17
Retention	pLnEffX[1]	ln-scale effort extrapolation parameters	1	0.00
	pLgtRet[1]	TCF: logit-scale max retention (pre-1997)	1	15.00
	pLgtRet[2]	TCF: logit-scale max retention (2005-2009)	1	2.10
	pLgtRet[3]	TCF: logit-scale max retention (2013+)	1	4.03
Survey	pQ[1]	NMFS trawl survey: males, 1975-1981	1	-0.69
	pQ[2]	NMFS trawl survey: males, 1982+	1	-0.45
	pQ[3]	NMFS trawl survey: females, 1975-1981	1	-0.69
	pQ[4]	NMFS trawl survey: females, 1982+	1	-0.92
Catchability	pDQ1[1]	Offset 1 for ln-scale catchability	1	0.00
	pDQ2[1]	Offset 2 for ln-scale catchability	1	0.00
	pDQ3[1]	Offset 3 for ln-scale catchability	1	0.00
	pDQ4[1]	Offset 4 for ln-scale catchability	1	0.00
	pMSE_LnC[1]	Catchability for mature male crab	1	-2.50

Appendix S.III: Graphical summary of the results of the MSE

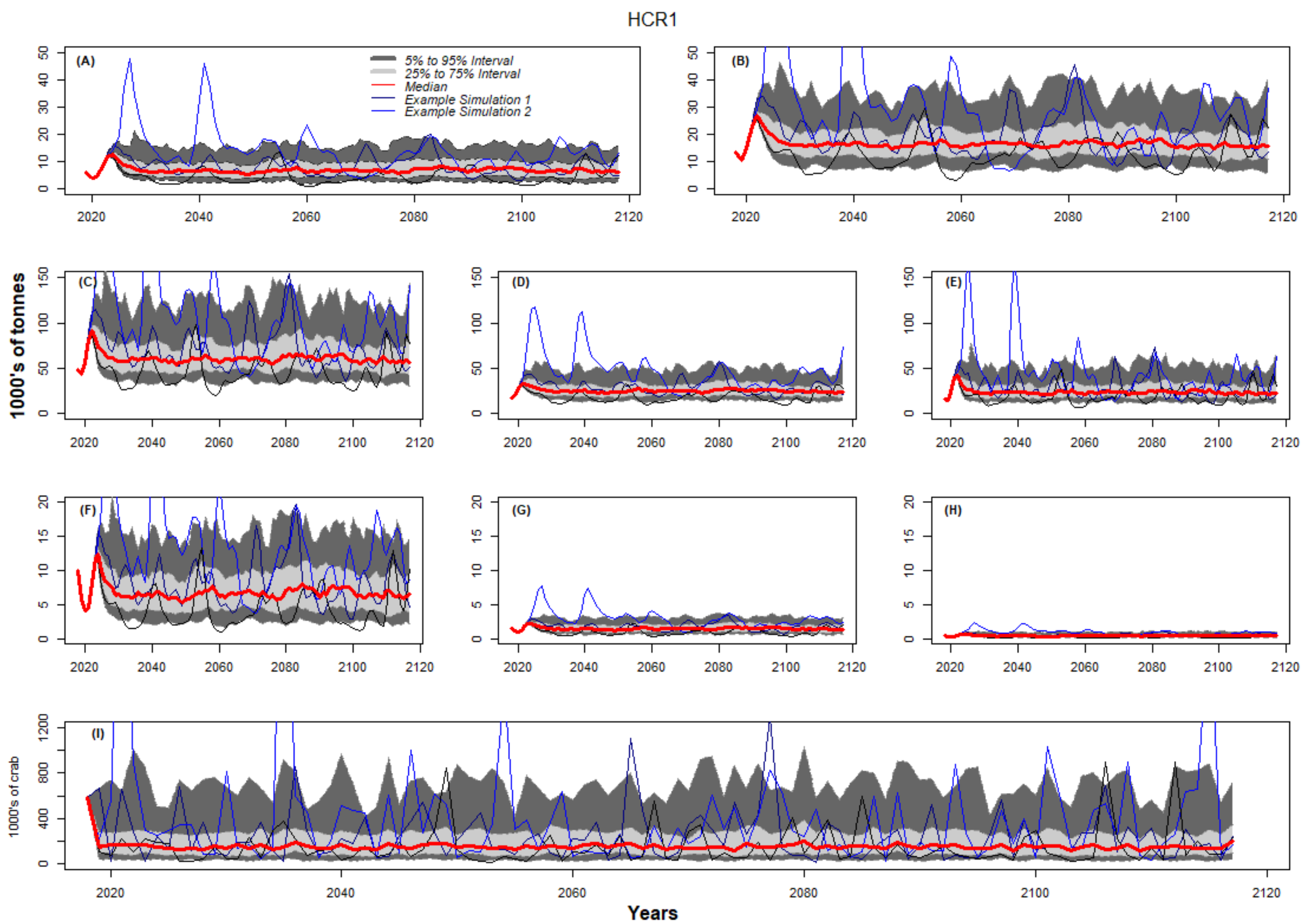


Figure A3.1: HCR1 model summary. The panels depict median values for all 100 simulations from 2018-2117 (except for TAC, which ranges from 2019-2118), with 5-95% intervals, 25-75% intervals, and two example simulations. Panels depict (A) TAC, (B) OFL, (C) MMB, (D) MFB, (E) ELM, (F) MMB catch (starting in 2018, in contrast to TAC which starts in 2019), (G) MMB discards, (H) MFB discards, and (I) recruitment.

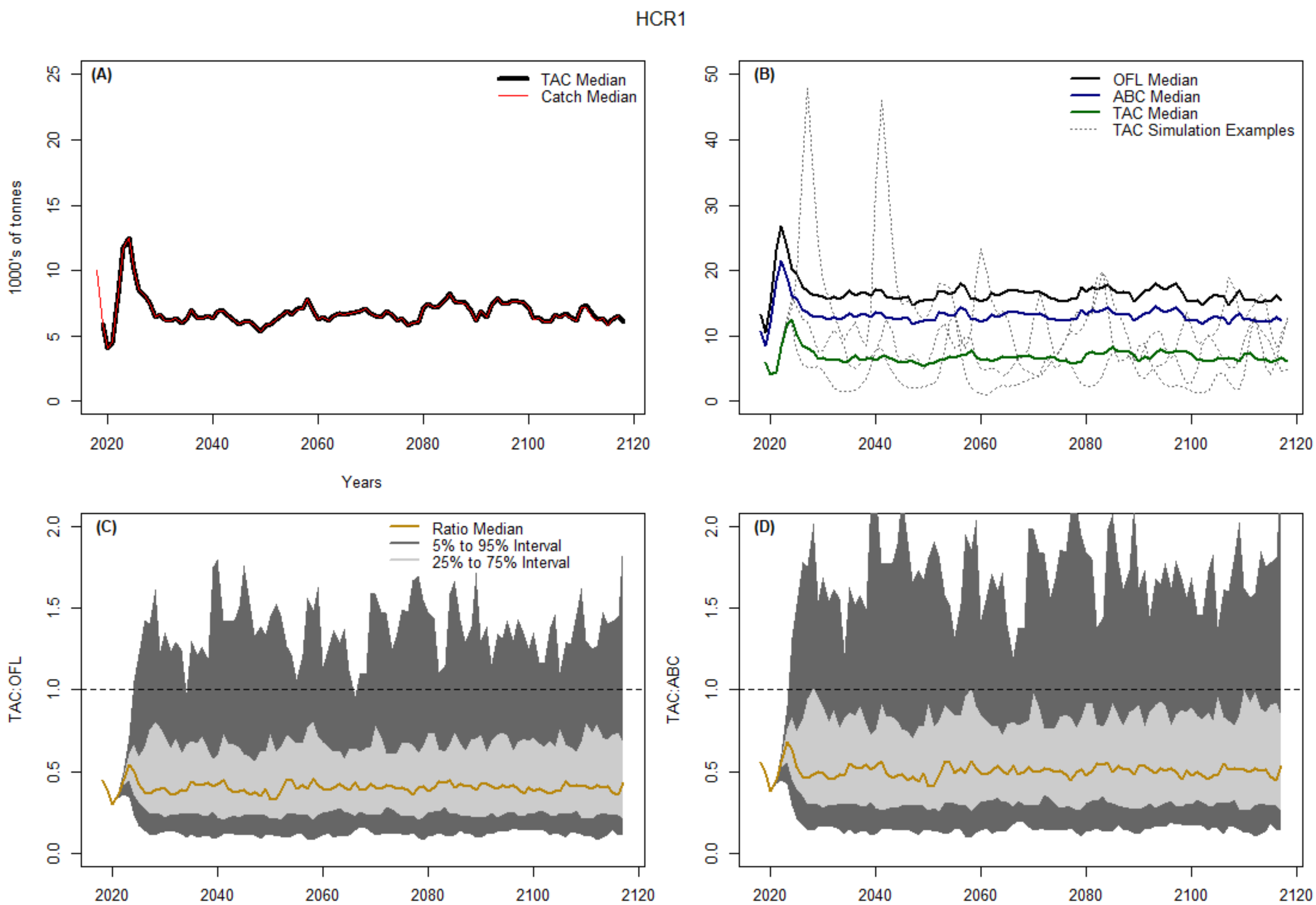


Figure A3.2: Additional results for HCR1: (A) median TAC over all simulations (2019–2118) compared to the median total catch from the operating model (2018–2017), (B) median OFL and ABC, compared to the median TAC, with two example TAC trajectories, (C) the median ratio of TAC to OFL, with 5-95%, and 25-75% intervals, and (D) the median ratio of TAC to ABC, with 5-95%, and 25-75% intervals.

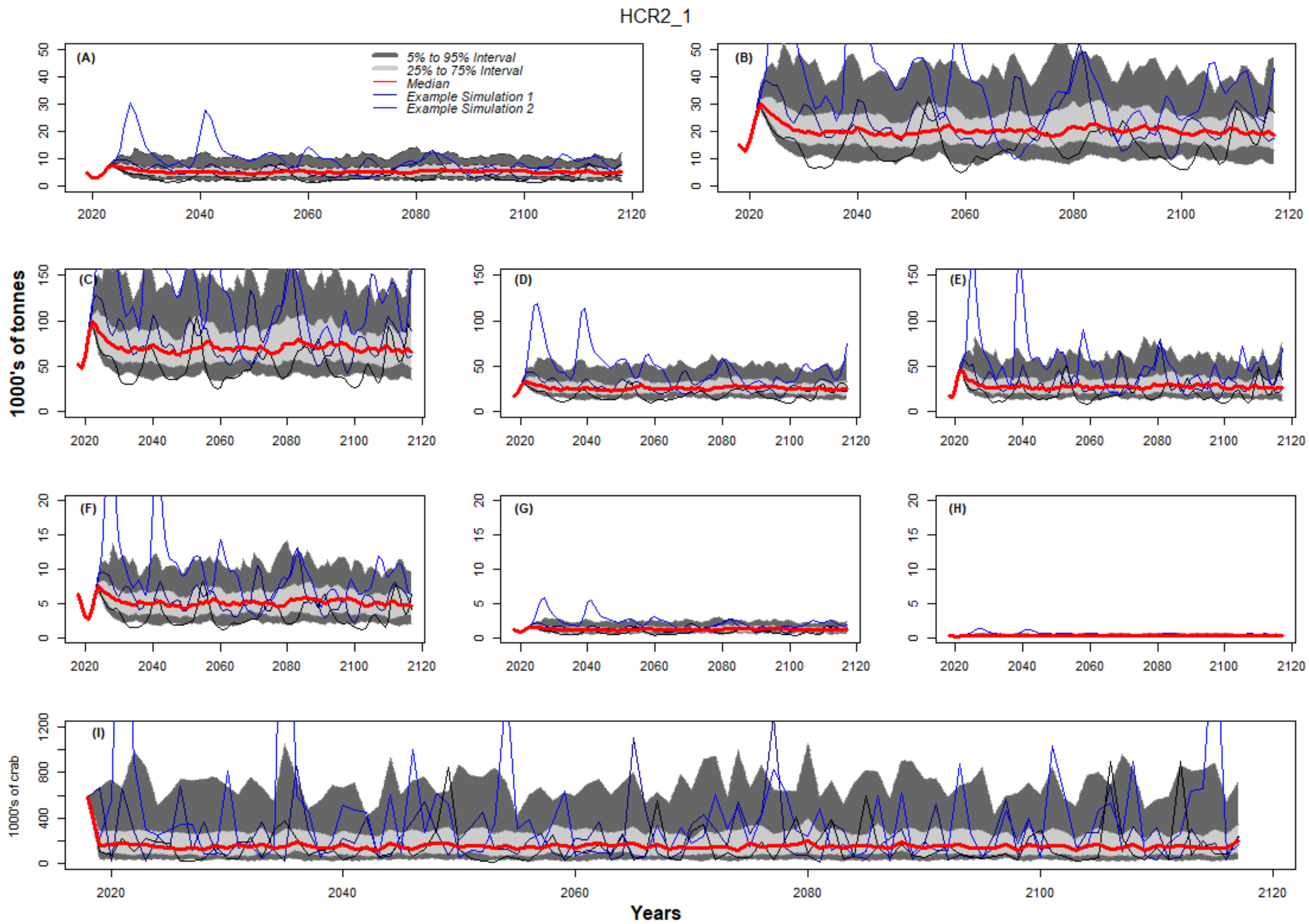
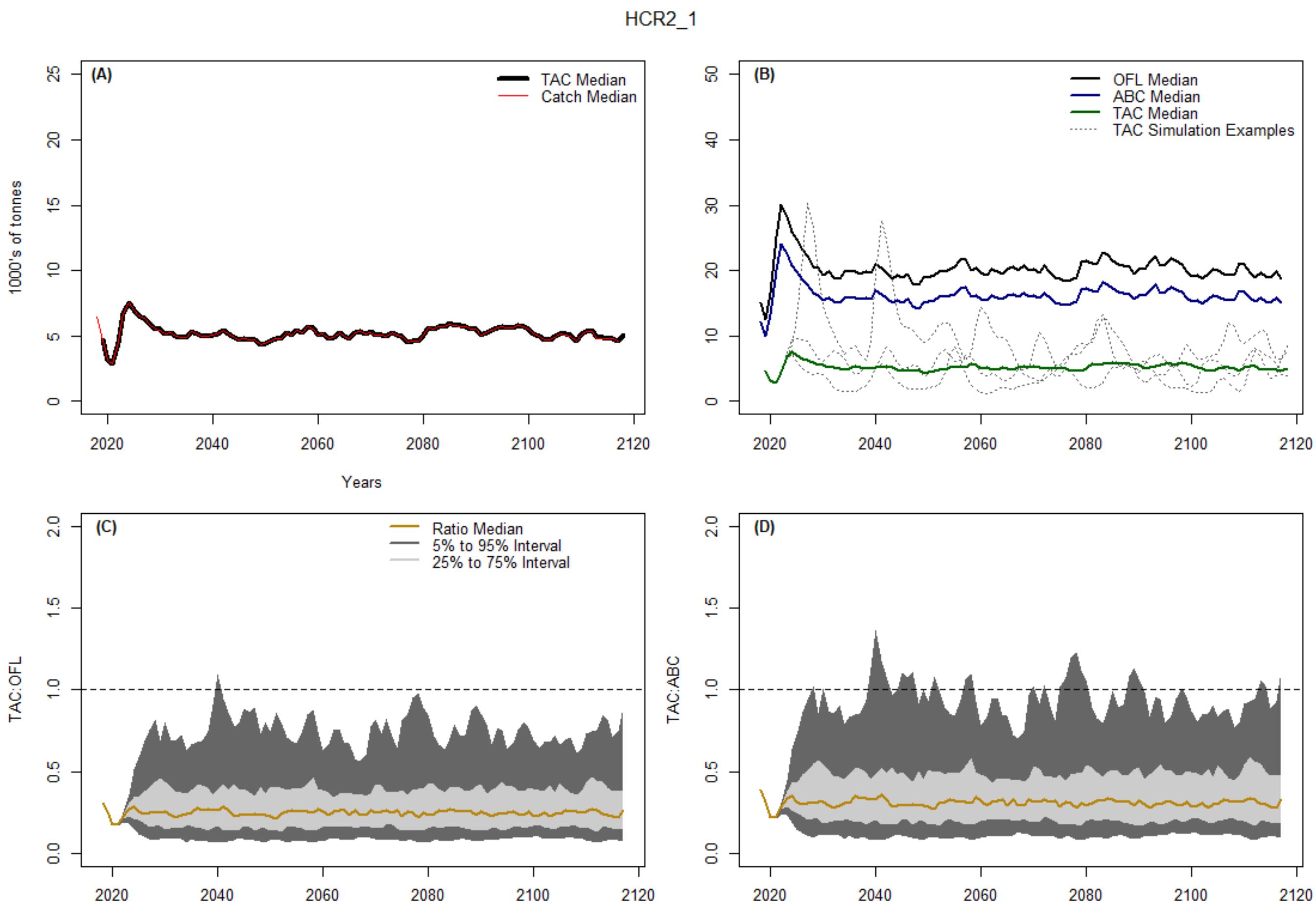


Figure A3.3: As for Figure A3.1 except for HCR2_1.



873 Figure A3.4: As for Figure A3.2, except for HCR2_1.

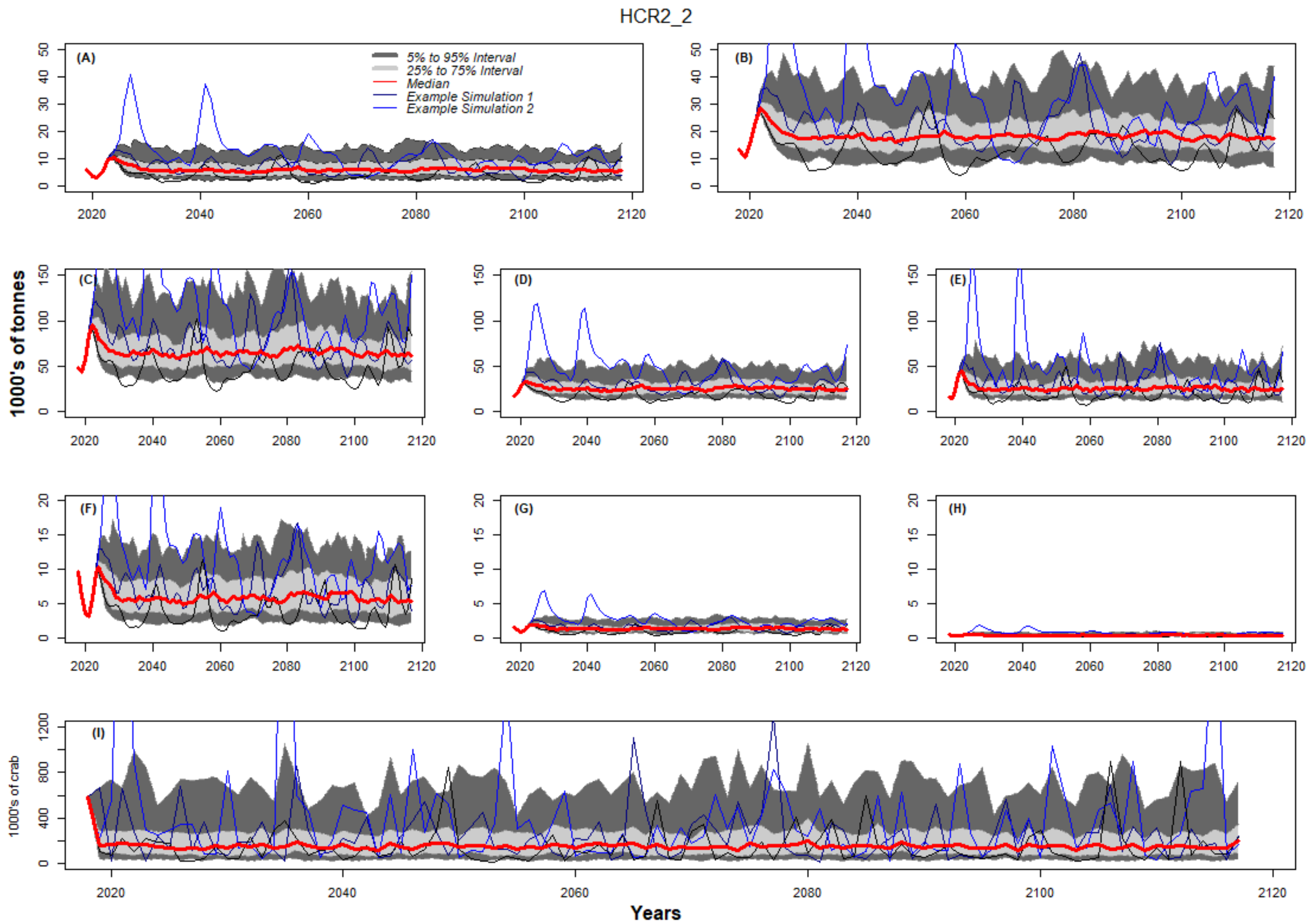


Figure A3.5: As for Figure A3.1 except for HCR2_2.

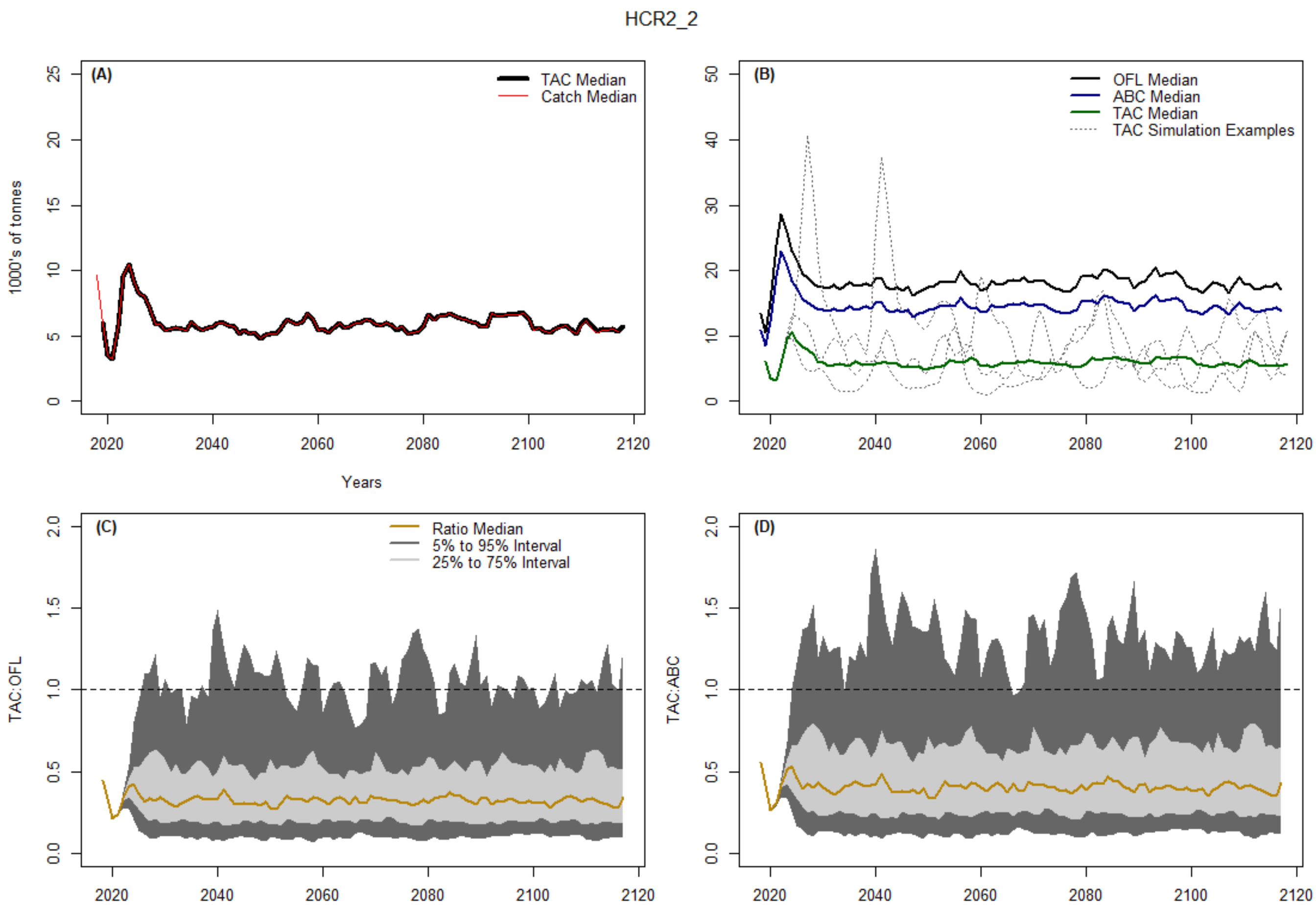


Figure A3.6: As for Figure A3.2, except for HCR2_2.

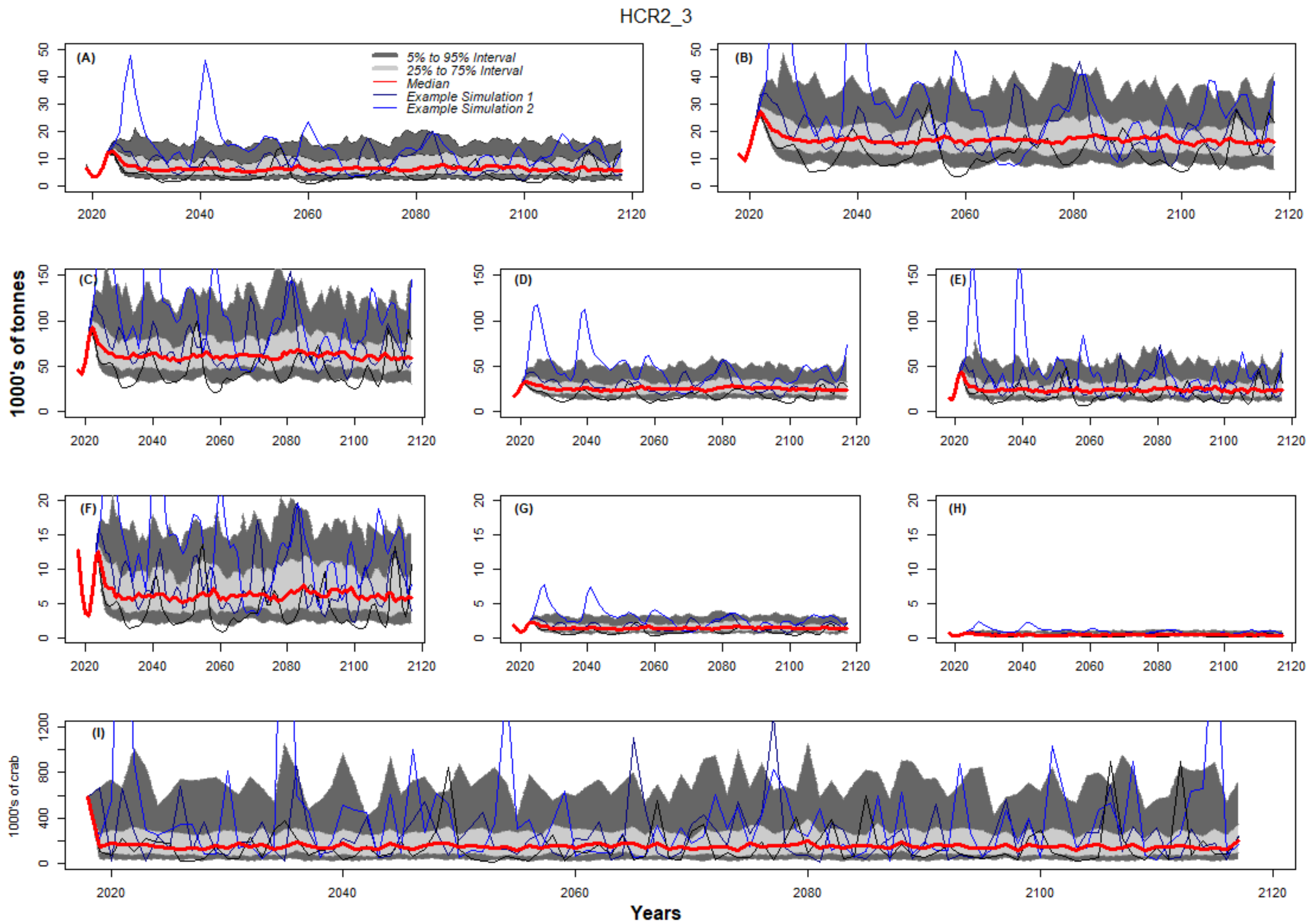


Figure A3.7: As for Figure A3.1 except for HCR2_3.

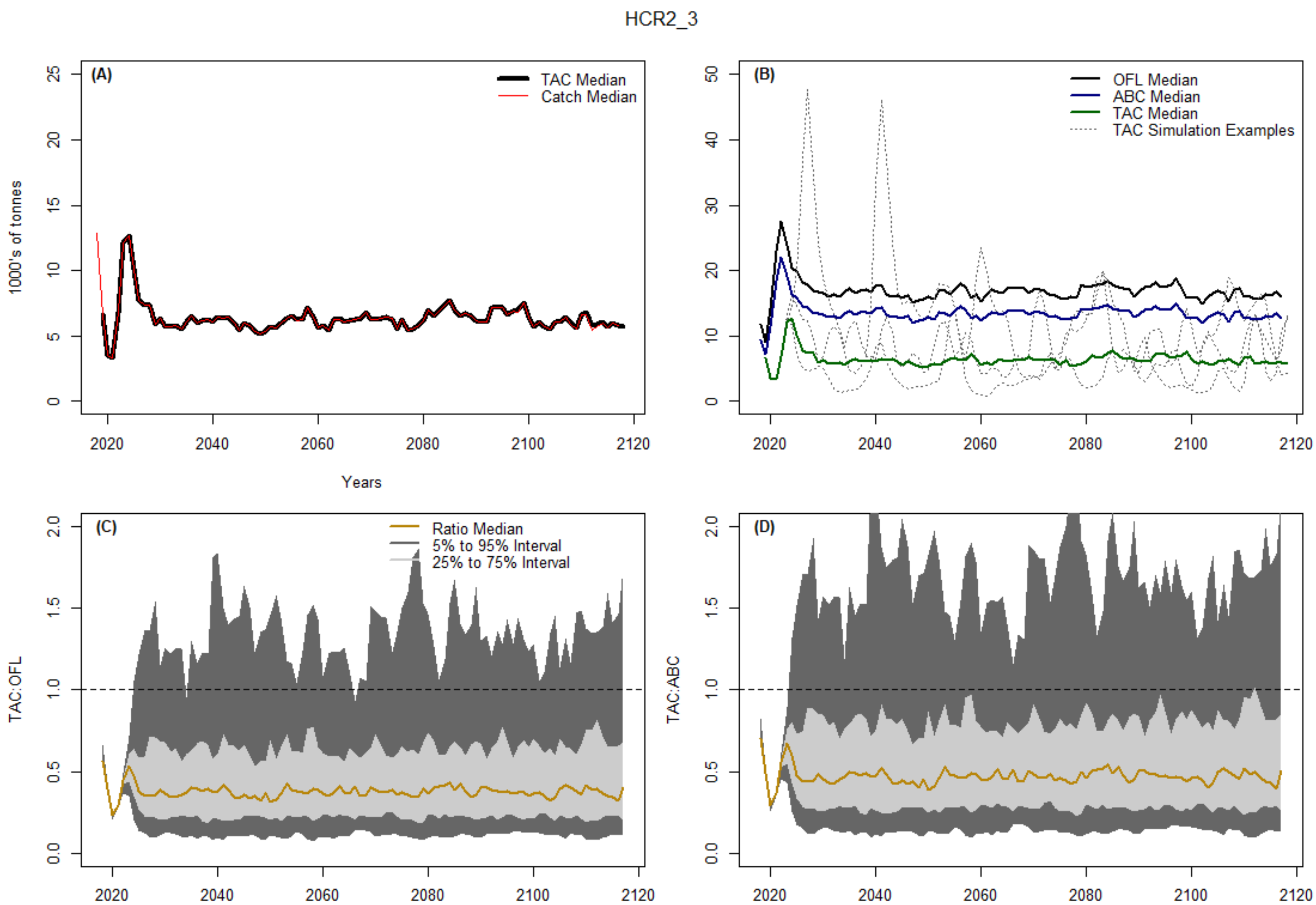
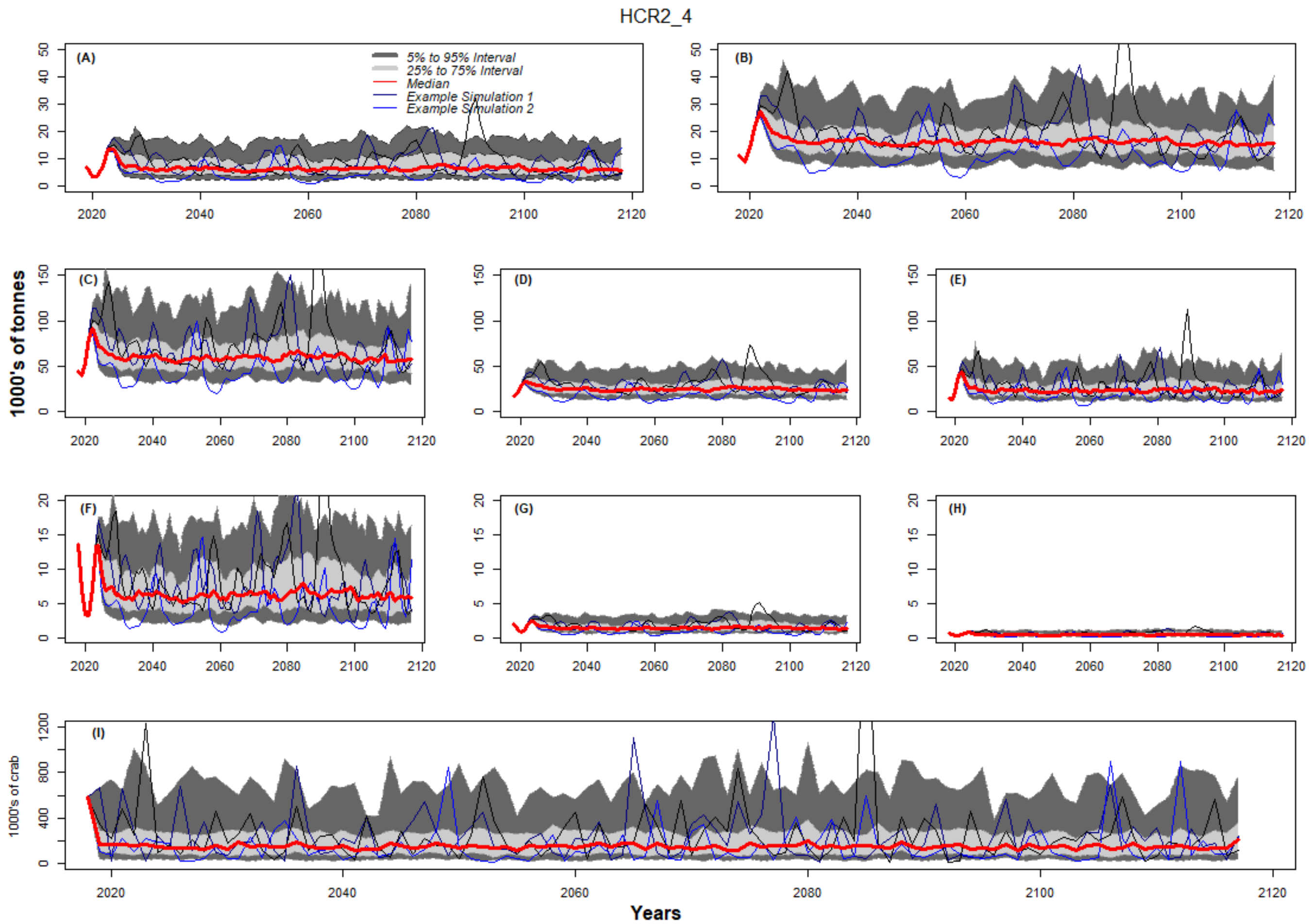


Figure A3.8: As for Figure A3.2, except for HCR2_3.



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887 Figure A3.9: As for Figure A3.1 except for HCR2_4.

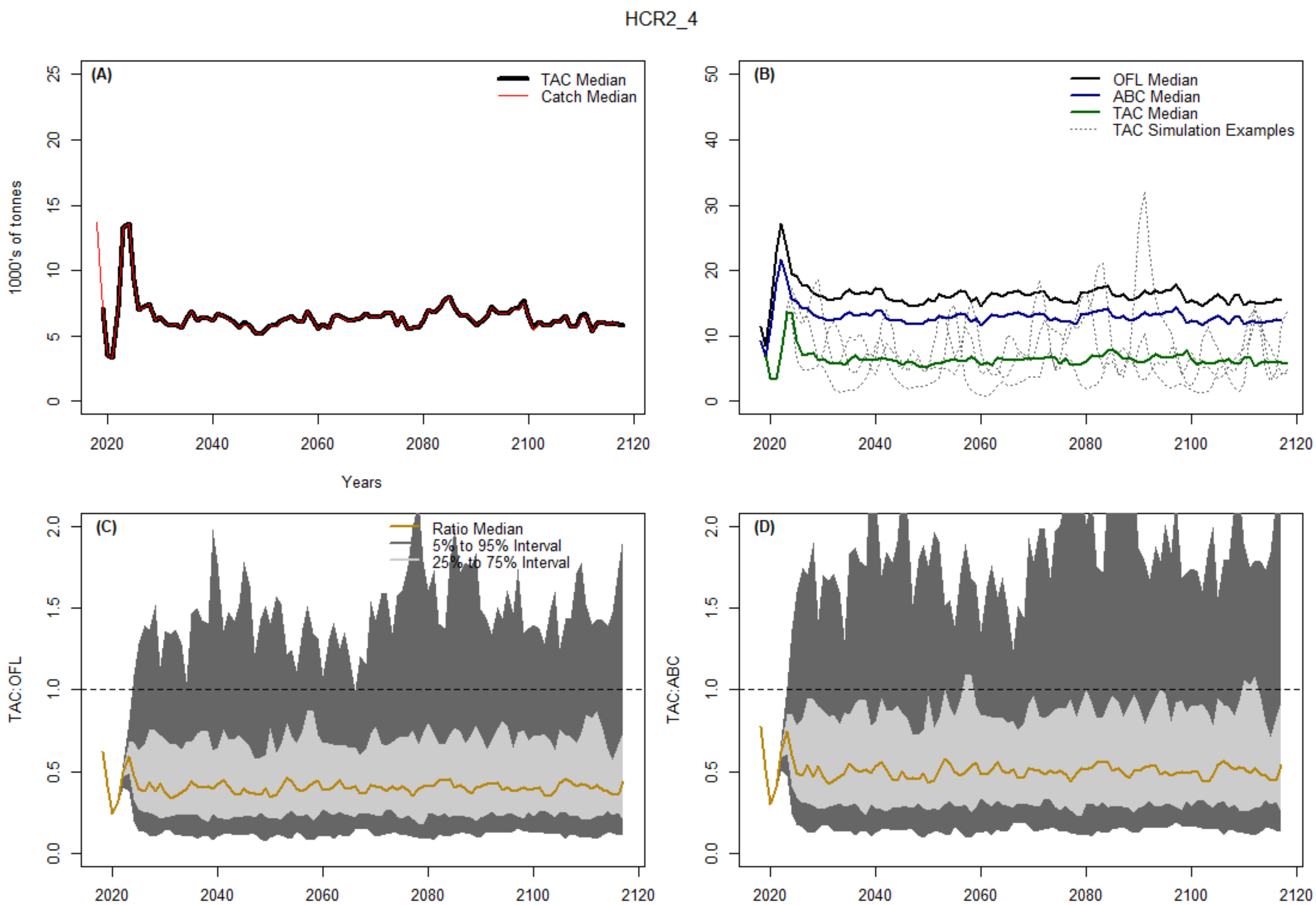

Figure A3.10: As for Figure A3.2, except for HCR2_4.

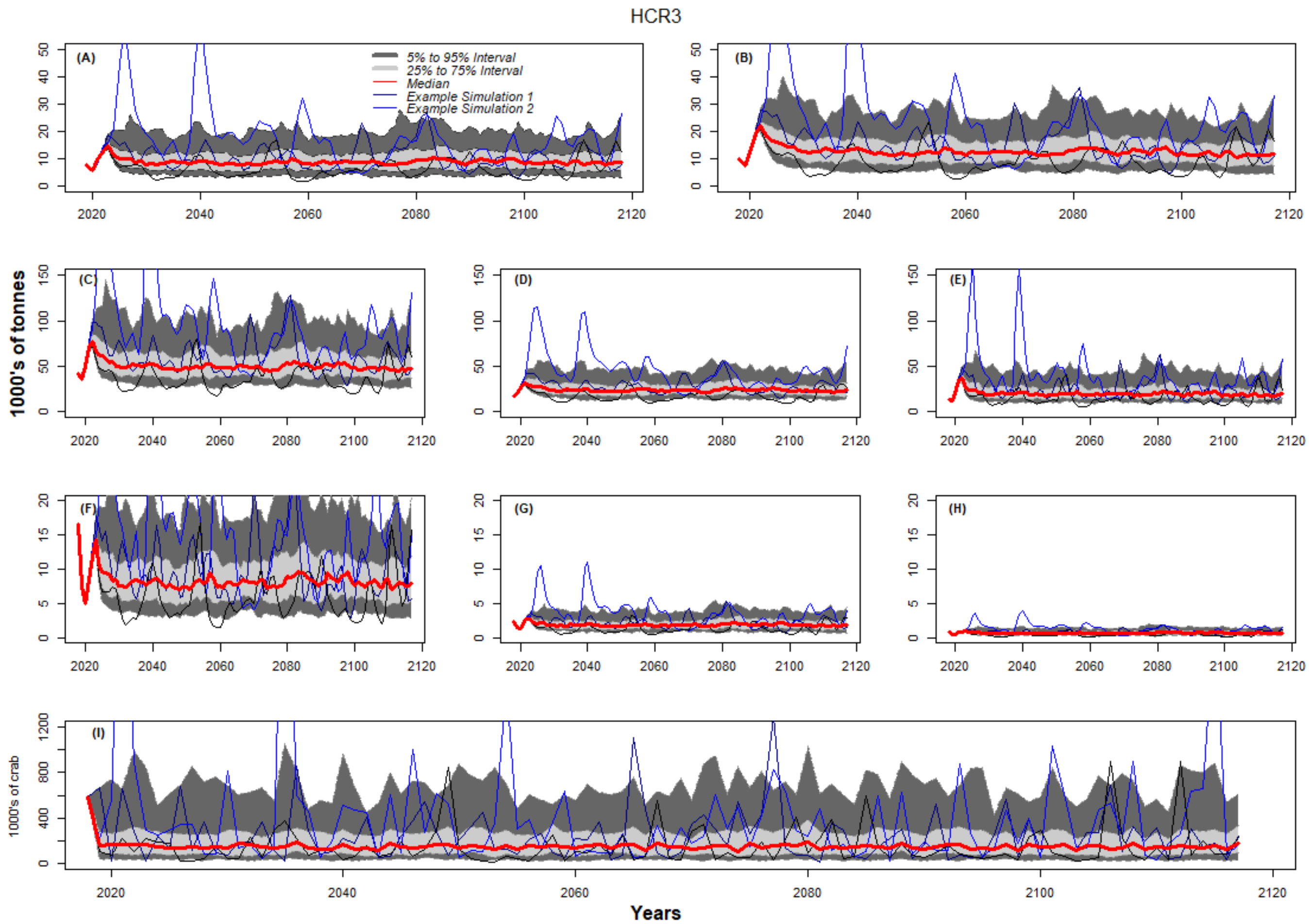

Figure A3.11: As for Figure A3.1 except for HCR3.

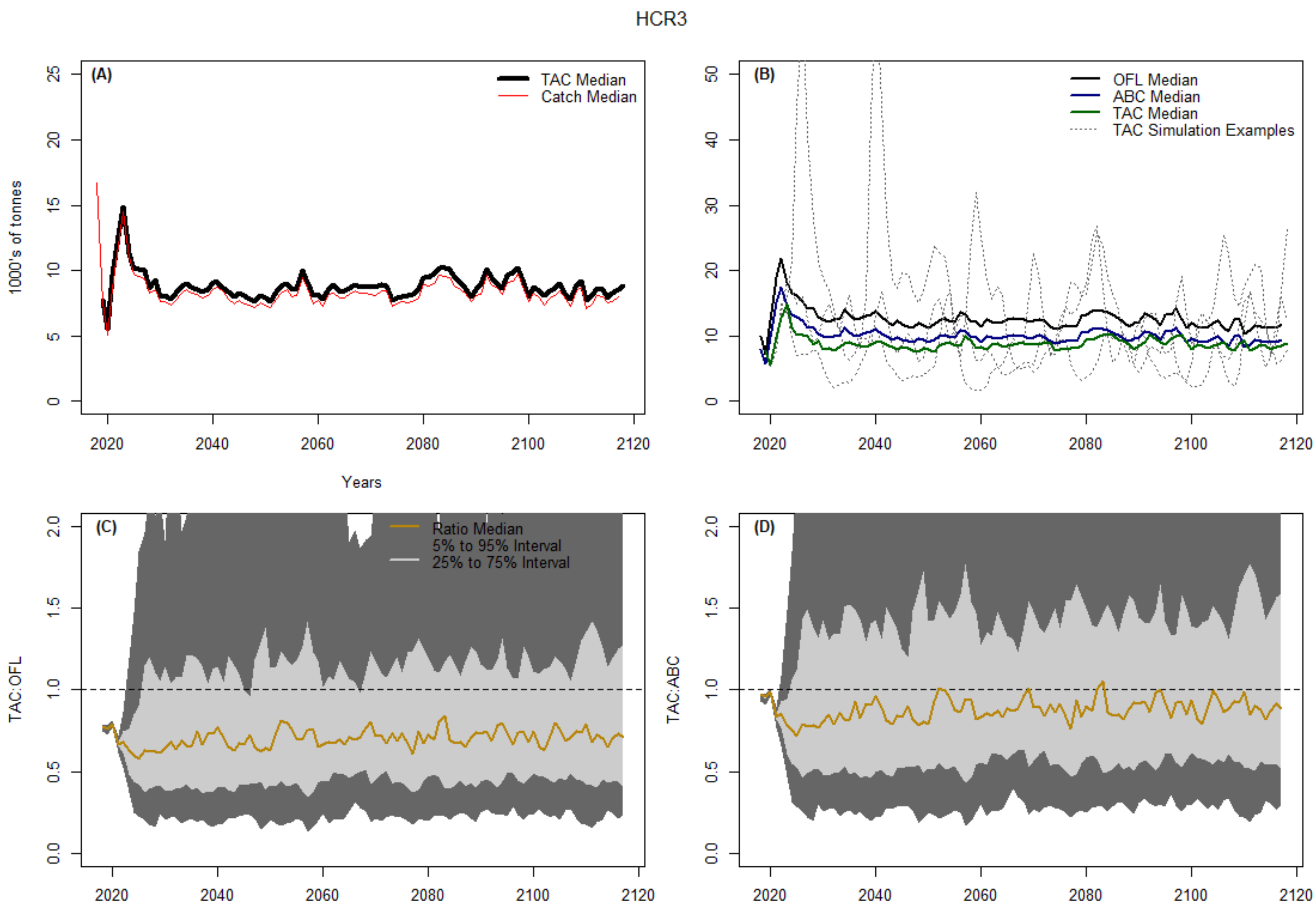

Figure A3.12: As for Figure A3.2, except for HCR3.

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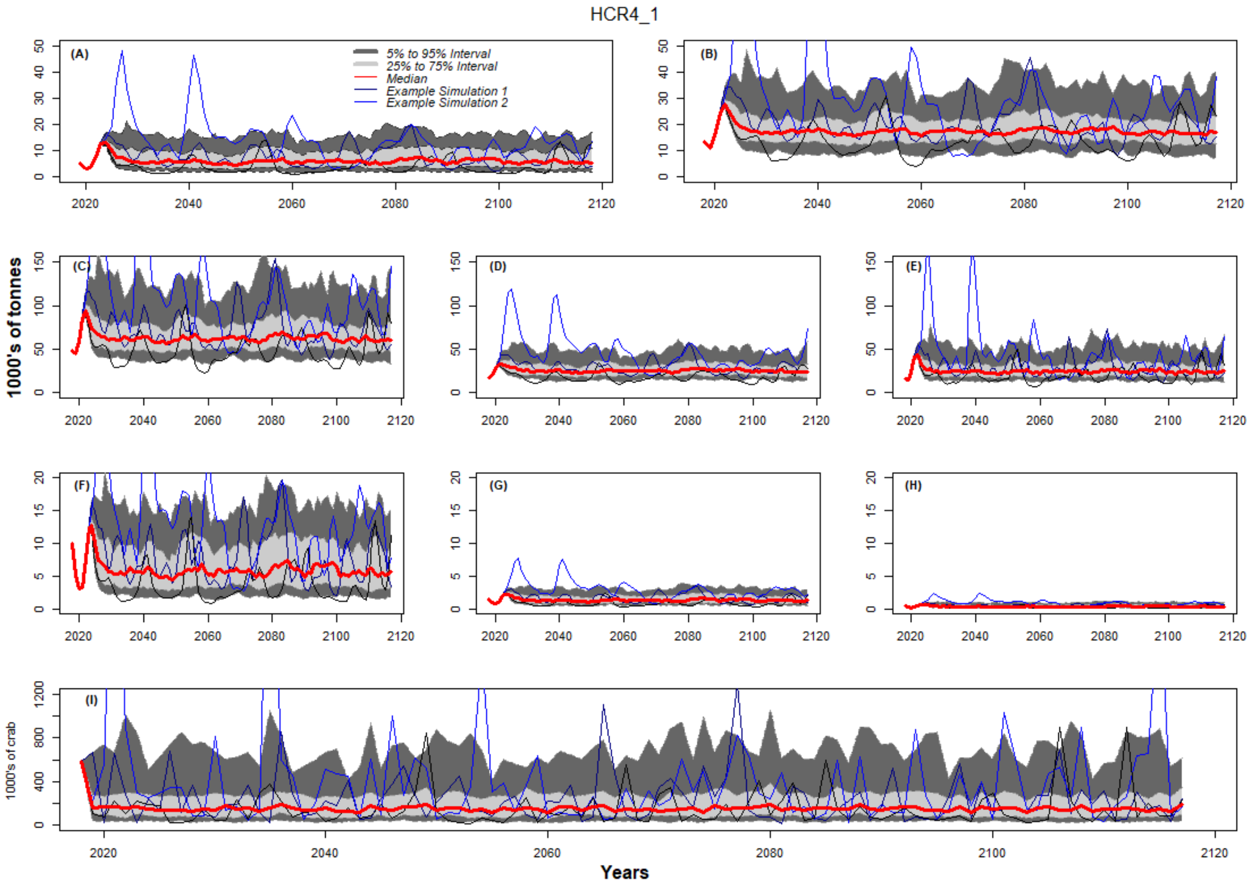

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900 Figure A3.13: As for Figure A3.1 except for HCR4_1.

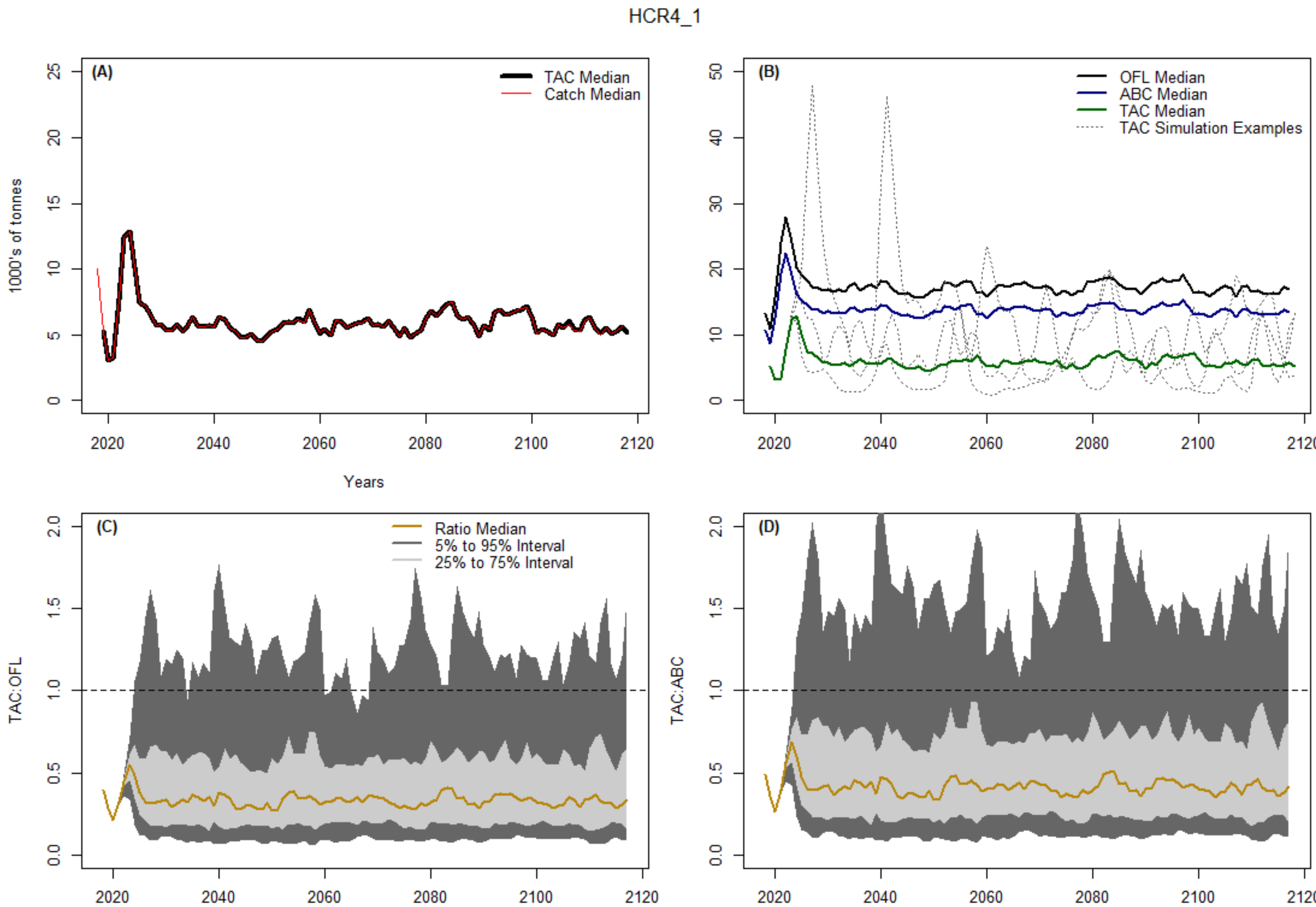

Figure A3.14: As for Figure A3.2, except for HCR4_1.

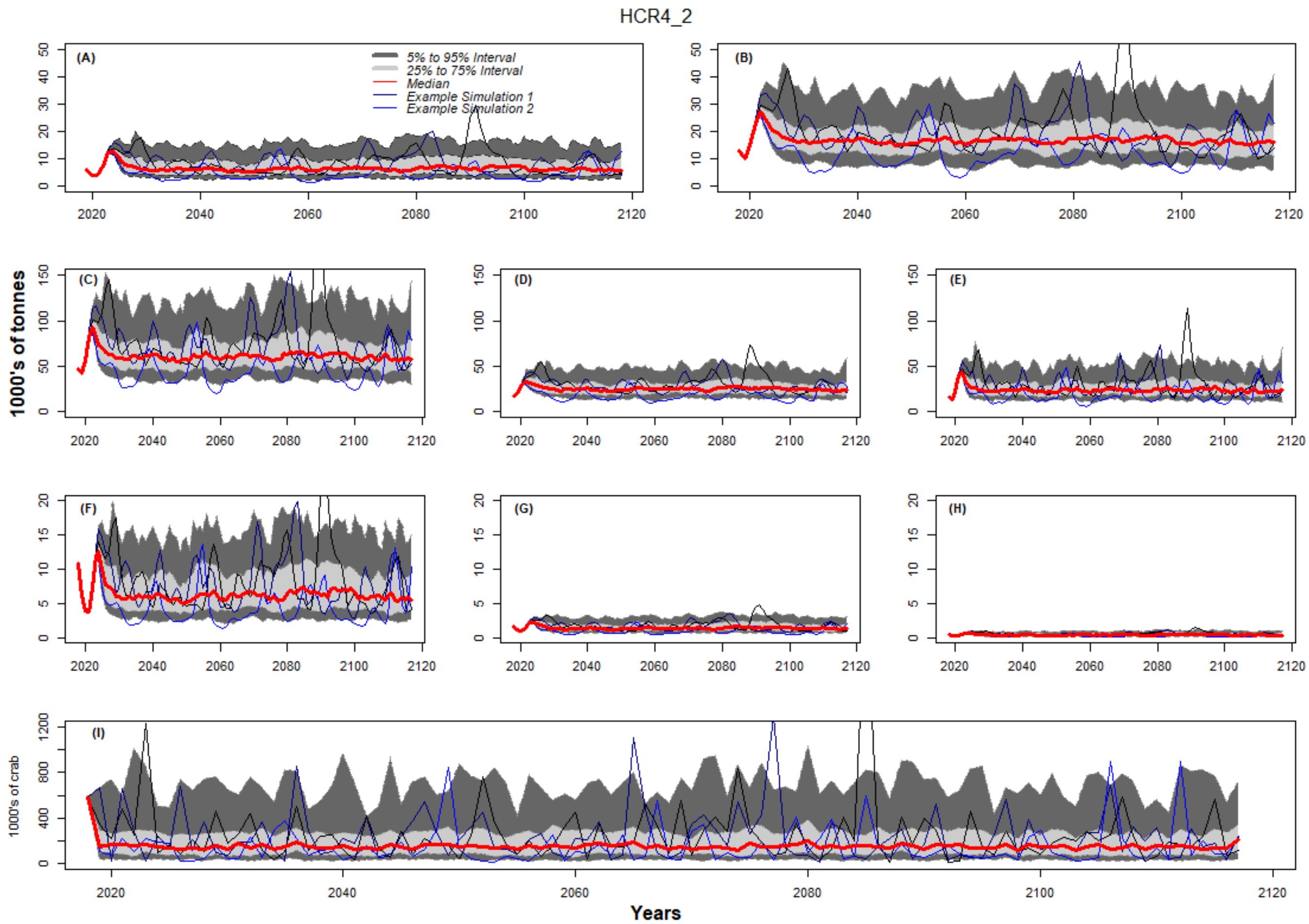

Figure A3.15: As for Figure A3.1 except for HCR4_2.

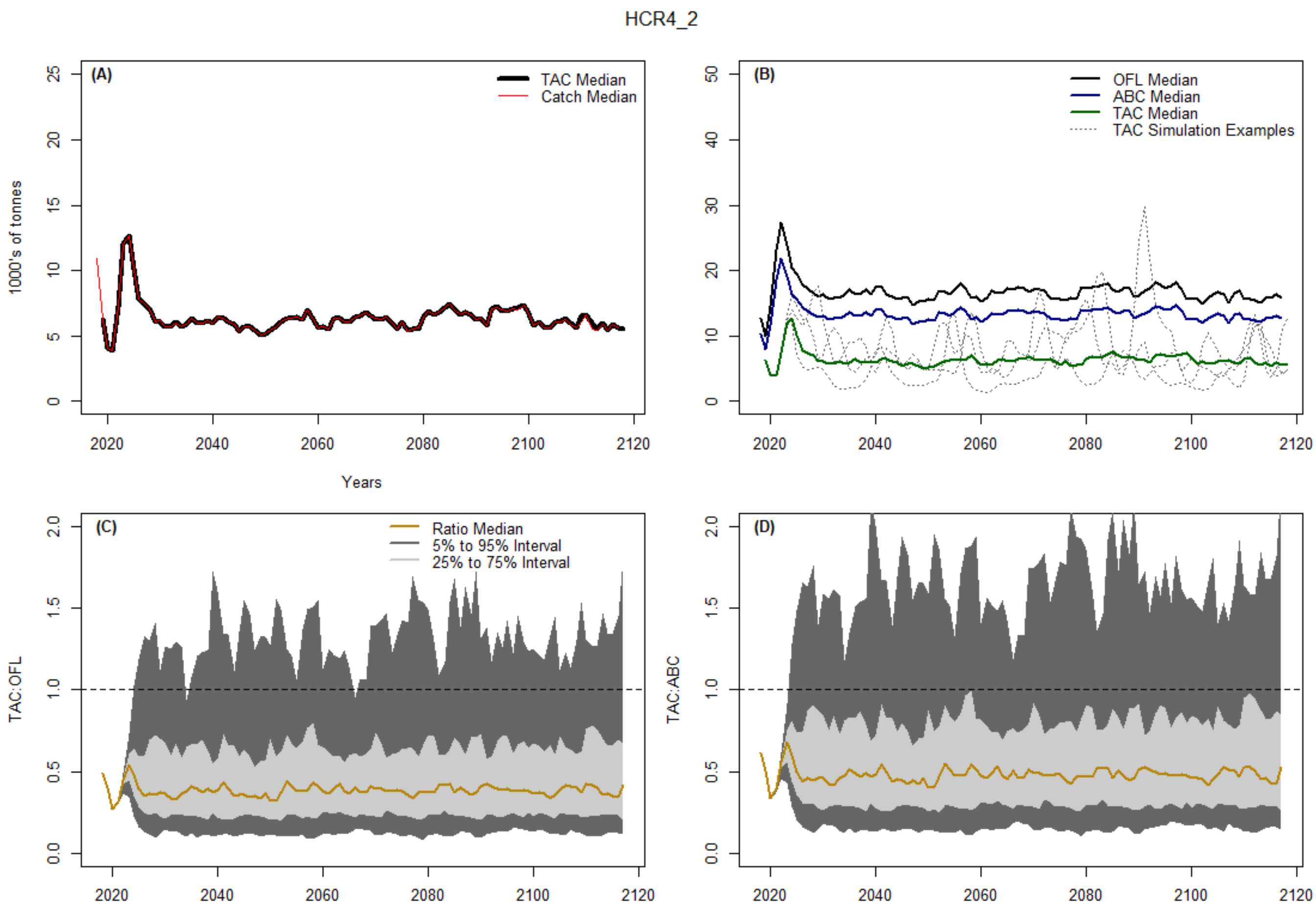

Figure A3.16: As for Figure A3.2, except for HCR4_2.

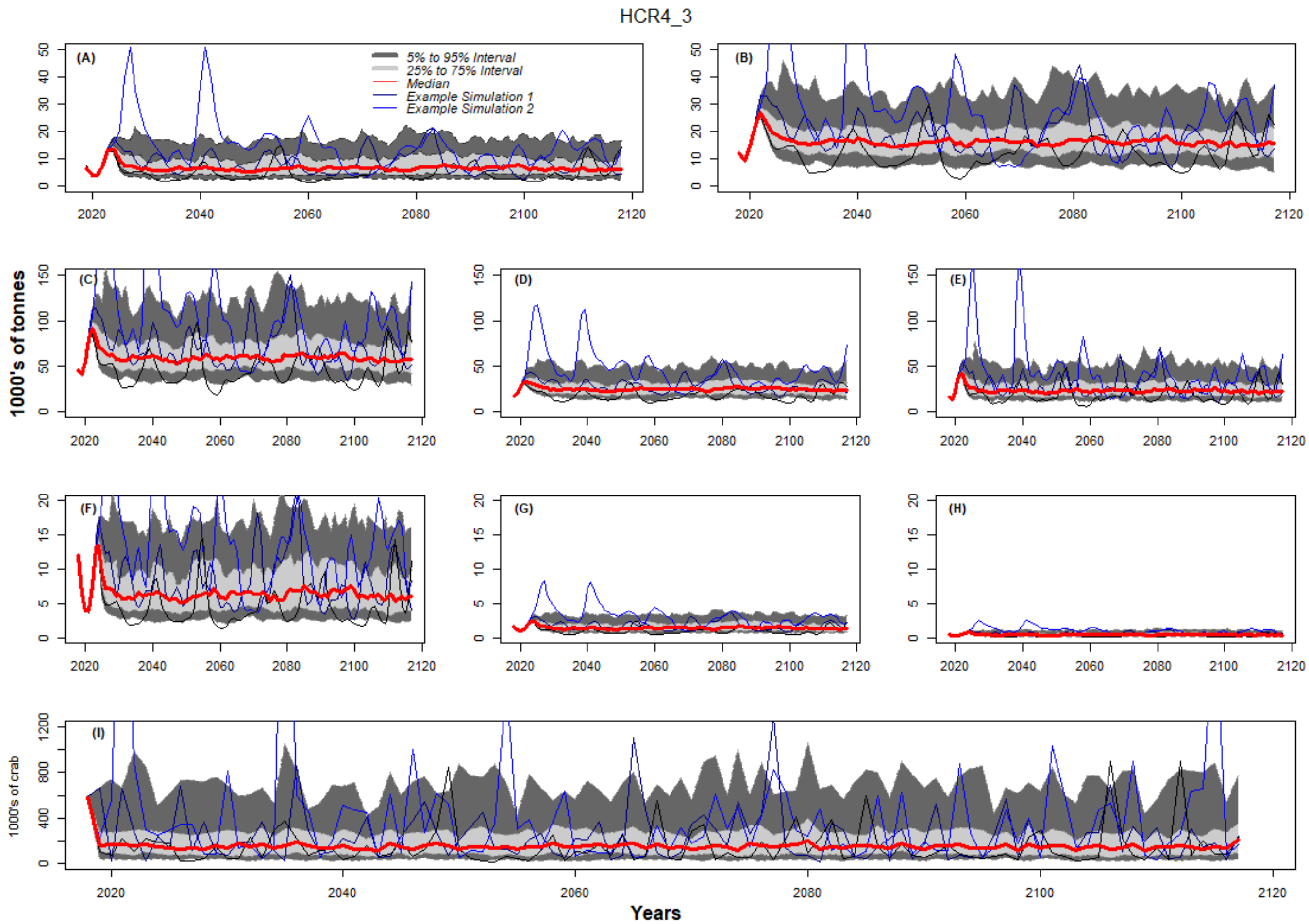

Figure A3.17: As for Figure A3.1 except for HCR4_3.

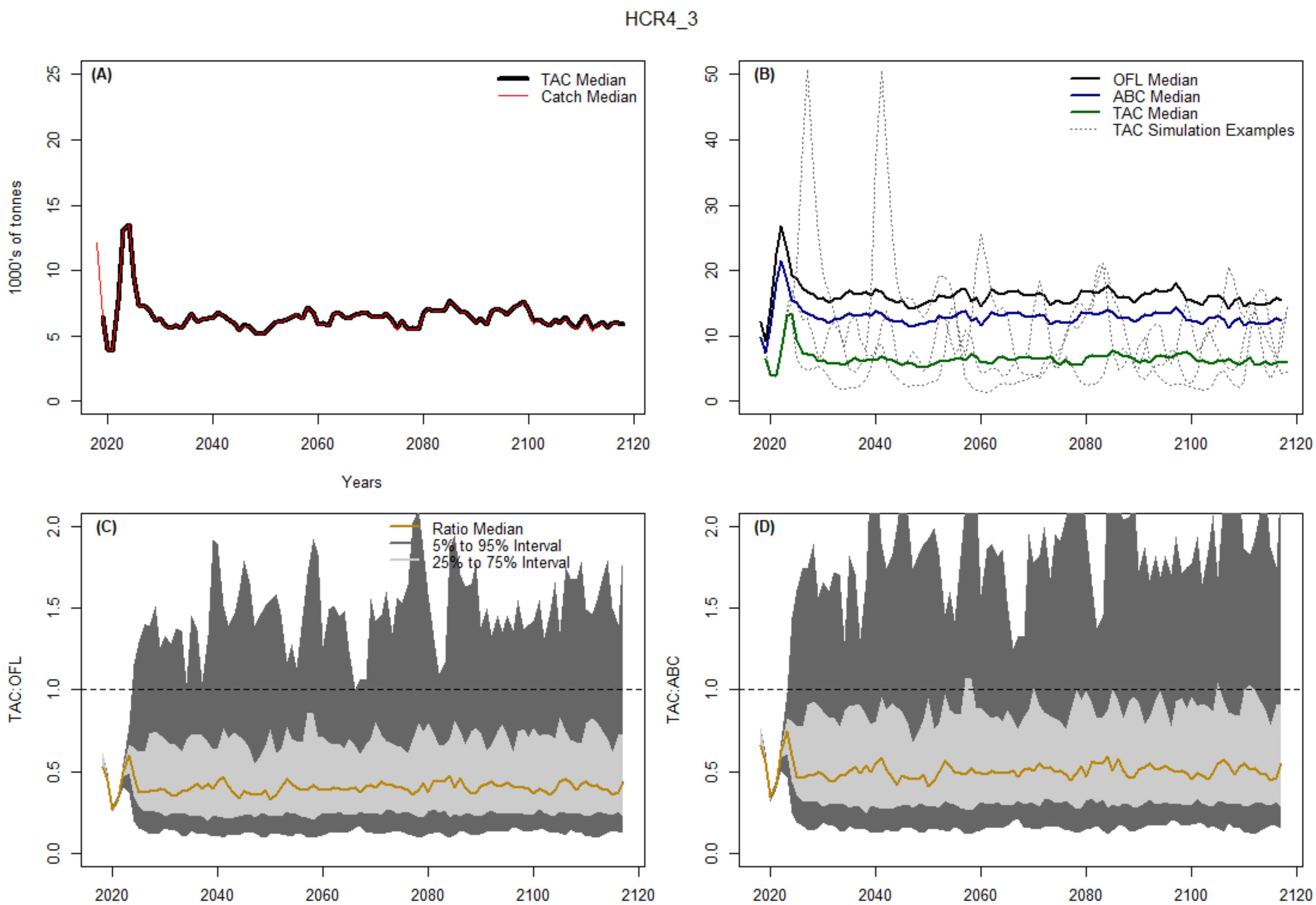

Figure A3.18: As for Figure A3.2, except for HCR4_3.

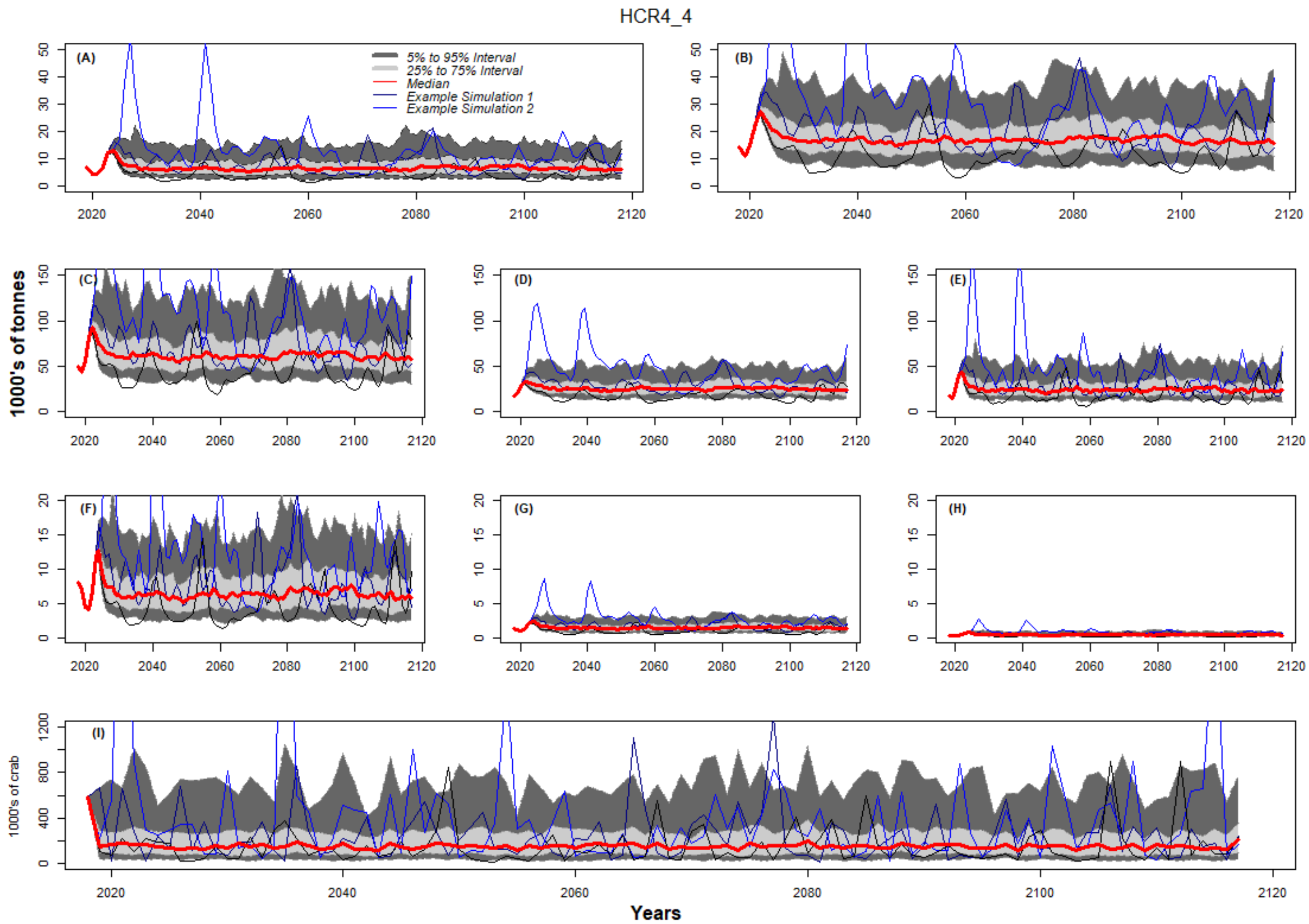

Figure A3.19: As for Figure A3.1 except for HCR4_4.

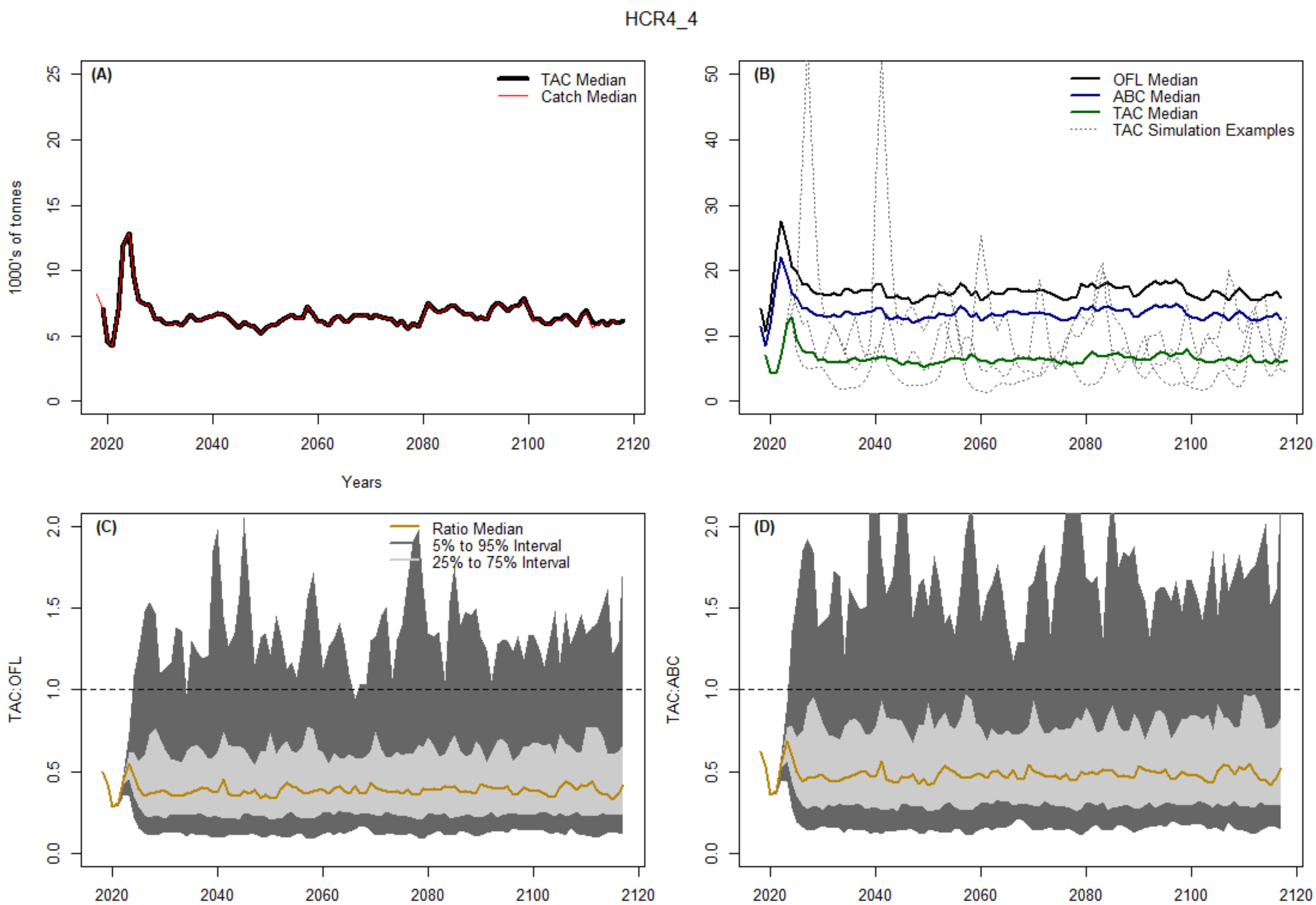

Figure A3.20: As for Figure A3.2, except for HCR4_4.

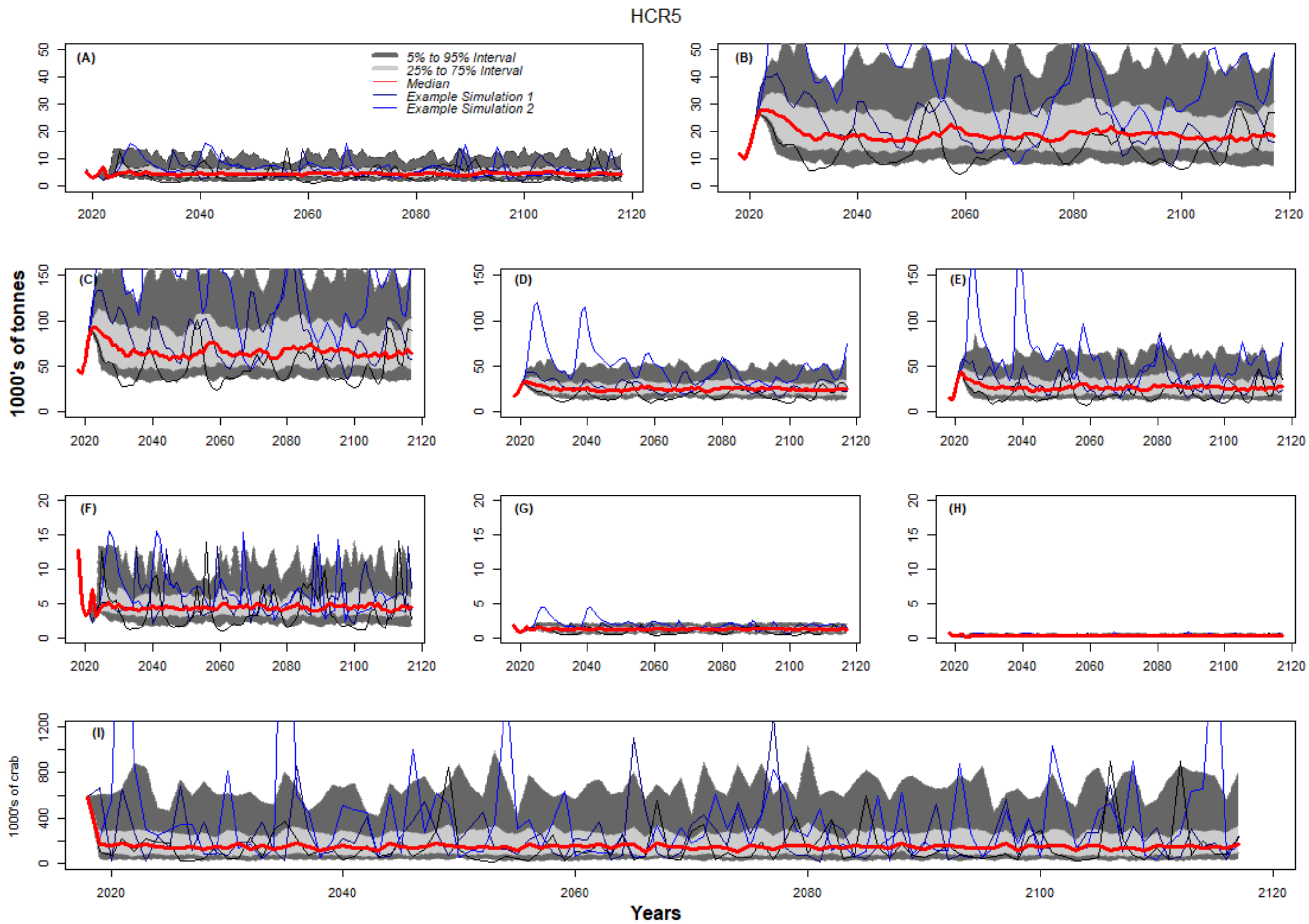

Figure A3.21: As for Figure A3.1 except for HCR5.

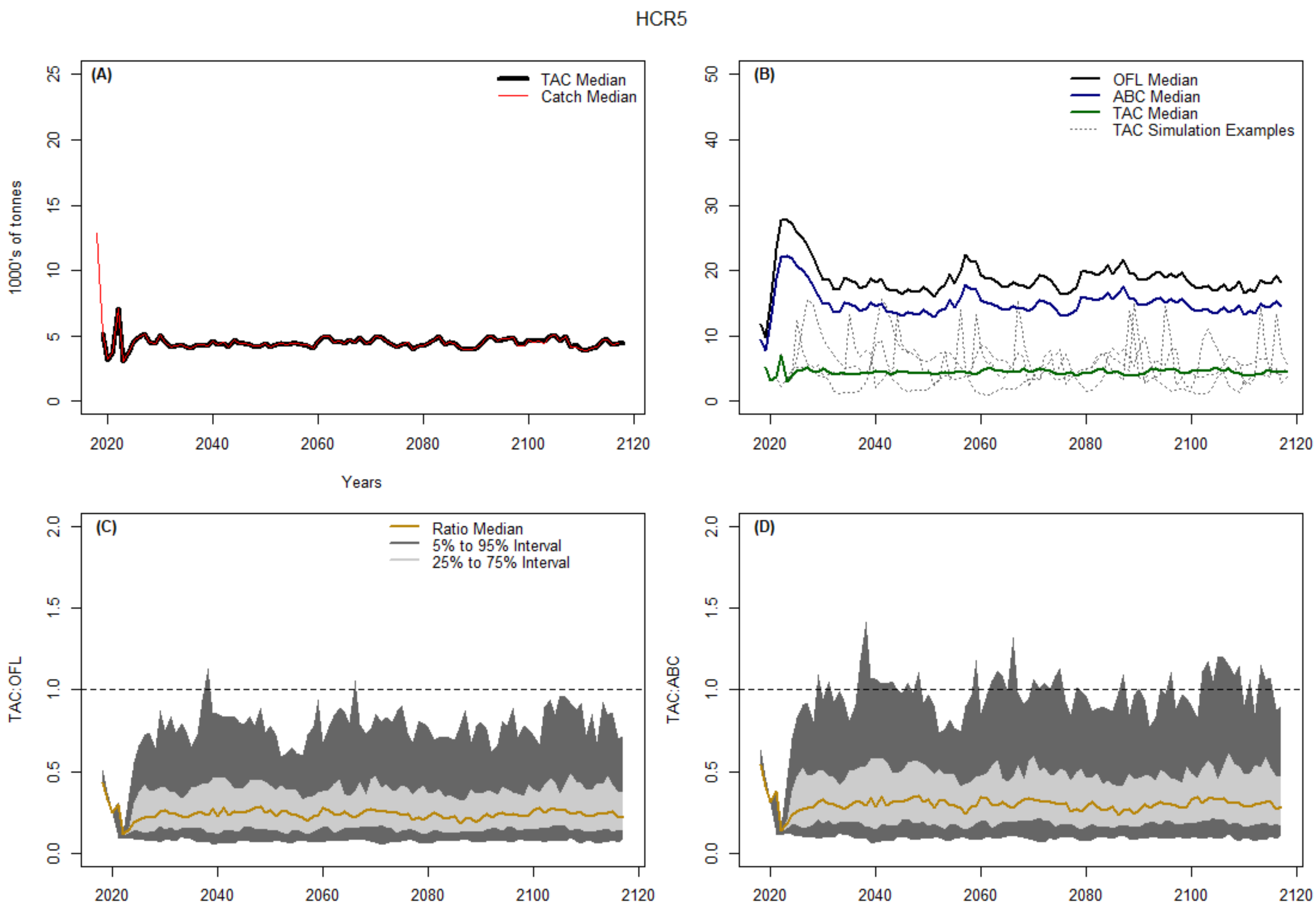

Figure A3.22: As for Figure A3.2, except for HCR5.

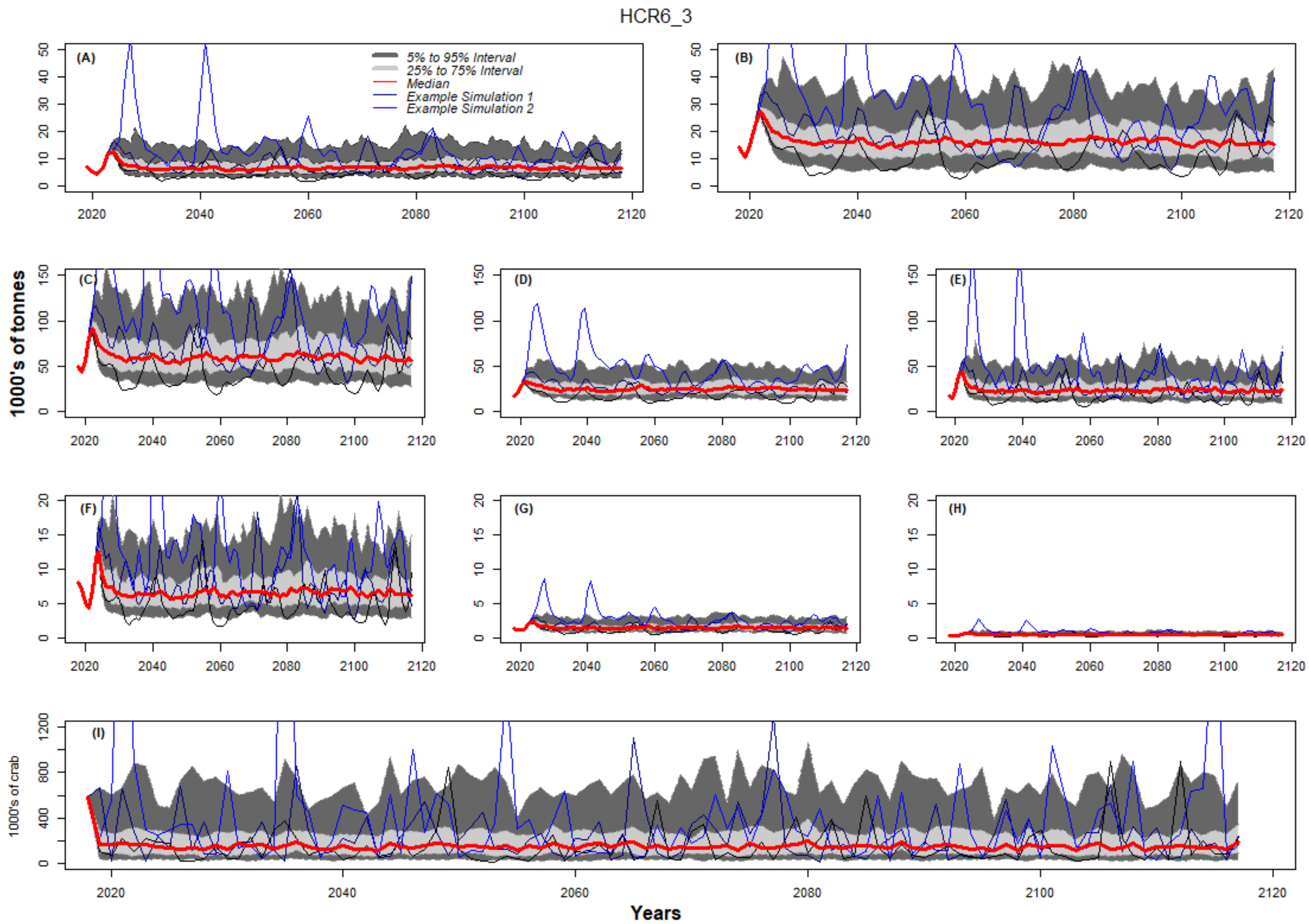

Figure A3.23: As for Figure A3.1 except for HCR6_3.

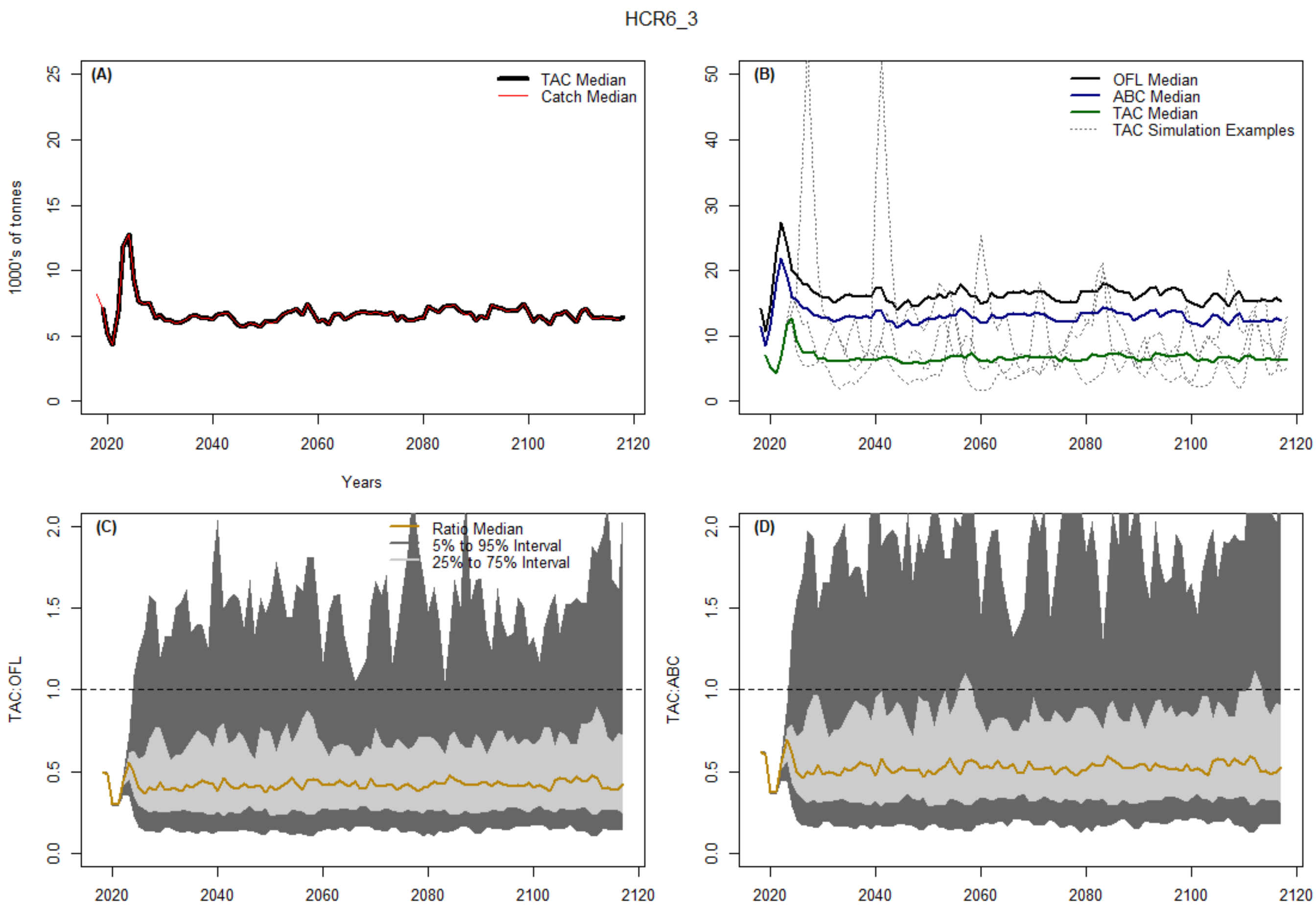

Figure A3.24: As for Figure A3.2, except for HCR6_3.

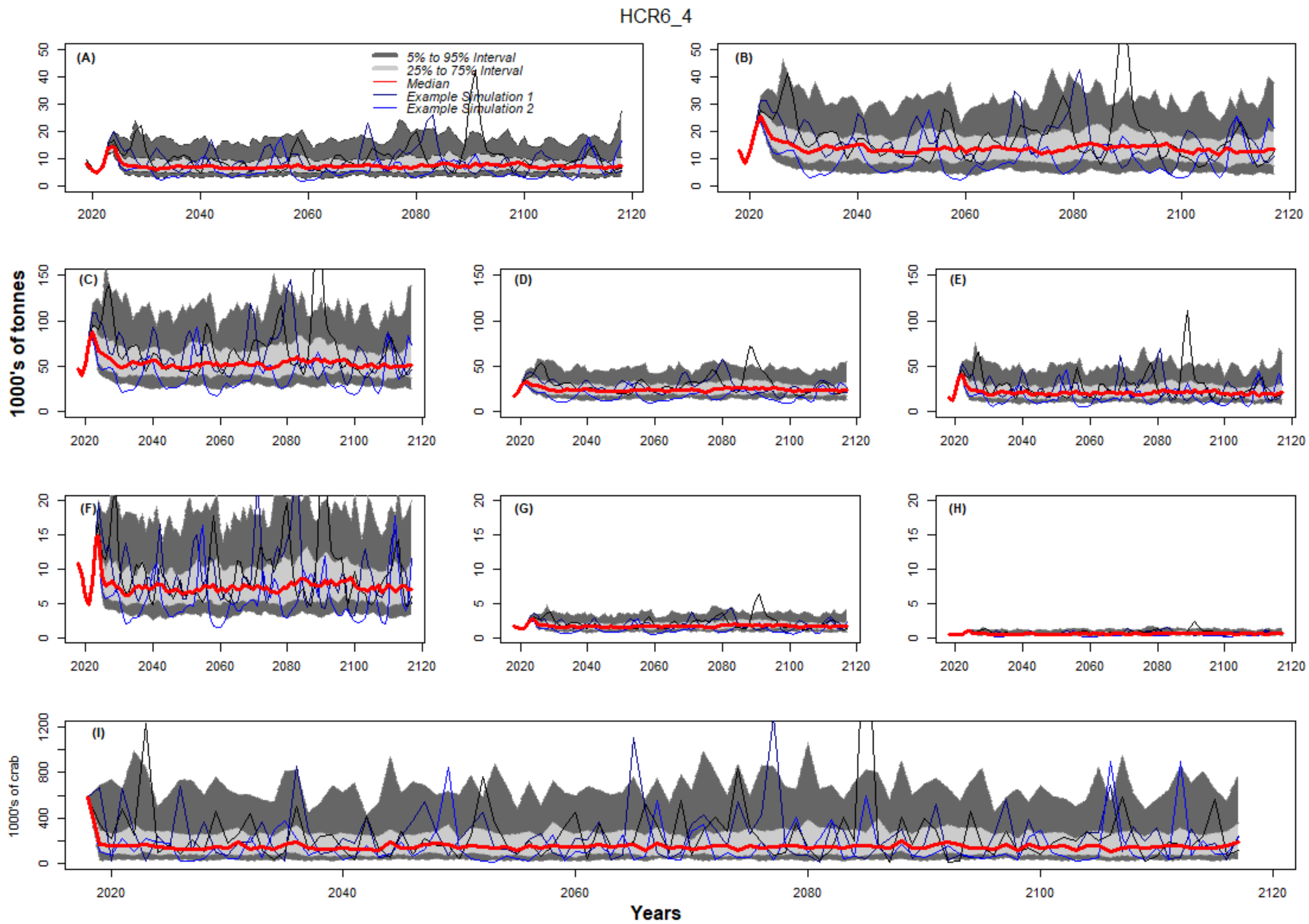

Figure A3.25: As for Figure A3.1 except for HCR6_4.

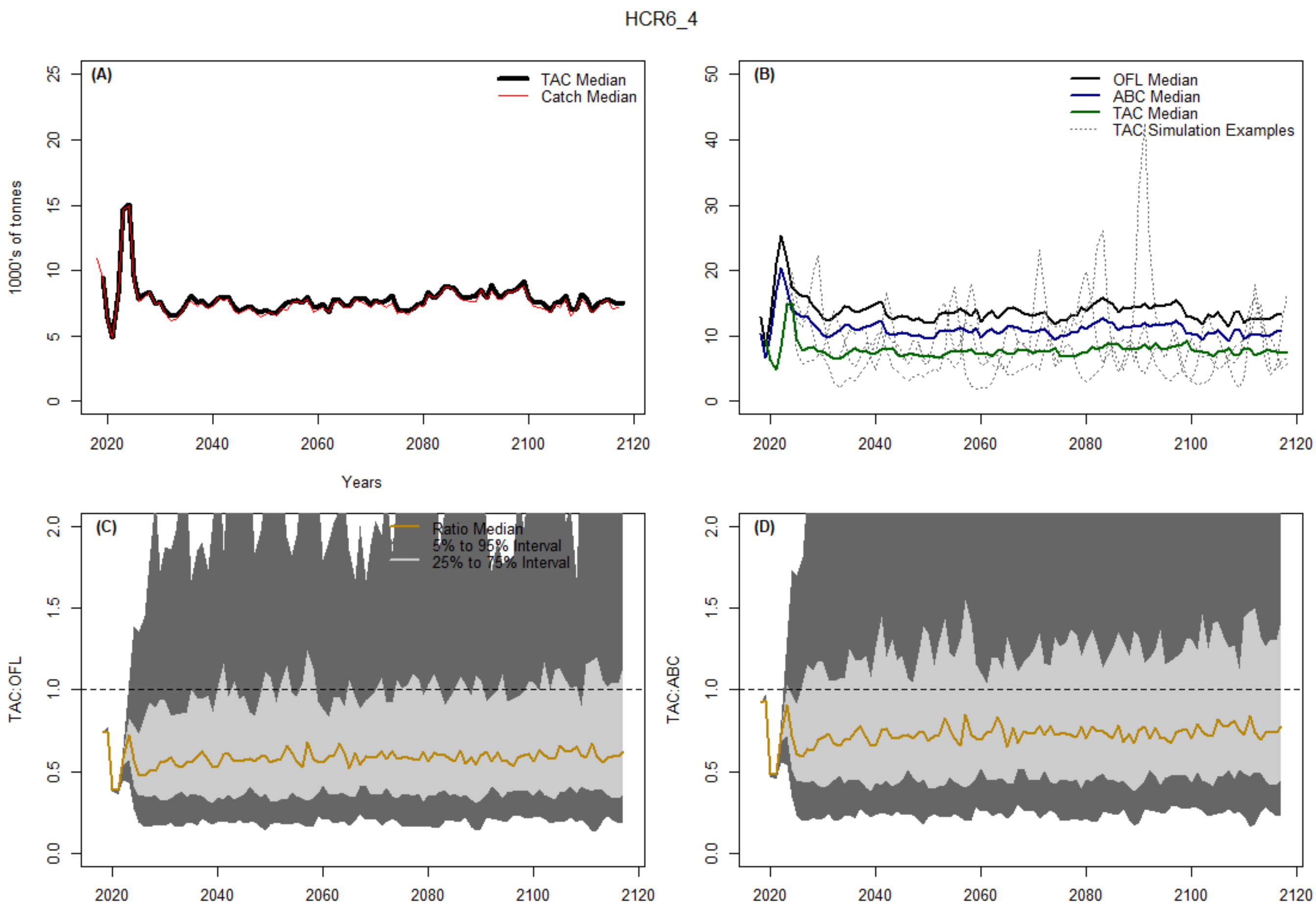

Figure A3.26: As for Figure A3.2, except for HCR6_4.

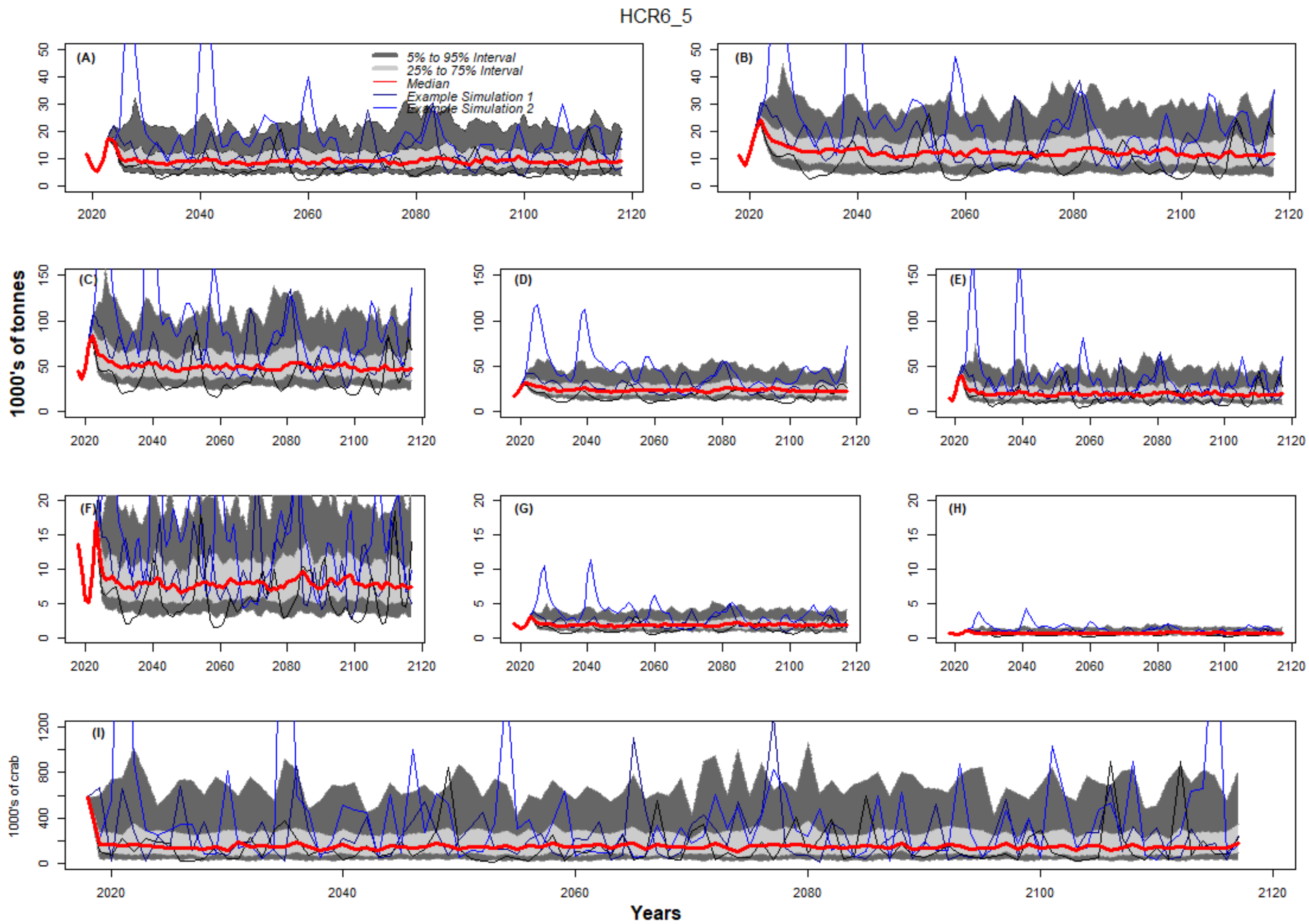

Figure A3.27: As for Figure A3.1 except for HCR6_5.

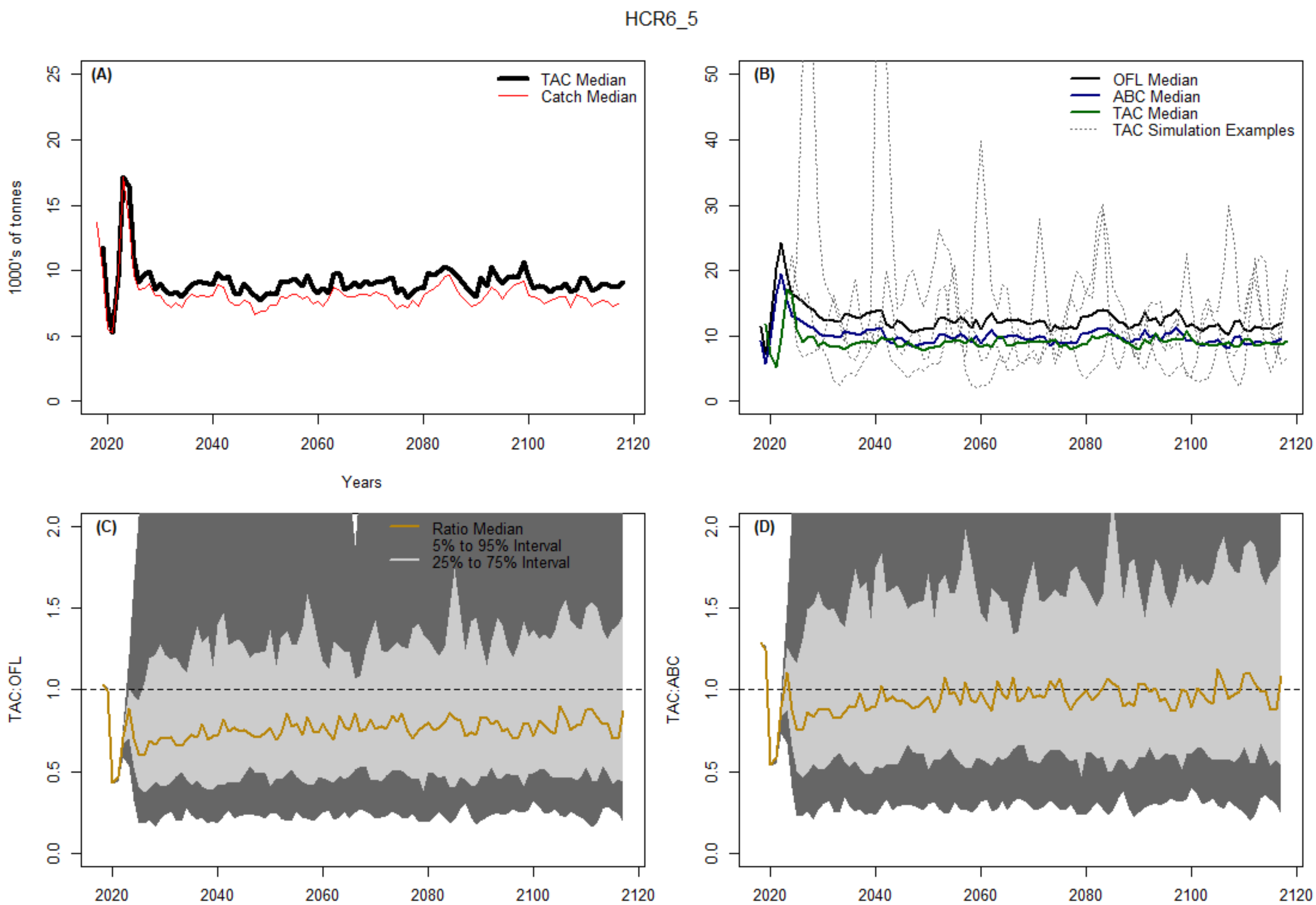

Figure A3.28: As for Figure A3.2, except for HCR6_5.

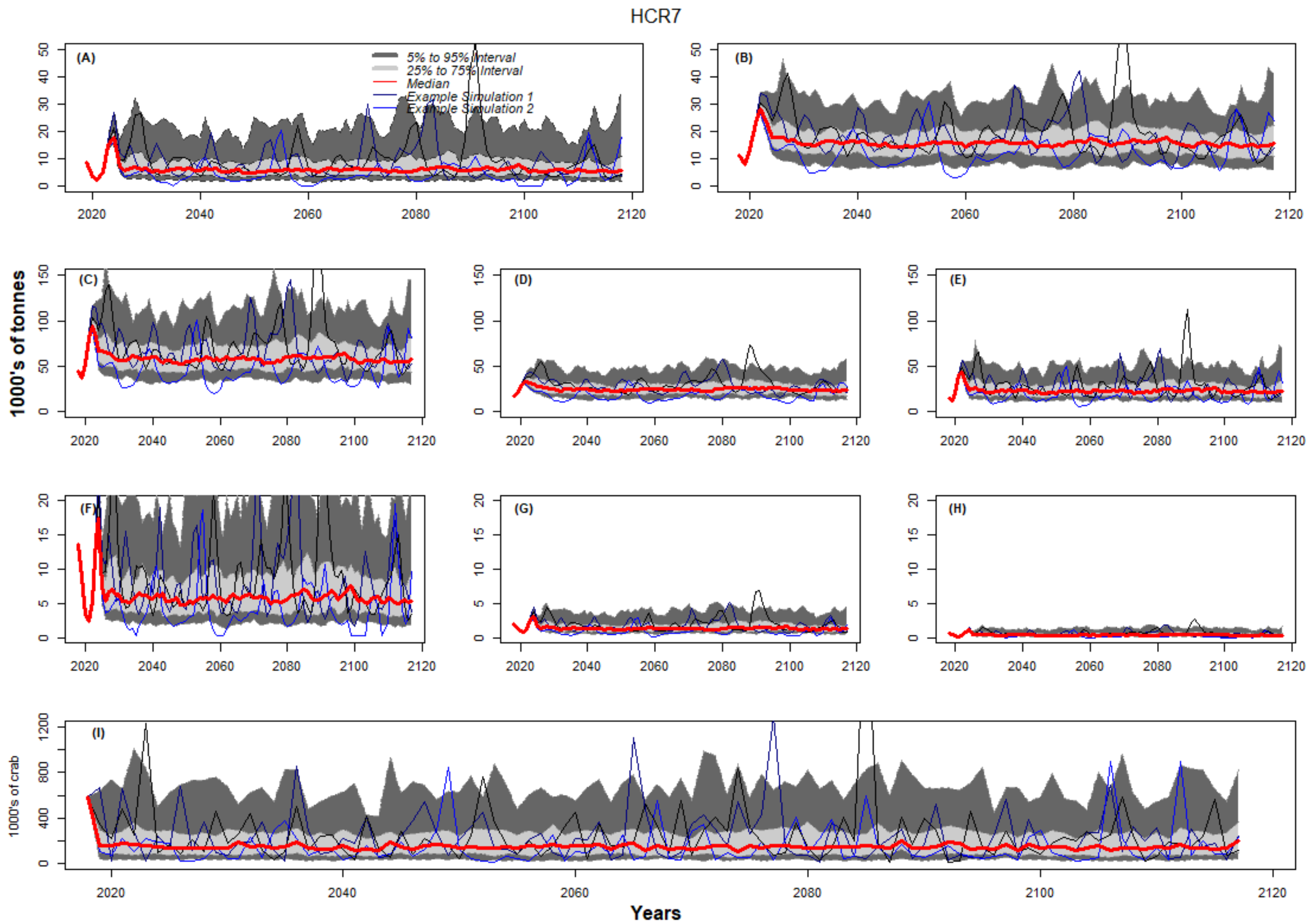

Figure A3.29: As for Figure A3.1 except for HCR7.

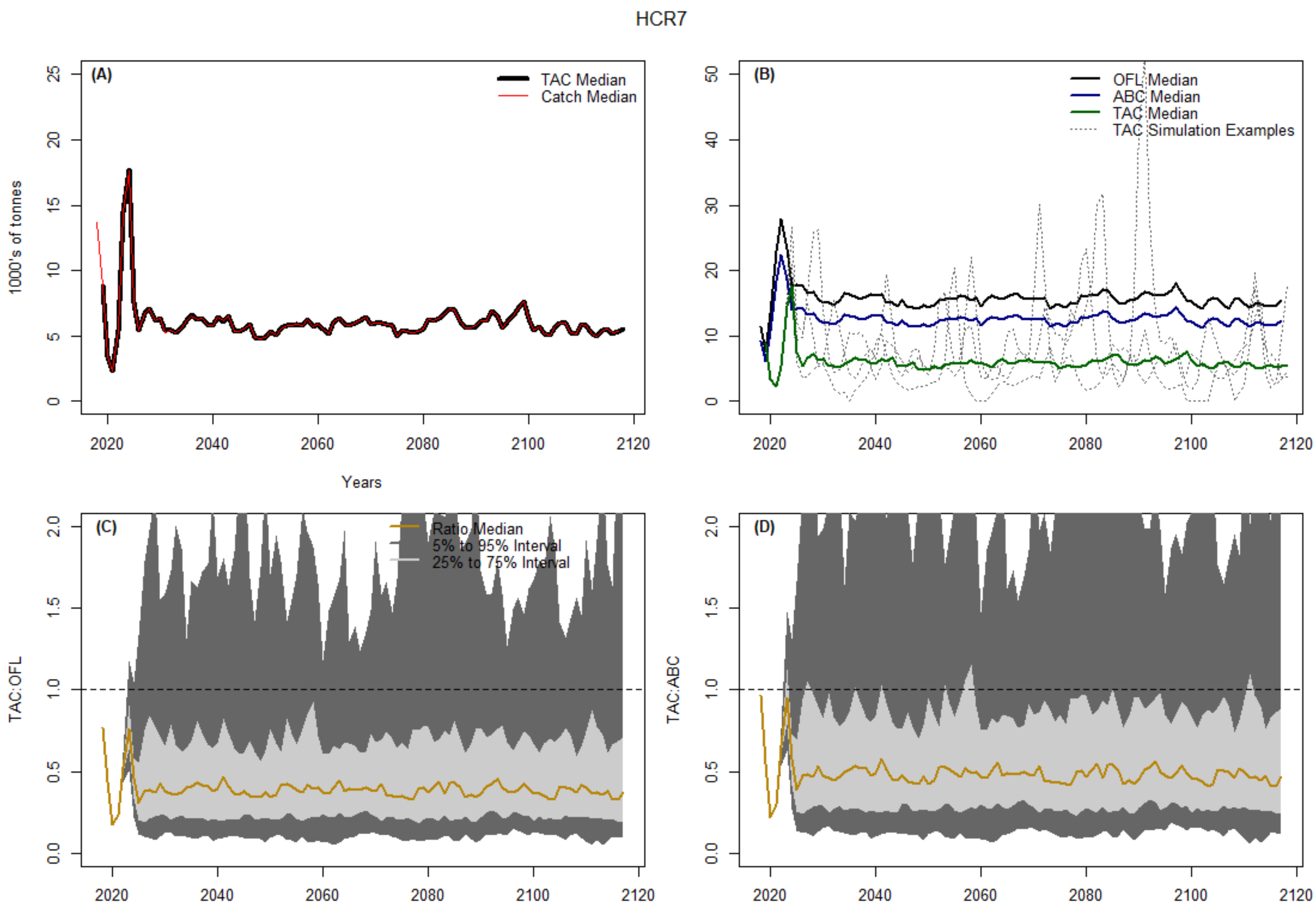

Figure A3.30: As for Figure A3.2, except for HCR7.