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Reproductive buffers on exploitation in male-only fisheries: Tanner Crab
(*Chionoecetes bairdi*) management strategy evaluation case study

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Abstract

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Eastern Bering Sea Tanner crab (*Chionoecetes bairdi*), one of Alaska's more cyclical fisheries, has one of the most complex harvest strategies of any Bering Sea-Aleutian Islands crab stock. This stock experiences major fluctuations in annual abundance and, although a male-only fishery, the state harvest control rule (HCR) used to set the allowable catch depends on the abundance of females. Failure to meet minimum thresholds on female abundance has led to fishery closures during five of the last ten fishing seasons. The economic performance of the fishery, linked to its frequent closures required by current management regulations, led to an industry-initiated effort to modify the state HCR to better account for stock status and reduce large inter-annual changes

in catch, as well as to evaluate the utility of including mature female biomass in the HCR. A workshop involving stakeholders, university affiliates, and managers concluded that management strategy evaluation was the most appropriate way to test candidate HCRs. Fifteen HCRs with various levels of incorporation of female stock levels (from primary to ignored) were tested using 100-year forecasts to evaluate how including females in harvest policies affected stock sustainability and productivity based on conservation and economic criteria. Several male-only HCRs performed similarly to HCRs that accounted for females, including those using mature female biomass (MFB) to determine the maximum exploitation rate on mature male biomass (MMB) as part of the HCR rather than as a threshold to open the fishery. HCRs including both sexes appropriately balanced conservation and economic considerations while acknowledging the uncertainty around reproductive dynamics given the lack of an identified stock-recruitment relationship. The harvest policy selected by the Alaska Board of Fisheries included: 1) a threshold for opening the fishery of 25% of average MMB during 1982–2018, 2) an exploitation rate for males based on the ratio of MMB to its long-term average, and 3) a maximum exploitation rate determined by the ratio of MFB to average MFB during 1982-2018. This HCR also included a maximum exploitation of 50% of exploitable, industry-preferred size legal male abundance.

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DEDICATION

This thesis is dedicated to women in science: those who have paved the way for following generations through their tenacity and leadership; those who are expanding on our understanding of the world today; and those who will attain unimaginable feats tomorrow. May we remember that we derive our strengths by persevering and supporting one another on our journeys.

Chapter 1. REPRODUCTIVE BUFFERS ON EXPLOITATION IN MALE-ONLY FISHERIES: TANNER CRAB (*CHIONOECETES BAIRDI*) MANAGEMENT STRATEGY EVALUATION CASE STUDY

1.1 INTRODUCTION

Fisheries management is a continually evolving process, and while managers and stakeholders often have competing objectives, tools for exploring management options through cooperation can be used when considering changes in management arrangements. Stakeholders have become integral to successful fisheries management, with stakeholder input in decision making becoming more common (Smith *et al.*, 1999). Decision-makers must identify risks and trade-offs associated with possible management strategies when balancing objectives. However, understanding risk and presenting management impacts on fisheries to stakeholders can be particularly challenging, especially when the context for management is complex, and the stock under review is subject to major fluctuations in abundance and biomass.

One complication to effective fisheries management is when stocks span multiple regulatory agencies, such as all the Eastern Bering Sea (EBS) crab stocks, which are co-managed by the National Marine Fishery Service (NMFS) and the Alaska Department of Fish and Game (ADF&G). The Fishery Management Plan (FMP) for these crab stocks establishes a State/Federal cooperative management regime that defers crab management to the State of Alaska with Federal oversight. Generally, the shared management occurs each year as part of the North Pacific Fishery Management Council process. This process involves conducting a federal stock assessment annually, incorporating index and length-composition data from the annual EBS bottom trawl survey, fishery data, and life history data (e.g., growth increments) to set Federal specifications for

stock status. Stock assessment models provide estimates of biomass and status relative to biological reference points. The primary biological reference points are the Overfishing Level (OFL; Appendix I) and the Allowable Biological Catch (ABC; the OFL reduced to account for scientific uncertainty, currently by 20%), which are requirements under the FMP. ADF&G then determines season openings and catch limits for the fishery (NPFMC, 2007) and though seasonal management must be consistent with Federal regulations, TAC setting is otherwise largely left to the ADF&G and the State of Alaska Board of Fisheries policy on stock-specific harvest. Each season, ADF&G determines if the fishery will open and sets a Total Allowable Catch (TAC) that must be lower than or equal to the retained legal component of the ABC using a harvest control rule (HCR; NPFMC, 2011).

Tanner crab (*Chionoecetes bairdi*) range from the western region of Bristol Bay into the Pribilof islands, overlapping in range with Bristol Bay red king crab (*Paralithodes camtschaticus*) and EBS snow crab (*Chionoecetes opilio*) (Zacher *et al.*, 2020). The EBS Tanner crab fishery is male-only, with a minimum legal landing size of 127 mm carapace width (CW) including the lateral spines (Zheng and Pengilly, 2011). Tanner crab are closely related to snow crab and, though larger, are often marketed as “snow crab,” as consumers do not recognize it as a separate species. Tanner and snow crabs experience a terminal molt to maturity (Stevens *et al.* 1993; Tamone *et al.* 2007), and the fishery prioritizes newly molted clean shell crab over old shell crab, often discarding a percentage of old shell crab caught. The directed fishery for Tanner crab is conducted using pot gear; Tanner crab are also caught as bycatch in the pot fisheries for snow crab and red king crab, and in bottom trawl fisheries for groundfish. Tanner crab are considered to be a single stock for calculation of the OFL and the ABC, but state management splits the fishery into two districts (East and West of 166° W longitude; Fig. 1) based on size at maturity (Somerton, 1981) and sets

separate TACs for each district based on the spatial distribution of crab biomass determined by the annual NMFS EBS shelf bottom trawl summer survey. OFLs for EBS Tanner crab are set by approximating B_{MSY} and F_{MSY} (the biomass and fishing mortality corresponding to maximum sustainable yield) by $B_{35\%}$ and $F_{35\%}$ (the biomass and fishing mortality corresponding to a reduction in spawning biomass per-recruit of 65%) (NPFMC, 2011).

The State TAC setting process is required to take both sexes into account when applying HCRs and in general, TAC setting for BSAI crab stocks uses a target exploitation rate for mature males as a function of estimated mature biomass (e.g., the Bristol Bay red king crab and snow crab fisheries; Zheng *et al.*, 1997; NPFMC, 2011). At the time this research was initiated, State HCRs for EBS Tanner crab were unique in that the biomass of females was required to exceed a minimum threshold for the Tanner crab fishery to open. If the female biomass is below the threshold, the fishery could not open and no further HCRs that determine male exploitation rates were considered. Thus, while fishing removals only minimally impact the biomass of females, the female biomass was a direct control on male exploitation rates. Part of the rationale for a two-sex system is the lack of a stock-recruitment (S-R) relationship, where spawning biomass cannot accurately predict incoming recruitment. From a management perspective, monitoring abundance and biomass of both sexes had led to additional conservation buffers when calculating desired exploitation levels. The last major update to Tanner crab management at the state level occurred in 2011 (Table 2), when the stock was declared overfished by the NMFS ($MMB < 0.5B_{35\%}$). This update involved changes to assumptions about terminal molt, and to size-at-maturity between the two districts. Under the 2011 strategy, a district was closed if the MFB for the year based on the NMFS survey was below 40% of the long-term (1975-2010) average. Similarly, a district was closed if MMB was below 25% of its long-term average. The calculated TAC for a year was halved

if the fishery was closed the previous year. This HCR was designed to maximize catch when both male and female biomass were high, with the 40% MFB threshold constraint imposed with the aim of ensuring recruitment success (Zheng and Pengilly, 2011). This HCR led to higher exploitation rates than the previous HCR (as expected), but peak exploitation rates failed to match the peaks in MMB (Fig. 2) and the HCR led to frequent season closures due to failure to reach the MFB threshold. These increasingly complex HCRs meant to improve Tanner crab management inadvertently widened the divide between resource conservation and fishery performance

The biomass of EBS Tanner crab has historically been cyclic due to highly variable recruitment (Stockhausen, 2018), resulting in frequent fishery closures (16 season closures since the establishment of the US fishery in 1974, and five during the last ten years) and changes to the state harvest strategy have often been considered reactionary, occurring after closure years. In March 2017, Tanner crab again became a focus of attention for stakeholders¹ and managers, and an HCR update was implemented with the understanding that a full re-evaluation of harvest management should occur. This update occurred following a fishery closure based on MFB the year after a two-decade peak in catches, despite a biomass of mature males that would support a fishery based on the ABC (Lang *et al.*, 2018). The State of Alaska Board of Fisheries modified the HCR language to match definitions from the federal assessment process, that is; female maturity was redefined based on morphology rather than carapace width, the definition of 'long-term average' was changed to 1982-2016 (to match the regime shift in recruitment when the Bering Sea changed to a fish-dominated system; Connors *et al.* 2002), the spatial range was expanded to include the entire EBS summer survey area, and an 'error band system' was introduced to account for survey

¹The Bering Sea Fisheries Research Foundation (BSFRF) prioritized Tanner crab research during 2017, focusing initially on working closely with Westward ADF&G staff on the small-scale revisions to the Tanner crab harvest strategy and communicating those changes to the industry. BSFRF hosted the collaborative workshop later in 2017 to set the stage for the development of the MSE and harvest strategy revision.

uncertainty that reduced the exploitation rate on males larger than 127 mm CW when the lower 95% confidence interval of the point estimate of MFB fell below 40% of the long-term average (ADF&G, 2017b; Table 2; Figs 3 and 4). The HCR for EBS Tanner previously had been the most complicated HCR for any BSAI crab stock, and the additional complexities introduced in 2017 raised questions as to whether these small but complicated changes were necessary and whether basing the fishery opening on a MFB threshold was appropriate (Daly, 2018). In December 2017, a cooperative effort between stakeholders and managers was convened through a workshop to evaluate Tanner crab research gaps and management options that could inform a simpler harvest strategy. The results of the cooperative workshop led to the recommendation for a full re-examination of Tanner crab HCR alternatives using a management strategy evaluation (MSE), with the HCR to be revised within the Alaska Board of Fisheries process and schedule.

Management Strategy Evaluation is the standard way to evaluate proposed alternative management strategies and includes stakeholder and manager input. MSEs can be used to evaluate the consequences of alternative management strategies (Punt *et al.* 2016) and 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. MSE has been used to evaluate the consequences of factors likely to influence the ability to achieve management objectives, such as natural mortality values or temperature changes (Mapstone *et al.*, 2007), or levels of exploitation and resulting trends in biomass for candidate strategies (Siddeek *et al.*, in press).

This paper provides a case study in the evaluation of candidate HCRs using MSE, informing decision-makers about the consequences of alternative HCRs tailored to the nature of the stock

while also integrating industry stakeholders at all levels of the process. 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 an HCR that is focused on male-only exploitation.

1.2 METHODS

1.2.1 *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 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 (Table 3), developed in collaboration with stakeholders, to identify an HCR that was simpler than the then-current HCR and that achieved the conservation and economic goals. The HCRs, which 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 an 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 developed iteratively and 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 Tanner crab assessment model, which is implemented in ADMB (Fournier *et al.*, 2012; Stockhausen, 2018), modified for MSE purposes. Each strategy was projected 100 times for 100 years to identify trends and evaluate risk in terms of sustainability and economic metrics. While MSE usually involves a larger number of simulations, this project 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).

1.2.2 *Operating model*

The operating model represents the “true” population in the MSE. For this study, it was based on the population dynamics model used for the 2017 federal Tanner crab assessment, TCSAM02, modified to conduct projections (see Appendix II for the values for the parameters of the operating model). TCSAM02 is a size-structured, two-sex, single-species model that keeps track of crabs by maturity state (immature and mature), and shell condition (old and new shell). The estimation method is based on maximum likelihood, but with Bayesian-like 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 in the

directed and bycatch fisheries). The model represents crab in 32, 5mm size-classes from 25-185 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 fishery, fishery for the red king crab in Bristol Bay, and various groundfish fisheries; Stockhausen, 2017). 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, $N_{y,x,m,s,z}^1$ (see Table 1 for a list of symbols) is calculated as:

$$N_{y,x,m,s,z}^1 = N_{y,x,m,s,z} e^{-M_{x,m,z} \delta^F} \quad (1)$$

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 partition², 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):

$$N_{y,x,m,s,z}^2 = N_{y,x,m,s,z}^1 e^{-F_{y,x,z}^T} \quad (2)$$

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

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

where $\tilde{F}_{f,y}$ is the mortality due to fishery f during year y , λ_f is the handling mortality for crab discarded by fishery f , $\theta_{f,x,z}$ is the fishery selectivity by fishery, sex, and size, and $\Omega_{f,x,z}$ is the retention probability by fishery, sex, and size, quantifying the proportion of crabs retained.

²Natural 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.

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 normal (i.e., "dome-shaped"). 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. Handling mortality was assumed to be 0.321 for pot fisheries and 0.80 for groundfish trawl fisheries.

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 tested strategies), 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:

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

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

$$N_{y,x,MAT,NS,z}^4 = \phi_{x,z} \sum_{i \leq z} X_{x,z,z'} N_{y,x,IMM,NS,z'}^3 \quad (5.1)$$

$$N_{y,x,IMM,NS,z}^4 = (1 - \phi_{x,z}) \sum_{i \leq z} X_{x,z,z'} N_{y,x,IMM,NS,z'}^3 \quad (5.2)$$

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, i.e., the probability of a crab of sex x and size z' molting to size z . The size transition matrix is calculated as:

$$X_{x,z,z'} = \left[\sum_{z'} [z - z']^{\alpha_{x,z'-1}} * e^{\frac{z-z'}{\beta_x}} \right]^{-1} [z - z']^{\alpha_{x,z'-1}} * e^{\frac{z-z'}{\beta_x}} \quad (6.1)$$

$$\alpha_{x,z'} = \frac{[\bar{z}_{x,z'} - z']}{\beta_x} \quad (6.2)$$

$$\bar{z}_{x,z'} = e^{\alpha_{x,z'} \beta_x} \quad (6.3)$$

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 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:

$$N_{y,x,MAT,OS,z}^4 = N_{y,x,MAT,OS,z}^3 + N_{y,x,MAT,NS,z}^3 \quad (7)$$

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 (\ddot{R}_z). The total recruitment is generated by randomly selecting a previously fit recruitment value from a pool of estimates from 1974-2017 in the stock assessment.

$$N_{y+1,x,m,s,z} = \begin{cases} N_{y,x,IMM,NS,z}^4 e^{-M_{x,IMM,z}(1-\delta^M)} + R_{y,x,z} & \text{when } m = IMM, s = NS \\ N_{y,x,m,s,z}^4 e^{-M_{x,m,z}(1-\delta^M)} & \text{otherwise} \end{cases} \quad (8.1)$$

$$R_{y,x,z} = \dot{R}_y \ddot{R}_x \ddot{R}_z \quad (8.2)$$

$$\ddot{R}_z = \frac{(z + \frac{\delta Z}{2} - z_{min})^{\frac{\partial}{\varphi} - 1} e^{-\frac{z + \frac{\delta Z}{2} - z_{min}}{\varphi}}}{\sum_z (z + \frac{\delta Z}{2} - z_{min})^{\frac{\partial}{\varphi} - 1} e^{-\frac{z + \frac{\delta Z}{2} - z_{min}}{\varphi}}} \quad (8.3)$$

where θ 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:

$$C_y^{Ret} = \sum_m \sum_s \sum_z w_{MALE,z} \frac{\Omega_{f,x,z} F_{DIR,y,MALE,z}}{F_{y,MALE,z}^T} (1 - e^{-F_{y,MALE,z}^T}) N_{y,MALE,m,s,z}^1 \quad (9.1)$$

$$C_y^T = \sum_x \sum_m \sum_s \sum_z w_{x,z} N_{y,x,m,s,z}^1 (1 - e^{-F_{y,x,z}^T}) \quad (9.2)$$

where C_y^{Ret} is landed catch biomass for the directed fishery during year y , C_y^T 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 fleet and by partition, $F_{y,x,z}^T$ is the fishing mortality on Tanner crab of sex x due to all fisheries by partition (Eq 3), and $N_{y,x,m,s,z}^1$ 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 by size class ($F_{DIR,y,MALE,z}$) is selected to minimize the sum of the squared differences between the TAC for year y ($TAC_y - C_y^{Ret}$)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 $100 (C_y^T - OFL_y - 0.01)^2$ if C_y^T is greater than OFL_y .

1.2.2.1 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) single molt growth increment data. No future growth 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.

1.2.3 *Estimation method*

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

1.2.4 *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}),

$$MMB_y = \sum_s \sum_z w_{x,z} N_{y,MALE,MAT,S,Z}^3 \quad (10.1)$$

$$MFB_y = \sum_s \sum_z w_{x,z} N_{y,FEM,MAT,S,Z}^3 \quad (10.2)$$

along with a threshold for opening the fishery (e.g., $MMB_y > 0.25MMB_{ave}$), 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):

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

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 127mm+ 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 ($E_{MMB,y}$) increases from 0.05 when MFB_y equals $0.25MFB_{ave}$ 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): $E_{MMB,y}$ increases from 0.05 when MMB_y equals $0.25MMB_{ave}$ to x_i when MMB_y is equal to or exceeds MMB_{ave} where x_i represents various maximum exploitation rates ($x_i=0.1, 0.15, 0.2, \text{ and } 0.225$) (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: $E_{MMB,y}$ depends on both MMB/MMB_{ave} and MFB/MFB_{ave} . $E_{MMB,y}$ increases from 0.05 when $MMB_y = 0.25MMB_{ave}$ 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 $E_{MMB,y}$ increases from 0.1 when $MMB_y = 0.25MMB_{ave}$ to 0.2 when $MFB \geq MFB_{ave}$ (Fig. 6D).

- HCR 4_3: same as HCR 4_1, except that $E_{MMB,y}$ increases from 0.1 when $MMB_y = 0.25MMB_{ave}$ 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 $E_{MMB,y}$ depends on blocked ranges of MFB_y/MFB_{ave} . The maximum $E_{MMB,y}$ starts at 0.05 if $MFB_y/MFB_{ave} < 0.3$ and increases to 0.1 when $0.3 < MFB_y/MFB_{ave} < 0.5$, to 0.15 when $0.5 < MFB/MFB_{ave} < 0.7$, and to 0.2 when $MFB/MFB_{ave} > 0.7$ (Fig. 6F) depending on MMB/MMB_{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): $E_{MMB,y}$ is set using a combination of the control rules 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:

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

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.

1.2.5 *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 as a factor 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).

The conservation performance metrics focus on satisfying pre-specified federal management objectives expressed in terms of the probability of MMB exceeding biological reference points, including the probability of MMB being below the minimum stock size threshold (MSST, the threshold for being “overfished” = $0.5B_{MSY}$ with $B_{35\%}$, i.e. [$B_{35\%}$ is 35% of the expected unfished MMB], being the proxy for B_{MSY}), the probability of total catch mortality (Eq 9b) exceeding the operating model (i.e., true) OFL and ABC, representing overfishing and being in the “danger zone” with a risk of approaching overfishing, and the probability of $MMB < B_{MSY}$. In addition, 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 the ratio of MMB to $B_{35\%}$ was also reported.

The economic performance metrics involved the probability of fishery closures, mean TAC (requested by stakeholders as a primary metric of interest), and average annual variation (AAV; over years (n_y) and simulations (n_s)) in TAC:

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

where $TAC_{y,s}$ is the TAC for year y and simulation s . Economic performance metrics also included 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. This probability was also indicative of population levels relative to the long-term average - a reference point requested by ADF&G. Additionally, the probability of the TAC exceeding catch limits was requested by industry stakeholders: 2,268, 4,536, and 9,072 metrics tons equivalent to 5, 10, and 20 million lb. respectively. Stakeholders 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. 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 summary statistics were based on the years once the model outputs stabilized.

To evaluate the combination of conservation and economic criteria, trade-offs between the highest priority economic metric for stakeholders and ADF&G, mean TAC (Table 5), were compared to conservation reference points 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 (Appendix III, Fig A3.1–A3.30)³.

³ Note that the median landed catch trajectory is not always equal to the TAC trajectory for strategies that involve higher exploitation rates because this would have led to total catches in excess of the OFL (e.g. Figures A3.12, A3.26, A3.28).

1.3 RESULTS

1.3.1 *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.

1.3.2 *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., $\Pr(\text{MMB} < \text{MSST})$; 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 very little fishing pressure on females (only discard in the pot fisheries, and fishing by the groundfish fishery) and 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 $\text{MMB}/B_{\text{MSY}}$ still exceeded 1.8 for these strategies.

1.3.3 *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 (5,200t and 5,600t, 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. 8E), with HCR 2_1 having the lowest TAC variability (0.18) and HCR 7 having the greatest (0.47) (Fig. 9). All HCRs, except 4_1, led to a probability of the TAC exceeding 5 million lbs. 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, was greater or equal to 0.5 for HCRs 3, 6_50, and 6_4. This probability and 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.

1.3.4 *Trade-offs*

Trade-offs are shown in Fig. 8 where mean TAC is plotted against the conservation metrics defined by ADF&G; $\Pr(\text{MMB} < B_{\text{MSY}})$ (Fig. 8A), $\Pr(C^T > \text{OFL})$ (Fig. 8B), $\Pr(C^T > \text{ABC})$ (Fig. 8C), and TAC variation (Figs 8D-E). Both ADF&G and stakeholders identified mean annual TAC variability as a metric for stability in a historically highly variable fishery. Generally, strategies that fall in the upper left-hand quadrants of Figs 8A-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 8A-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 50% 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 falling into the danger zone approaching overfishing (upper-right-hand quadrant), 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. All remaining scenarios had average TACs that were above 10m lbs. (Fig. 8E).

HCRs 2_1, 2_2, and 5 were in the lower left-hand quadrant in Figs 8A-C, with lower TACs and lower risk of exceeding conservation thresholds. When considering TAC variability, HCR 5 was in the lower right-hand quadrant, with a low average TAC and higher TAC variability. HCR 7, the status quo rule, was in the upper left quadrant with a higher average TAC and a lower conservation risk, except for TAC variability, where it was in the upper right-hand quadrant exhibiting 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.

1.4 DISCUSSION

This The fifteen potential state HCRs evaluated in this work arose from extensive discussion and deliberation among Tanner crab stakeholders and managers who recognized the inconsistency between fishable biomass and TAC setting resulting from the conservative nature of the then-current strategy. The aim of the MSE was to evaluate and compare HCRs that included conservation buffers and set TACs to maintain the reproductive capacity of the stock without sacrificing catch when the stock is healthy.

The process initially started with seven candidate HCRs (1, 2_3, 3, 4_1, 5, 6_3, 6_4, 6_5, 7), which became the base HCR categories for the suite of fifteen HCRs as managers responded to industry feedback and preliminary results.

1.4.1 *Initial strategy elimination*

The ADF&G ranked the candidate HCRs based on the MSE outcomes and input from stakeholders. Given the results for the conservation and economic metrics, they eliminated some strategies given 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 OFL determined under the federal assessment process. These three rules were consequently removed from further consideration. The least risky HCRs in terms of conversation were 2_1, 2_2, and 5, and while they were sufficiently cautious, they performed relatively poorly in terms of the economic criteria and were eliminated from further consideration.

The remaining nine HCRs had similar mean TACs and values for the other performance statistics, but differed in how females were treated, and the upper and lower bounds for exploitation rate. 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, an HCR for a male-only fishery based only on MFB was not an option that stakeholders were willing to accept, especially given the recent fishery closures based on MFB relative to its long-term average. The variants of HCR 4, with different maximum 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 voiced 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 control rules (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.

1.4.2

Sex-based reproduction buffers

The next step in the selection process was to consider whether reproductive buffers should be included in the final strategy or to move to a male-only HCR. The discussion over reproductive buffers in turn relies on how reproduction in fisheries assessments can be quantified using a stock-recruitment (S-R) relationship. The S-R relationship 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 generally do not have a well-defined S-R relationship due to major uncertainties in processes that impact survival in juvenile stages (Wahle, 2003). While some crab stocks (e.g., Bristol Bay red king crab) have a weak S-R relationship, Tanner crab have recruitment events that are highly erratic with no clear relationship to the abundance of spawning 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 an index of reproductive potential (e.g., Webb *et al.*, 2016). Conservation buffers applied in years with low MFB were designed to ensure sperm availability for females. However, there has been no indication of failed fertilization in female Tanner crab in the EBS, and thus recruitment variability may depend more on environmental factors such as food availability or predation.

Despite lack of evidence for recruitment failure being related to insemination of females, *Chionoecetes* species have a temporal maturity mismatch, where females mature more quickly and at smaller sizes than males (Donaldson *et al.*, 1981) and trends in mature male biomass can lag those in females. Given the uncertainty in recruitment, paired with a possible offset in the mating

windows of male and female Tanner crab, there were conservation concerns by ADF&G related to the preservation of adequate males to be available to mate with females. Specifically, there was concern that harvest could occur under a male-only HCR if there were a surplus of males available for mating but female abundance and biomass were depressed. This was the rationale for the original female threshold on/off switch, and later the revised HCR options that included female determination of the exploitation range for mature male exploitation.

1.4.3 *Policy decision*

While HCRs 2_3, 2_4, 4_1, 4_2, and 4_3 all had similar values for the performance metrics, given the poor understanding and ability to quantify reproductive dynamics, ADF&G noted that male-only control rules would be inconsistent with the Board of Fisheries policy on Tanner crab management (ADF&G, 1990⁴) and HCRs 2_3, and 2_4 were removed from consideration. The decision by the *bairdi ad hoc* committee was to bring the suite of HCR4 strategies (4_1, 4_2, and 4_3) forward for presentation to the Alaska Board of Fisheries (the decision-maker). This decision was supported, and mirrored, by the ADF&G cooperative research partners responsible for oversight of the Bering Sea fisheries (ADF&G Westward staff). 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 Alaska Board of Fisheries. Any of the presented

⁴ 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.

strategies would have resulted in a substantial increase in TAC compared to the existing strategy, and this 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 lead the Board to adopt HCR 4_1 (Daly *et al.*, 2020) with threshold year averages updated to 1982-2018, given that this rule slightly favored conservation over economic metrics compared to the alternatives.

1.4.4 *MSE limitations*

HCR 7 acted as a proxy for the status-quo, or previously implemented, HCR in the MSE. While the HCR performed well in terms of both economic and conservation criteria, it also had a low chance of fishery closures, which is not reflective of reality. The actual implementation of the status-quo strategy allows 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 not met. While the MSE was able to generally capture the cyclic nature of population dynamics, MFB was generally stable (Appendix III Fig. A3.29), so female biomass did not drop below thresholds that would have resulted in a fishery closure, and this resulted in HCR 7 having better performance in the MSE than in reality. The operating model does not account for the uncertainty surrounding Tanner crab spawning dynamics. The MSE used the federally approved assessment model as the foundation for the operating model, but given the lack of an understood S-R relationship for Tanner crab, future recruitment was generated by resampling from historical estimates of recruitment. This implies that (hypothetically) there should be recruitment even in the absence of females. 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 given the confidence they had in it, and the estimation model was also based on the same assessment.

1.4.5 *Cooperative engagement and conclusions*

MSEs are based on understanding uncertainties and modeling limitations, and are an effective way to compare exploitation controls in a simulated setting, therefore protecting fisheries from harvest experimentation. Cooperative efforts involving managers, scientists, and industry representatives, ensure that 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 polarizing concepts such as whether to include females in the HCR for a male-only fishery that minimally impacts females.

This MSE was proposed following a challenging time between the crab industry and managers, and managers recognized that the HCR for Tanner crab needed to be re-evaluated. The *bairdi* workshop initiated a new relationship for the Tanner crab industry and state managers, providing a platform where industry concerns and ideas could be directly included in a robust evaluation of HCR strategies using MSE to better address both industry and state management objectives. The MSE aimed to explore how HCRs with, and without, female consideration would perform, and decision-makers were faced with choosing between a male-only control rule, and a two-sex control rule. There was distrust by industry representatives on any inclusion of females, as they were seen as a hurdle to fishing and not as a conservation metric, especially given the past performance of the status quo HCRs in reality, which used female biomass as a threshold for opening the fishery.

The use of females to determine the maximum exploitation rate, as opposed to an on/off switch, was more generally accepted by industry. Moreover, the similar performance of the male-only vs. the two-sex rules using females to scale maximum exploitation instead of closing the fishery helped with acceptance of reproductive conservation buffers as part of the HCRs, given evidence of similar average TACs, with lower TACs in years where biomass of males and females were declining.

Comprehensive discussion, appropriate additions to tested HCRs, and corresponding performance criteria, as requested by state managers and industry, led to a cooperative environment built on trust. This trust allowed for a robust and transparent re-evaluation of the Tanner crab strategy leading to a rapid adoption of a new HCR with a unified body of supporters. The cooperative effort was vital in addressing previous frustrations; it established new relationships and ultimately made possible the adoption of a strategy inclusive of both sexes in a less restrictive manner. This process represented the best available method to select a strategy that would best serve to improve the fishery stability and satisfy stakeholders, while accounting for conservation metrics critical to Alaskan state management.

TABLES

Table 1 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	
<i>ELM</i>	Exploitable Legal Males	z
FMP	Fishery Management Plan	
F_{MSY}	Fishing Mortality corresponding to maximum sustainable yield, approximated by the F that reduces in spawning biomass per-recruit of 65%	
HCR	Harvest Control Rule	
MFB	Mature Female Biomass	
MFB_{ave}	Long Term Average Mature Female Biomass	
MMB	Mature Male Biomass	y
MMB_{ave}	Long Term Average Mature Male Biomass	
MSE	Management Strategy Evaluation	
NPFMC	North Pacific Fisheries Management Council	
NMFS	National Marine Fishery 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
\bar{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
\dot{R}	Recruitment	y,x,z
Parameters		
$\alpha, b, \text{ and } \beta$	Arithmetic-scale parameters	x
α	Mean molt increment scaled by β	x,z'
δ 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
X	Size transition matrix	x, z, z'
\bar{z}	Mean size after molting	x,z'

Table 2 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 \geq 79 mm CW, east of 173° W)	0.40 of 1975-2010 average (females \geq 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 \geq 9,525 metric tons and <20,411, 0.20 when females are \geq 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 \geq 139 mm CW x fishery selectivity; West: males \geq 127 mm CW x fishery selectivity	East: males \geq 127 mm CW x fishery selectivity; West: males \geq 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 3 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	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+MMB}	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 4 Summary of how the future 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 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	$\Pr(\text{MMB} < \text{MSST})$	Probability of the stock being in an overfished state	S, F, I
Conservation	$\Pr(C^T > \text{OFL})$	Probability of overfishing occurring	S, F, I
Conservation	$\Pr(C^T > \text{ABC})$	Probability of getting close to overfishing	S, F, I
Conservation	$\Pr(\text{MMB} < B_{\text{MSY}})$	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	$\text{MMB}/B_{\text{MSY}}$	Ratio MMB to B_{MSY}	S, F
Economic	$\Pr(\text{Closure})$	Probability of fishery closure	S, F, I
Economic	Mean TAC	Average TAC	S, I
Economic	TAC Variation	Interannual variability in TACs	S, I
Economic	$\Pr(\text{TAC} > 5\text{m lbs})$	Probability of TAC greater than 5m lbs	I
Economic	$\Pr(\text{TAC} > 10\text{m lbs})$	Probability of TAC greater than 10m lbs	I
Economic	$\Pr(\text{TAC} > 20\text{m lbs})$	Probability of TAC greater than 20m lbs	I
Economic	$\Pr(\text{MMB} < \text{Ave})$	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 columns highs and the – columns 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 1000's 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 columns highs and the – columns lows (omitted for columns with multiple zero values).

HCR	Pr(Closure)	Mean TAC	TAC Variability	Pr(TAC > 5m lbs)	Pr(TAC > 10m lbs)	Pr(TAC > 20m 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	

FIGURES

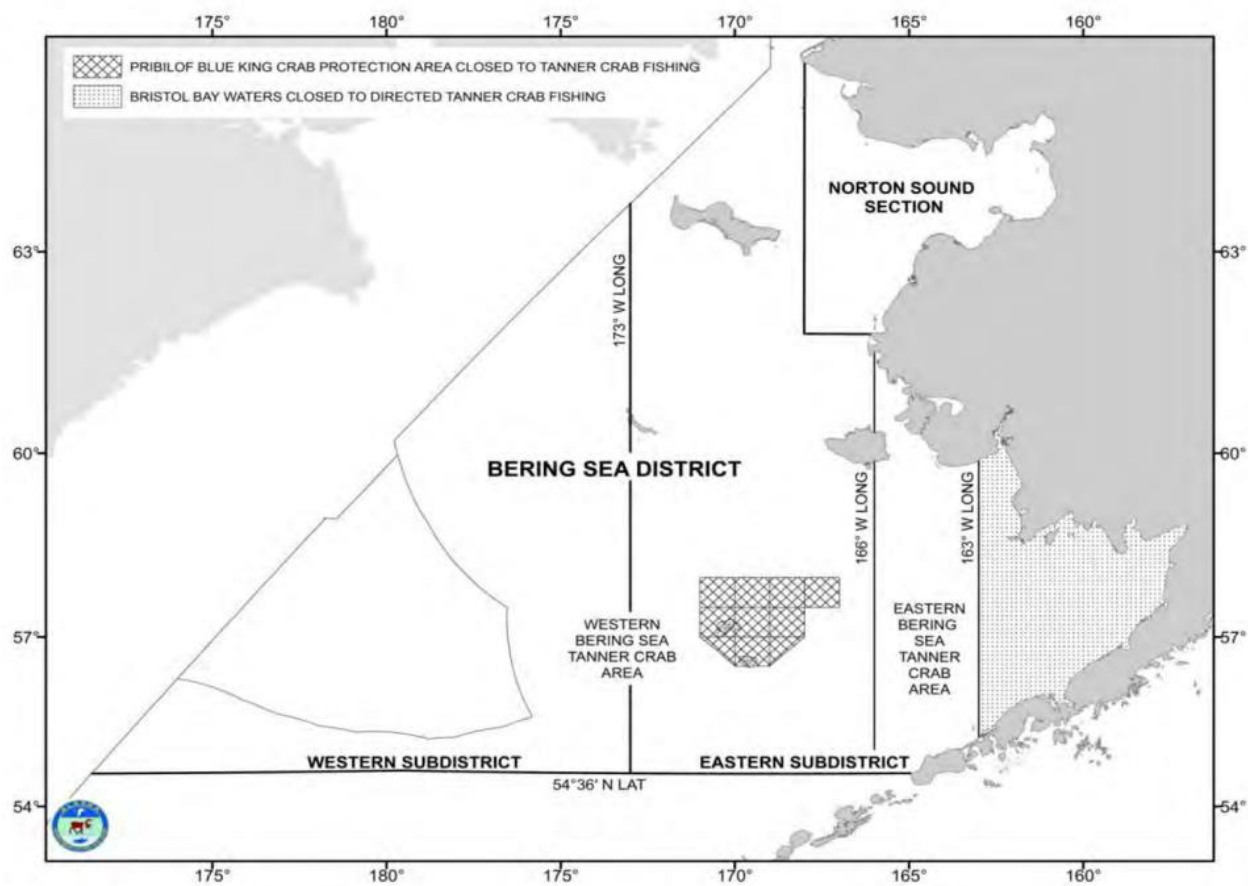


Figure 1 Bering Sea ADF&G district boundaries, where the western Bering Sea Tanner crab district is west of 166° W and the eastern district is east of 166° W to 163° W.

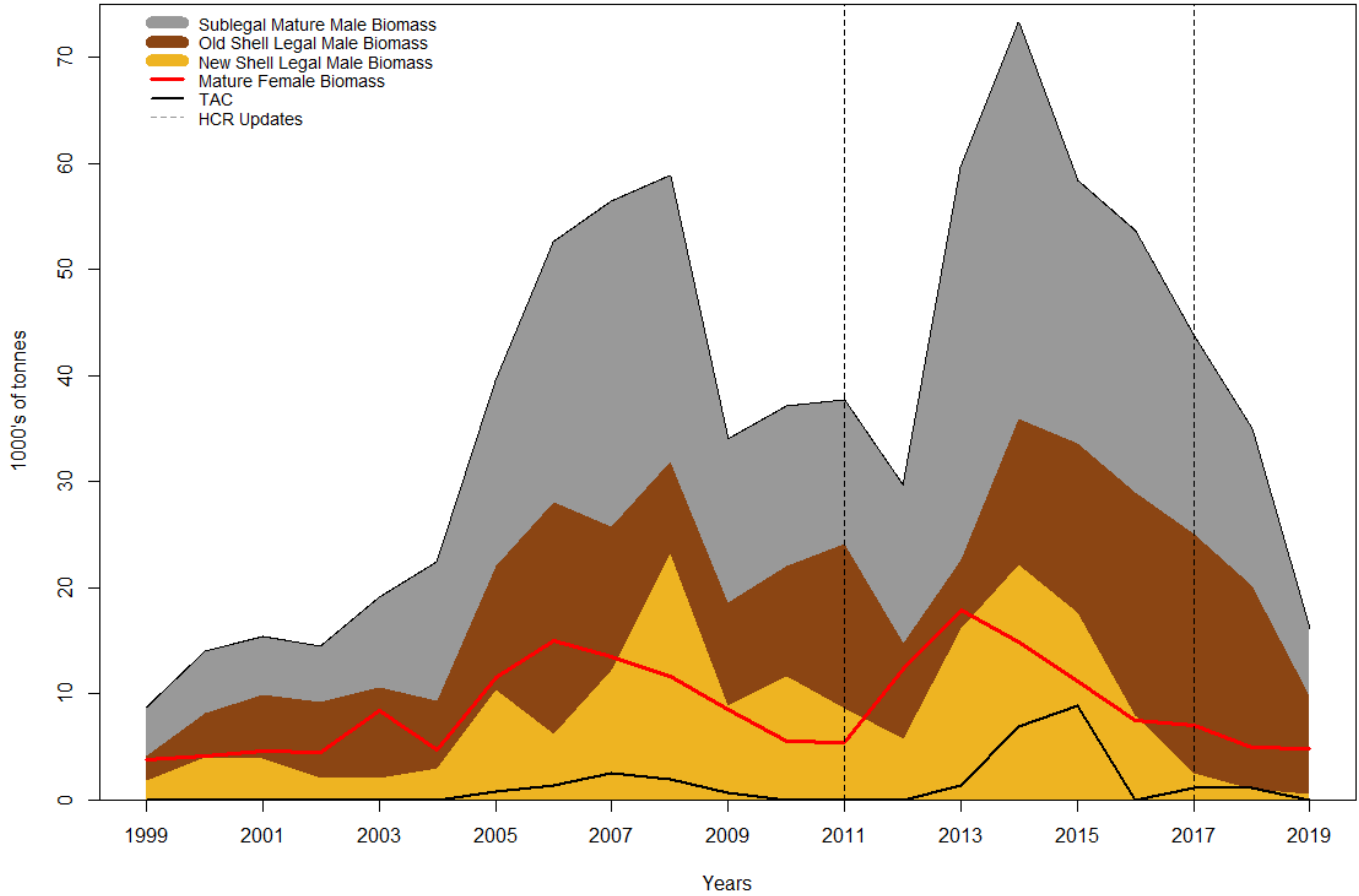


Figure 2 Tanner crab survey MMB partitioned by the proportion of sublegal MMB (CW less than 127mm; grey), old shell legal MMB (brown), new shell legal MMB (gold), and MFB (red line) and TAC (black line) from 1999 to 2019. State harvest strategy updates in 2011 and 2017 are indicated by the dashed lines.

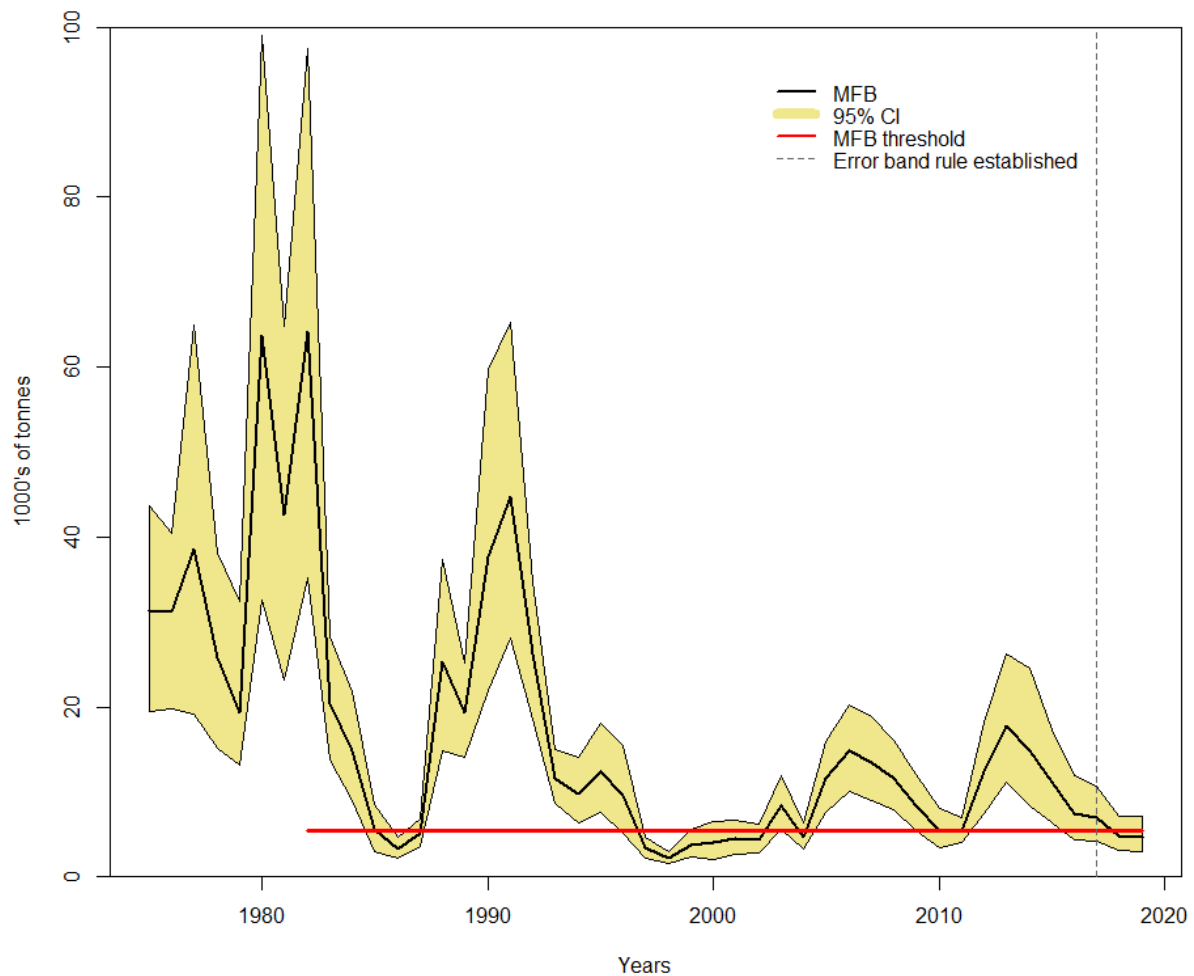


Figure 3 Error band rule, established in 2017 (dashed line) where MFB from NMFS survey estimates and 95% bootstrapped confidence interval (5,000 replicates) are depicted with the MFB threshold. The fishery is closed if the MFB estimate falls below the threshold (e.g., 1997–1999), there is reduced harvest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

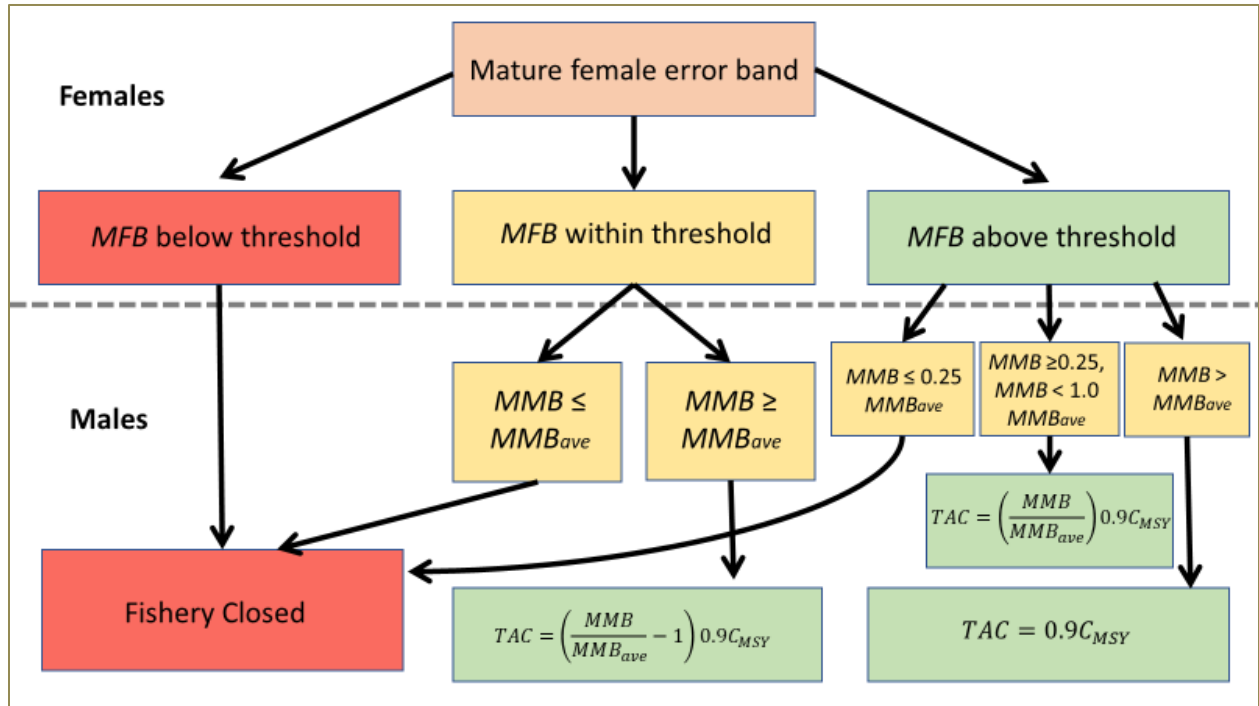


Figure 4 Flow chart showing, how the female error band rule (Fig. 4) scales harvest. The error band is determined by bootstrapping MFB survey data to establish a 95% CI. This error band is then compared to the female threshold of $0.4MMB_{ave}$. The fishery is closed if the error band is fully below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

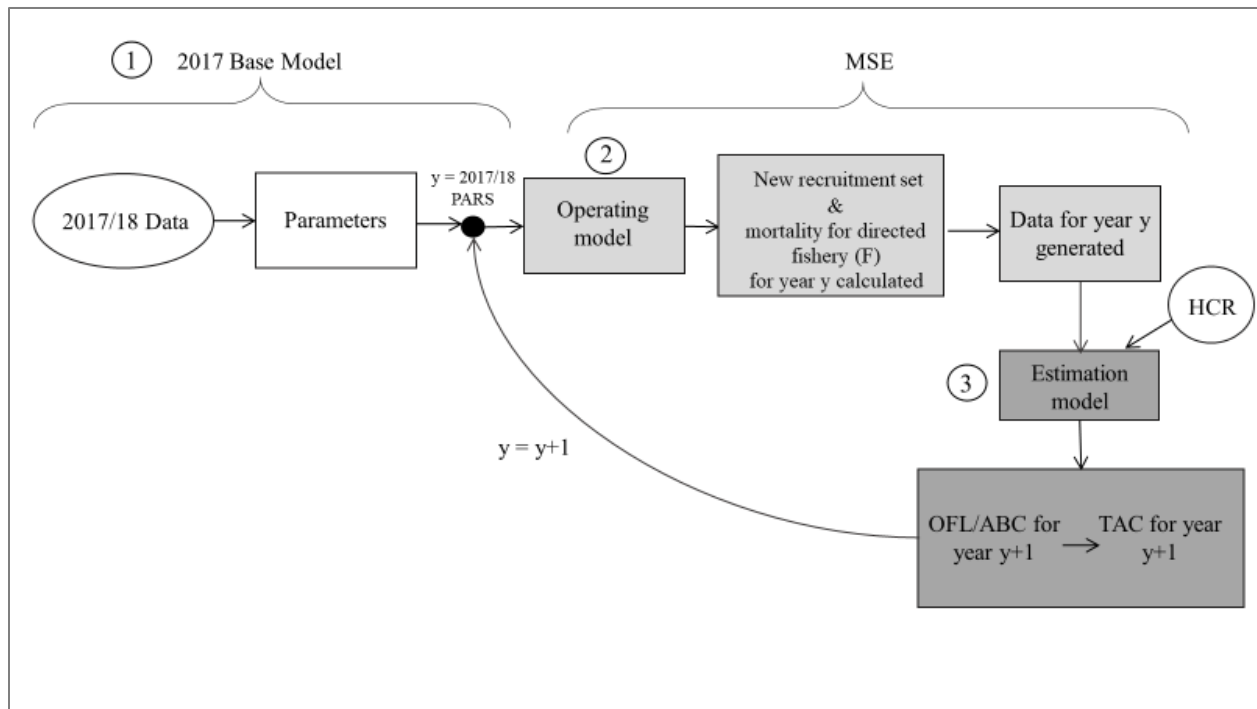


Figure 5 Flow chart of the MSE process, where the parameters of the operating model are set based on the 2017 stock assessment (1). The operating model (2) generates recruitment, calculates the fishing mortality rate for the year and generates survey data, which are provided to the estimation method (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.

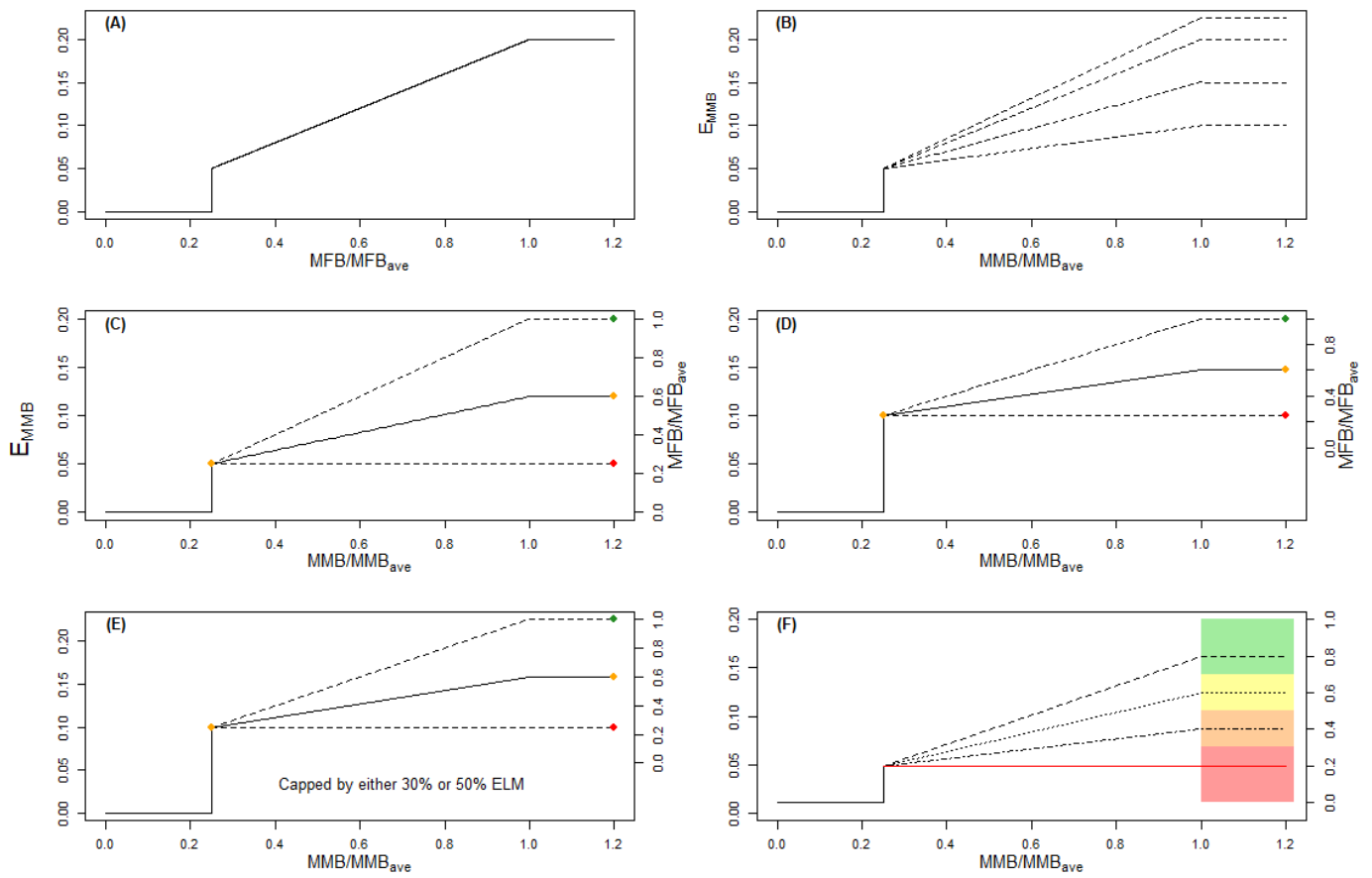


Figure 6 Ten of the HCRs—the female only HCR1 (A), the male only HCR2_1, HCR2_2, HCR2_3, and HCR2_4 (B), the female dimmer HCR4_1 (C), HCR4_2 (D), HCR4_3 and HCR4_4 (E) and the female blocked dimmer HCR5 (F).

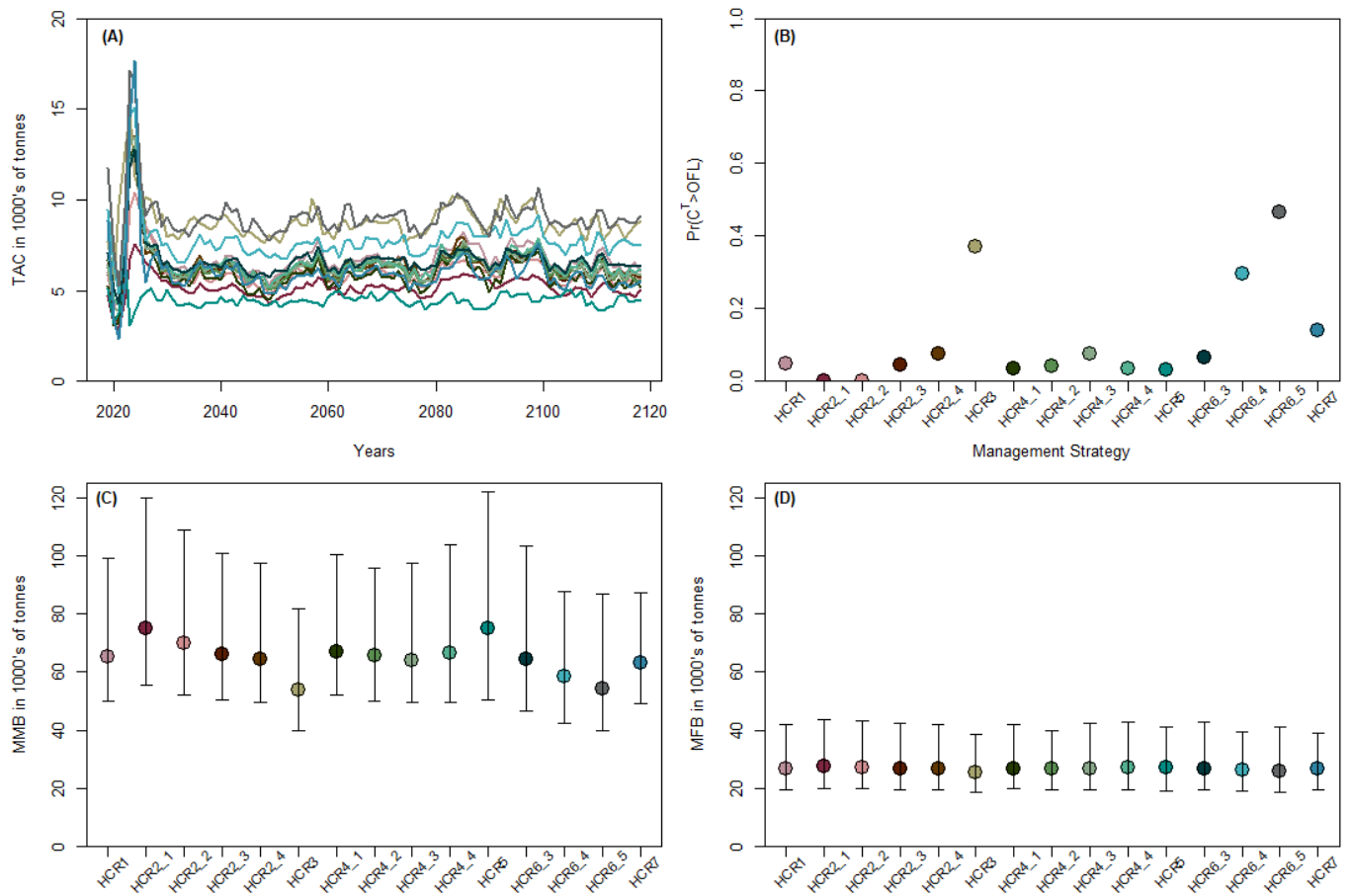


Figure 7 Median TAC over time by HCR (A), probability of total catch mortality exceeding the OFL (B), MMB (median and 90% intervals) (C), and MFB (median and 90% intervals) (D).

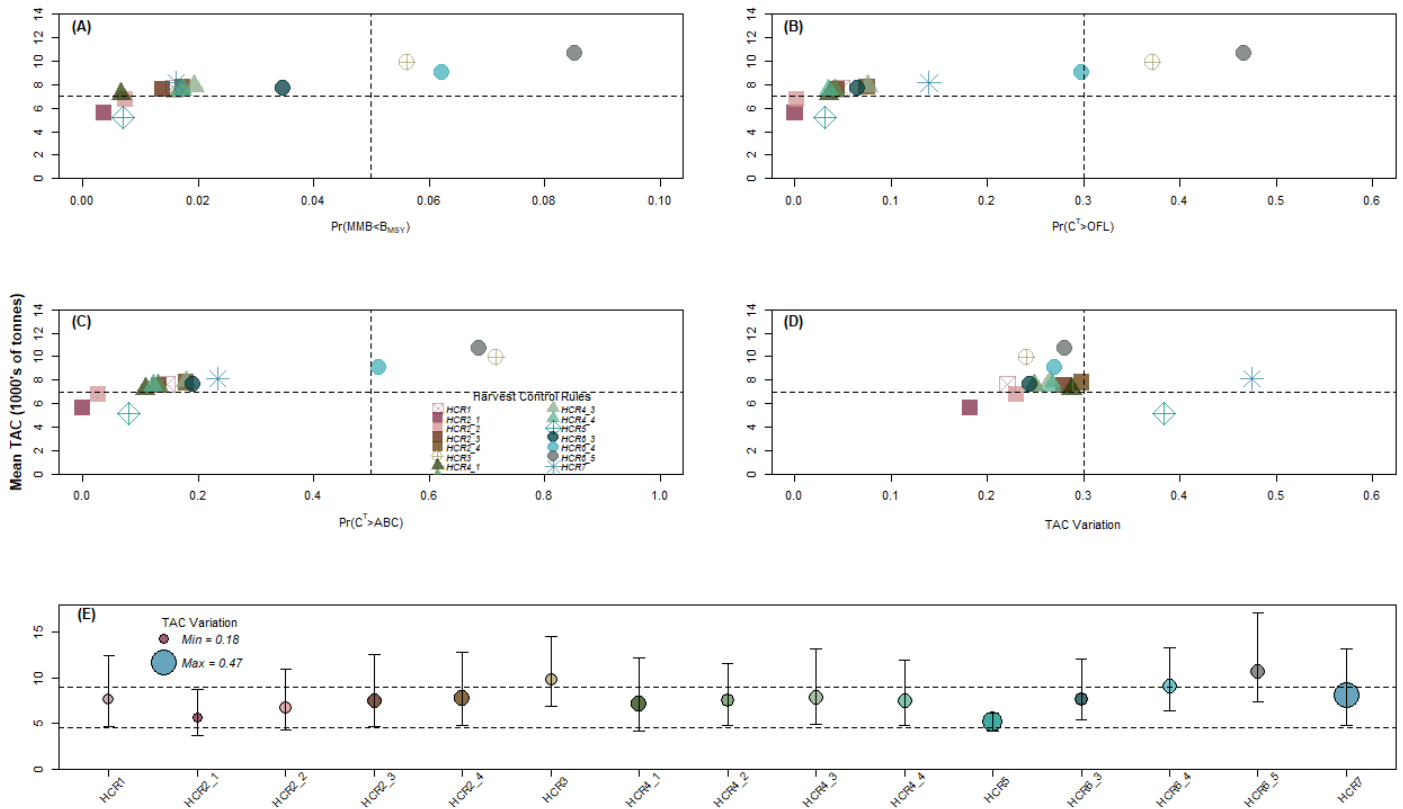


Figure 8 Panels A-D show mean TAC plotted against the probability of MMB falling below B_{MSY} (A), probability of overfishing (B), the probability of approaching overfishing (C), and TAC variation (D). Panel E shows mean TAC (and 90% intervals) for all 15 HCRs where the bubble size is the TAC variation. The dotted lines represent 10 and 20 million pounds, values that were desirable to industry stakeholders.

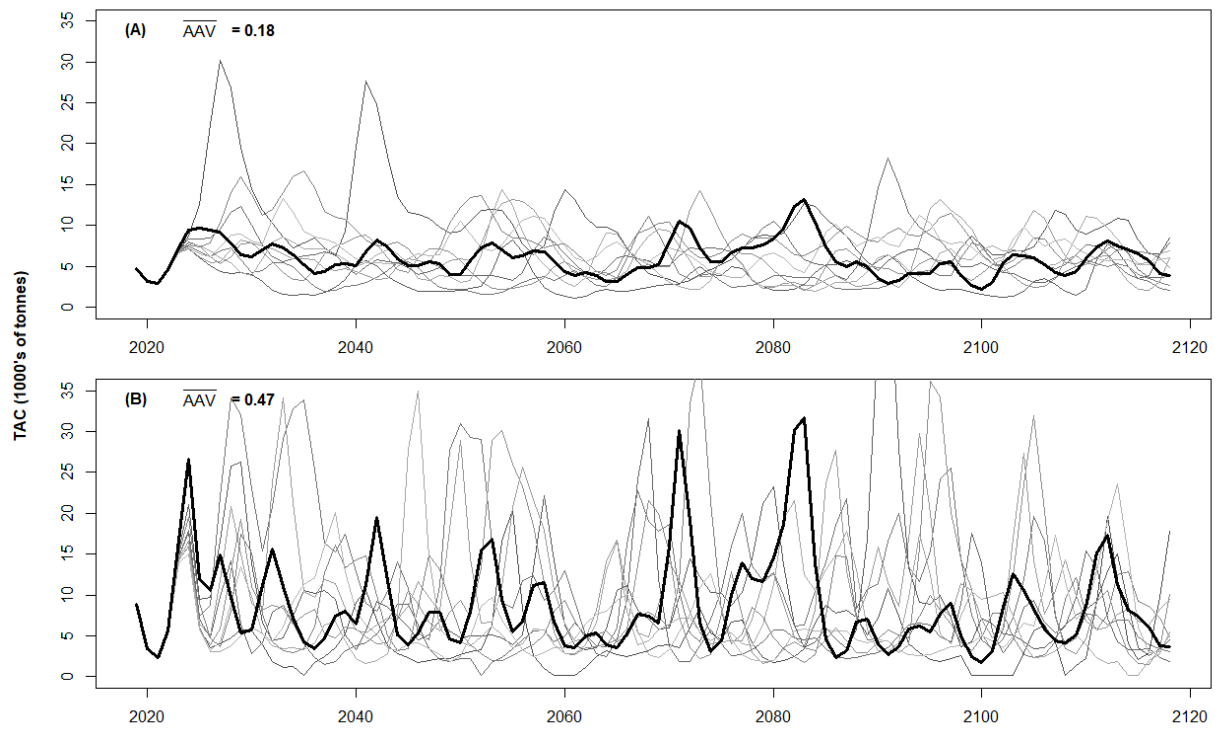


Figure 9 Panels A and B show the difference in TAC variability (AAV) between the strategy with the lowest TAC variability (HCR2_1; A), and that with highest TAC variability (HCR7; B). Each plot has 10 example trajectories of TAC, with one simulation bolded for clarity.

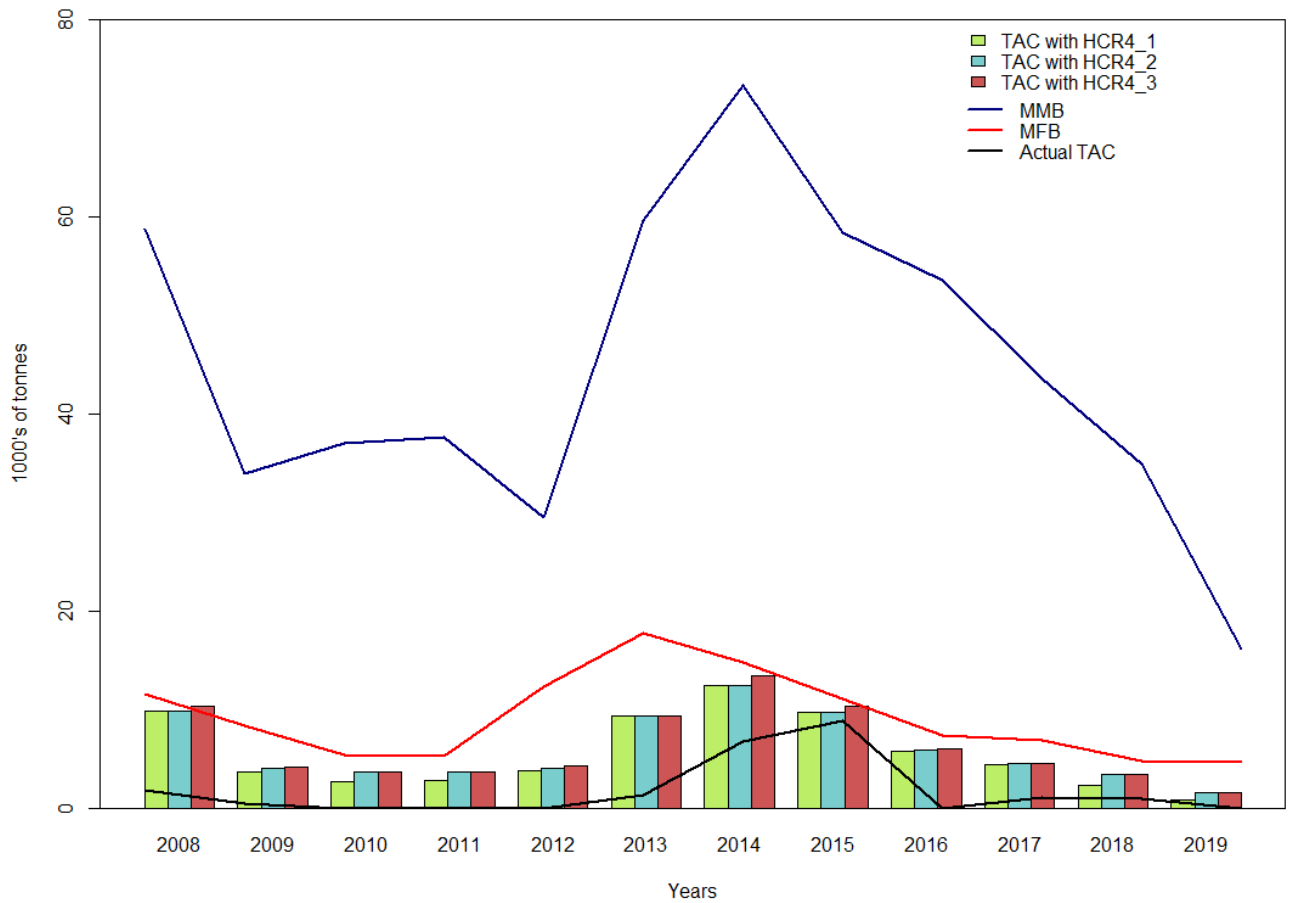


Figure 10 Historical MMB, MFB, and TAC values. The bars represent what the TACs that would have been set given the biomass estimates for the year concerned for HCR4_1, HCR4_2, and HCR4_3. Note that there is no feedback between the TAC implied by the HCR for one year and the biomass for the next year.

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

	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

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 B: OPERATING MODEL PARAMETER VALUES

Table AB.1 Operating model parameter values from the 2017 assessment base model. Mean size at 50% or 95% selectivity or retention 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
Growth	pGrA[1]	Mean growth coefficient 'a' for males		33.09
	pGrA[2]	Mean growth coefficient 'a' for females		34.46
	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
Natural Mortality	pDM1[1]	Multiplier for immature crab		1.00
	pDM1[2]	Multiplier for mature males		1.15
	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
Recruitment	pLnR[1]	Log mean recruitment: Historical recruitment period		5.66
	pLnR[2]	Log mean recruitment: Recent recruitment period		5.14
	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

Table AB.1 Continued

Process	Name	Label	Index	Value
Recruitment	pDevsLnR [1]	Recruitment deviations (1949-1974)	1965	1.62
			1966	1.37
			1967	1.21
			1968	1.19
			1969	1.25
			1970	1.23
			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			

Table AB.1 Continued

Process	Name	Label	Index	Value
Recruitment	pDevsLnR [2]	Recruitment deviations (1975-2018)	2007	-1.08
			2008	-0.65
			2009	1.22
			2010	1.08
			2011	0.17
			2012	-1.43
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]	logit-scale parameters for Pr(molt-to-maturity size) for males by 5mm size class (27-182mm)	27	-12.03
			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			

Table AB.1 Continued

Process	Name	Label	Index	Value
Molt to maturity	pLgtPrM2M[1]	logit-scale parameters for Pr(molt-to-maturity size) for males by 5mm size class (27-182mm)	167	13.91
			172	14.35
			177	14.69
			182	15.00
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

Table AB.1 Continued

Process	Name	Label	Index	Value	
Selectivity and Retention	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	
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	
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

Table AB.1 Continued

Process	Name	Label	Index	Value
Selectivity and Retention	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
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]	$\ln(z_{95}-z_{50})$ for RKF selectivity (males, pre-1997)		3.07
	pS2[23]	$\ln(z_{95}-z_{50})$ for RKF selectivity (males, 1997-2004)		3.55
	pS2[24]	$\ln(z_{95}-z_{50})$ for RKF selectivity (males, 2005+)		3.52
	pS2[25]	$\ln(z_{95}-z_{50})$ for RKF selectivity (males, pre-1997)		2.79
	pS2[26]	$\ln(z_{95}-z_{50})$ for RKF selectivity (males, 1997-2004)		2.86
	pS2[27]	$\ln(z_{95}-z_{50})$ 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]	$\ln(dz_{50}-az_{50})$ for SCF selectivity (males, pre-1997)		3.96
	pS3[2]	$\ln(dz_{50}-az_{50})$ for SCF selectivity (males, 1997-2004)		3.72
	pS3[3]	$\ln(dz_{50}-az_{50})$ 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

Table AB.1 Continued

Process	Name	Label	Index	Value	
Selectivity and Retention	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	
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 TCF: 1965-1984, 1987-1996, 2005-2009, 2013-2015, 2017	1965	-0.55
				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				

Table AB.1 Continued

Process	Name	Label	Index	Value
Capture	pDevsLnC[1]	In-scale annual capture rate devs TCF: 1965-1984, 1987-1996, 2005-2009, 2013- 2015, 2017	1989	0.67
			1990	1.35
			1991	1.35
			1992	2.05
			1993	1.44
			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]	In-scale annual capture rate devs SCF: 1992+	1992	1.94
			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			

Table AB.1 Continued

Process	Name	Label	Index	Value
Capture	pDevsLnC[2]	ln-scale annual capture rate devs SCF: 1992+	2016	0.20
			2017	-0.46
Capture	pDevsLnC[3]	ln-scale annual capture rate devs GF all gear: 1973+	1973	1.31
			1974	1.70
			1975	0.86
			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			
			1975	1.13
			1976	0.46
			1977	-0.16
			1978	0.00
			1979	-0.25
			1980	-0.23
			1981	-0.34
			1982	-0.59
			1983	-0.78
			1984	-0.90
			1985	-0.91

Table AB.1 Continued

Process	Name	Label	Index	Value
Capture	pDevsLnC[3]	ln-scale annual capture rate devs GF all gear: 1973+	1986	-1.07
			1987	-0.94
			1988	-0.91
			1989	-0.95
			1990	-0.89
			1991	-1.02
Capture	pDevsLnC[4]	ln-scale annual capture rate devs RKF: 1992+	1992	0.84
			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

Table AB.1 Continued

Process	Name	Label	Index	Value
Catchability	pDQ4[1]	Offset 4 for ln-scale catchability	1	0.00
	pMSE_LnC[1]	Catchability for mature male crab	1	-2.50

APPENDIX C: GRAPHICAL SUMMARY OF THE RESULTS OF THE MSE

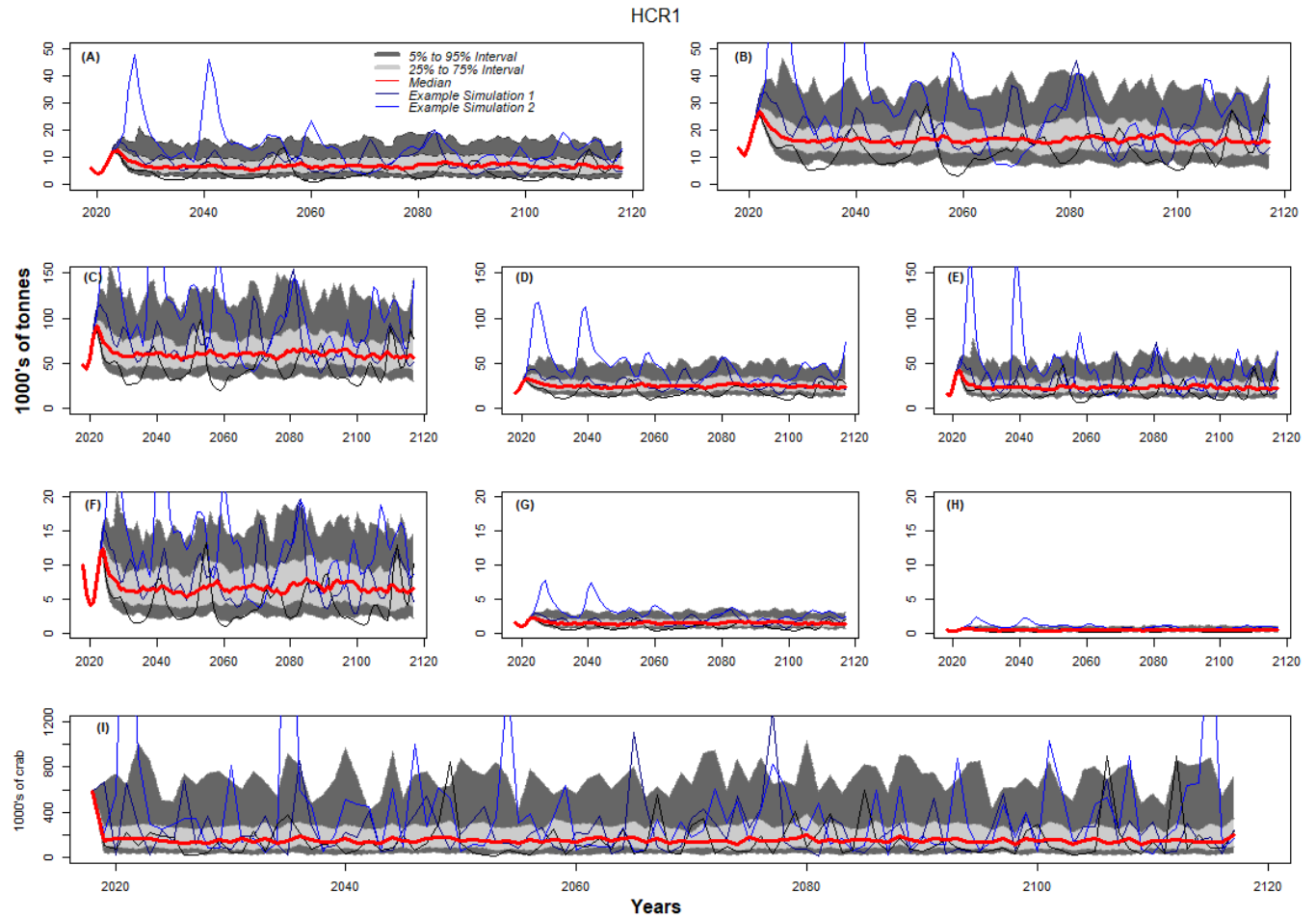


Figure AC. 1 HCR1 model summary. The panels depict median values for all 100 simulations from 2018-2117 (except for TAC, which ranges from 2019-2118), with 5-95% intervals, 25-75% intervals, and two example simulations. Panels depict (A) TAC, (B) OFL, (C) MMB, (D) MFB, (E) ELM, (F) MMB catch (starting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

HCR1

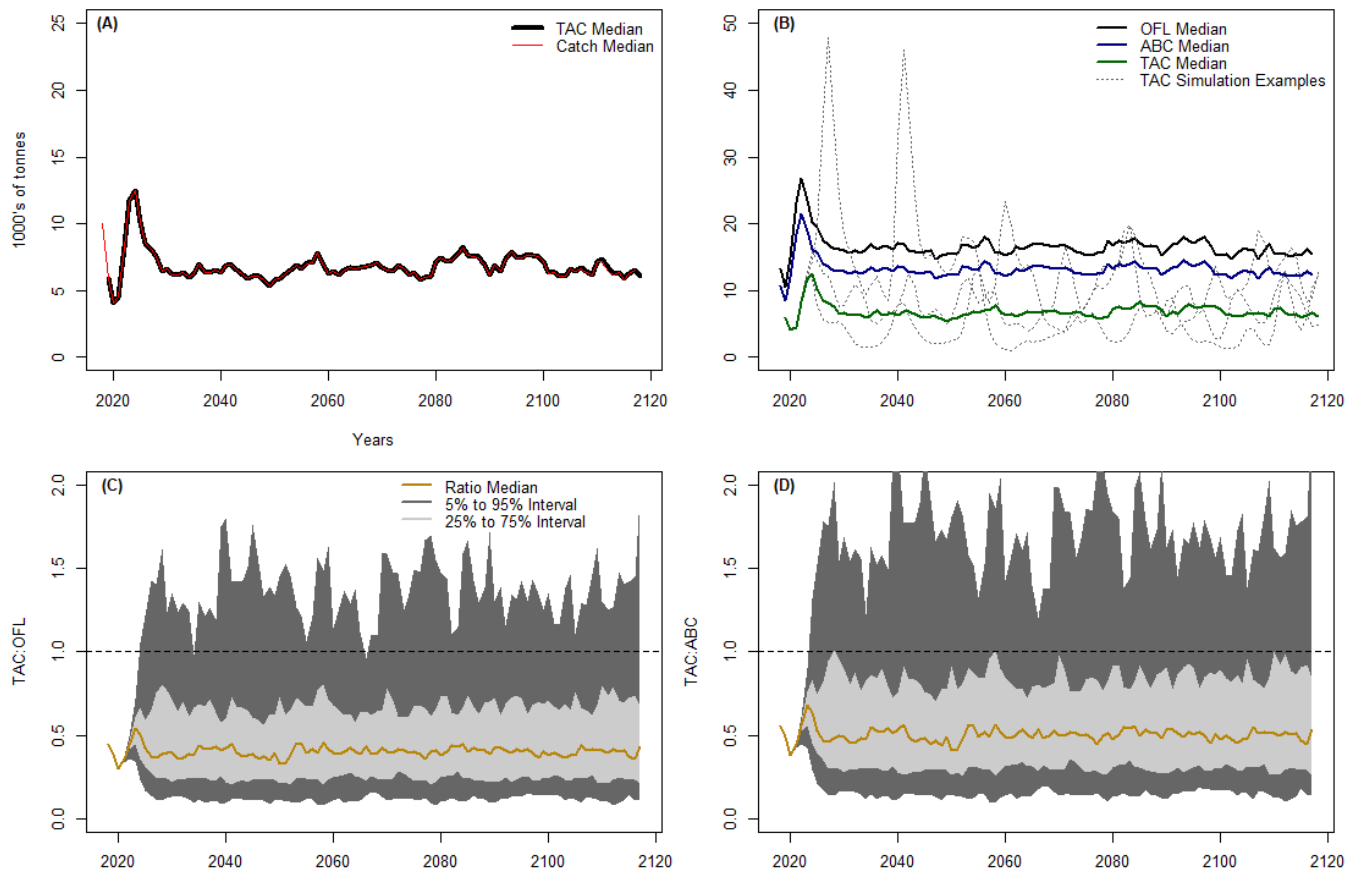


Figure AC. 2 Additional results for HCR1: (A) median TAC over all simulations (2019–2118) compared to the median total catch from the operating model (2018–2017), (B) median OFL and ABC, compared to the median TAC, with two example TAC trajectories, (C) the median ratio of TAC to OFL, with 5-95%, and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

HCR2_1

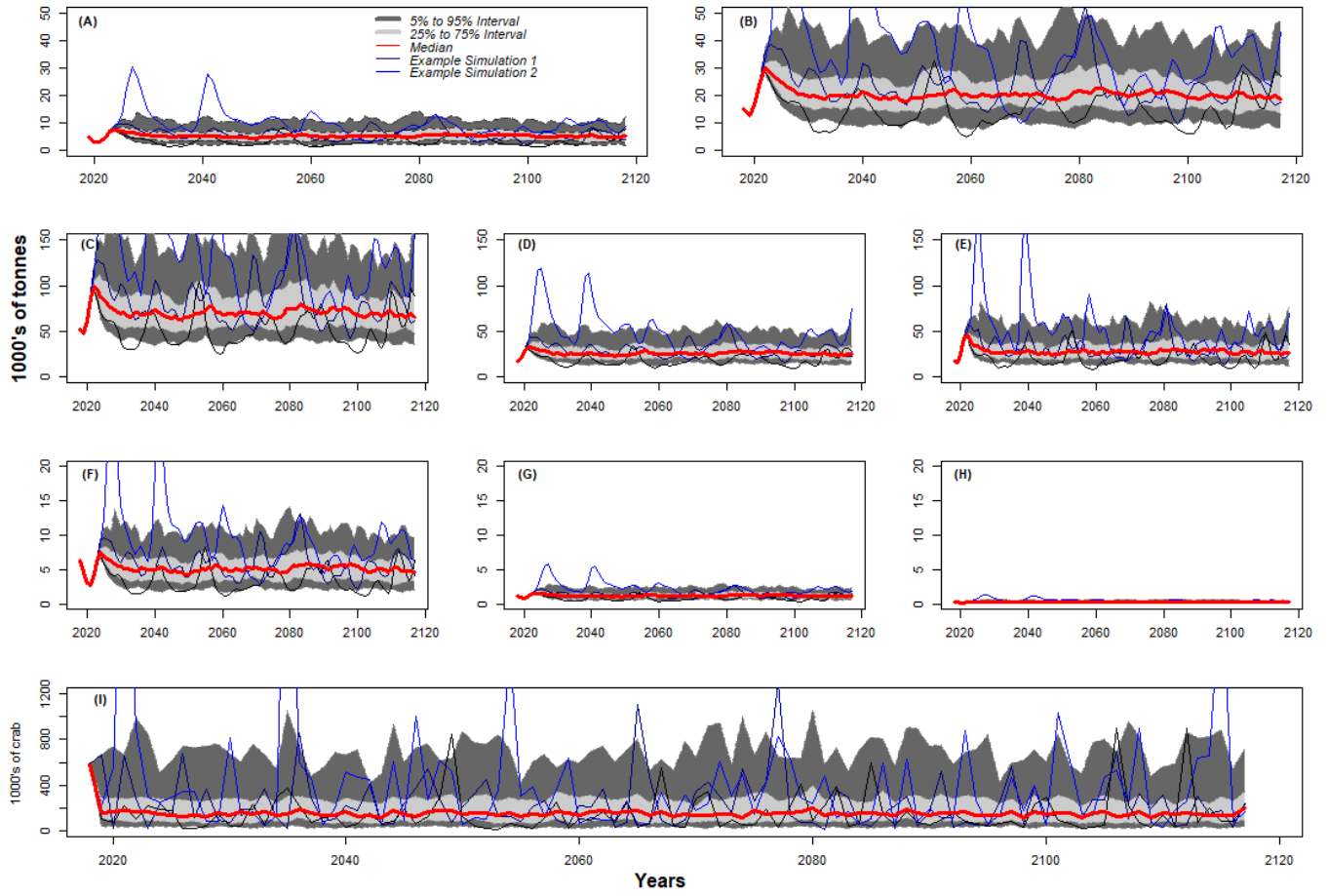


Figure AC. 3 As for Figure A3.1 except for HCR2_1.

HCR2_1

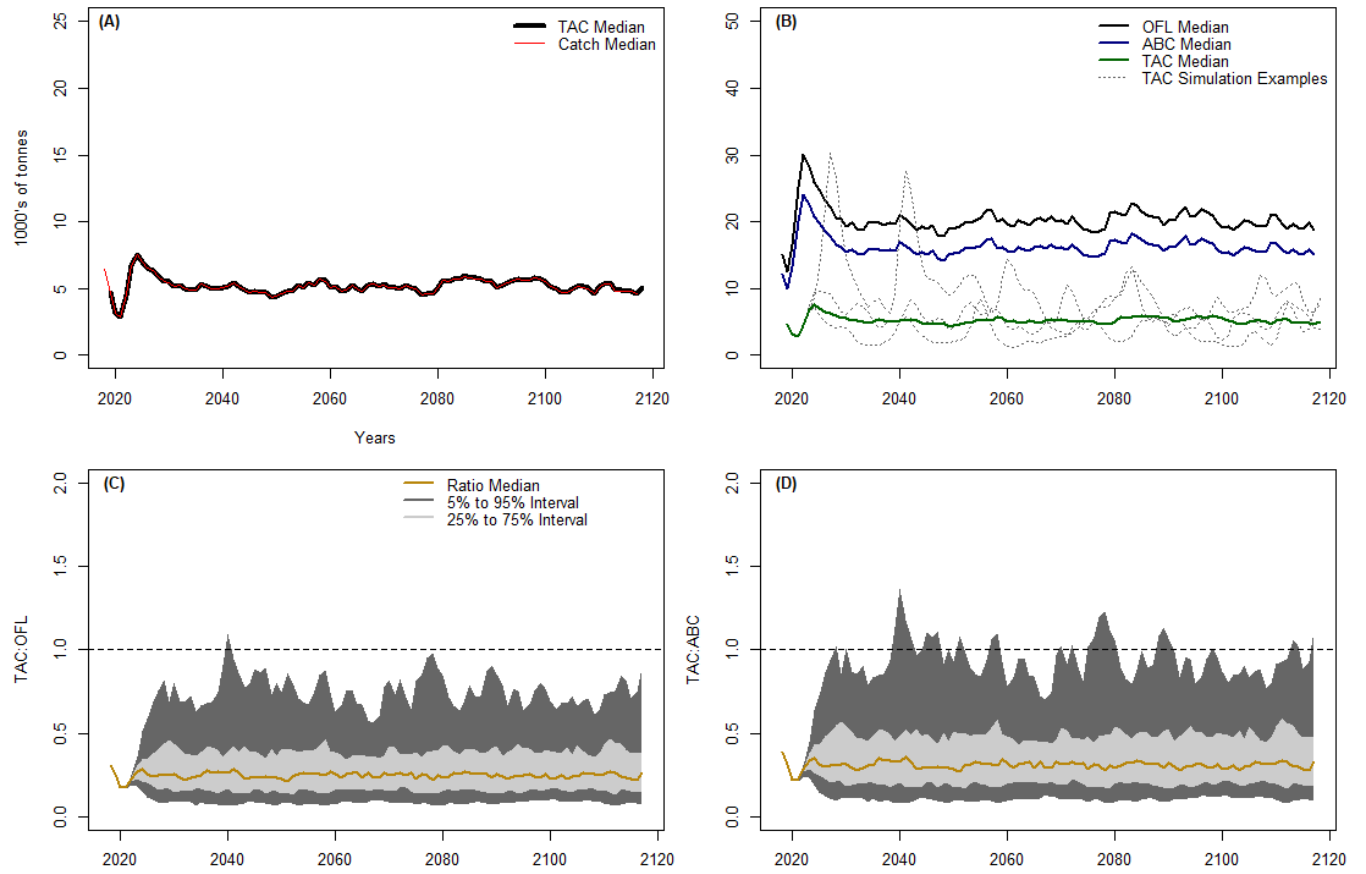


Figure AC. 4 As for Figure A3.2, except for HCR2_1.

HCR2_2

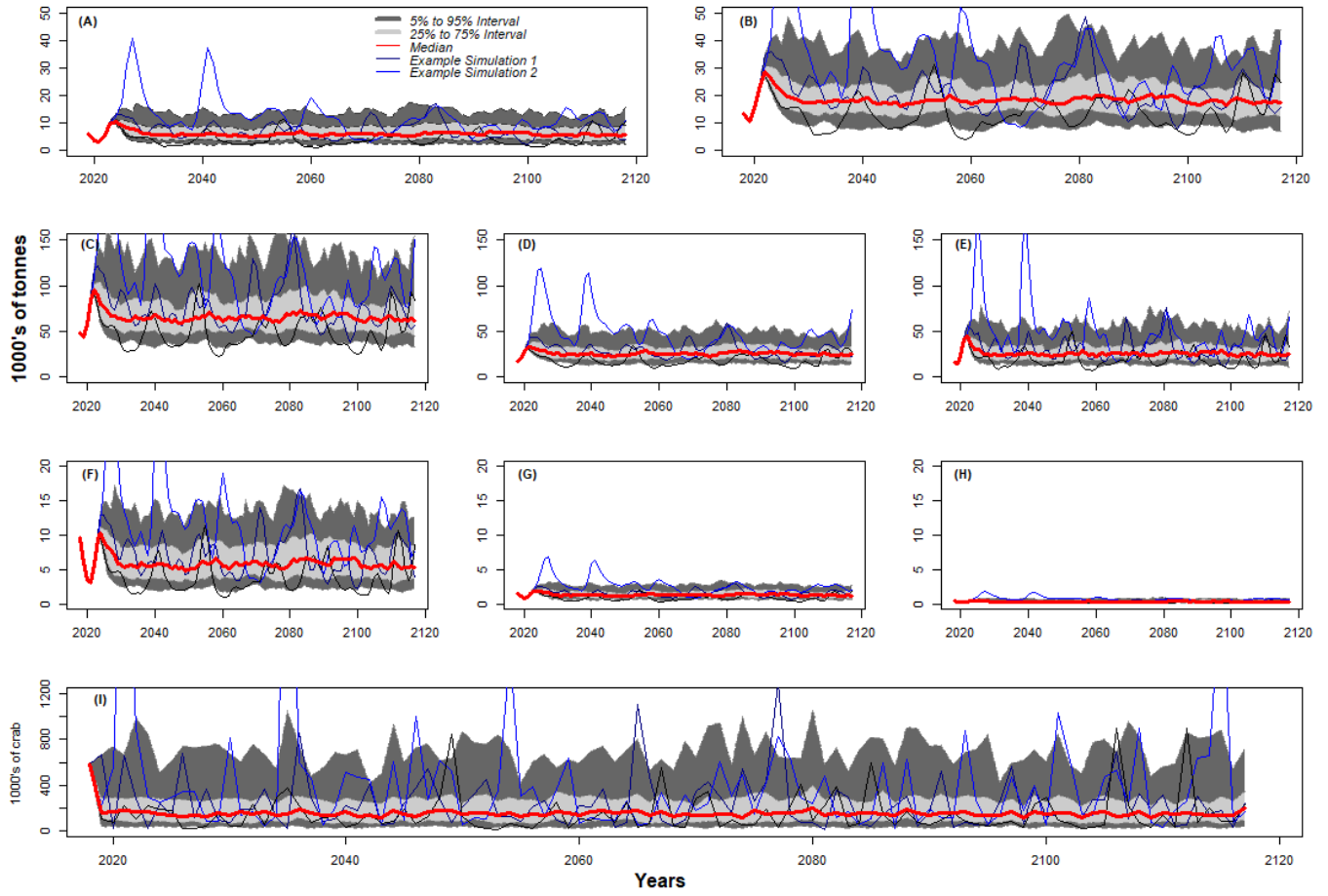


Figure AC. 5 As for Figure A3.1 except for HCR2_2.

HCR2_2

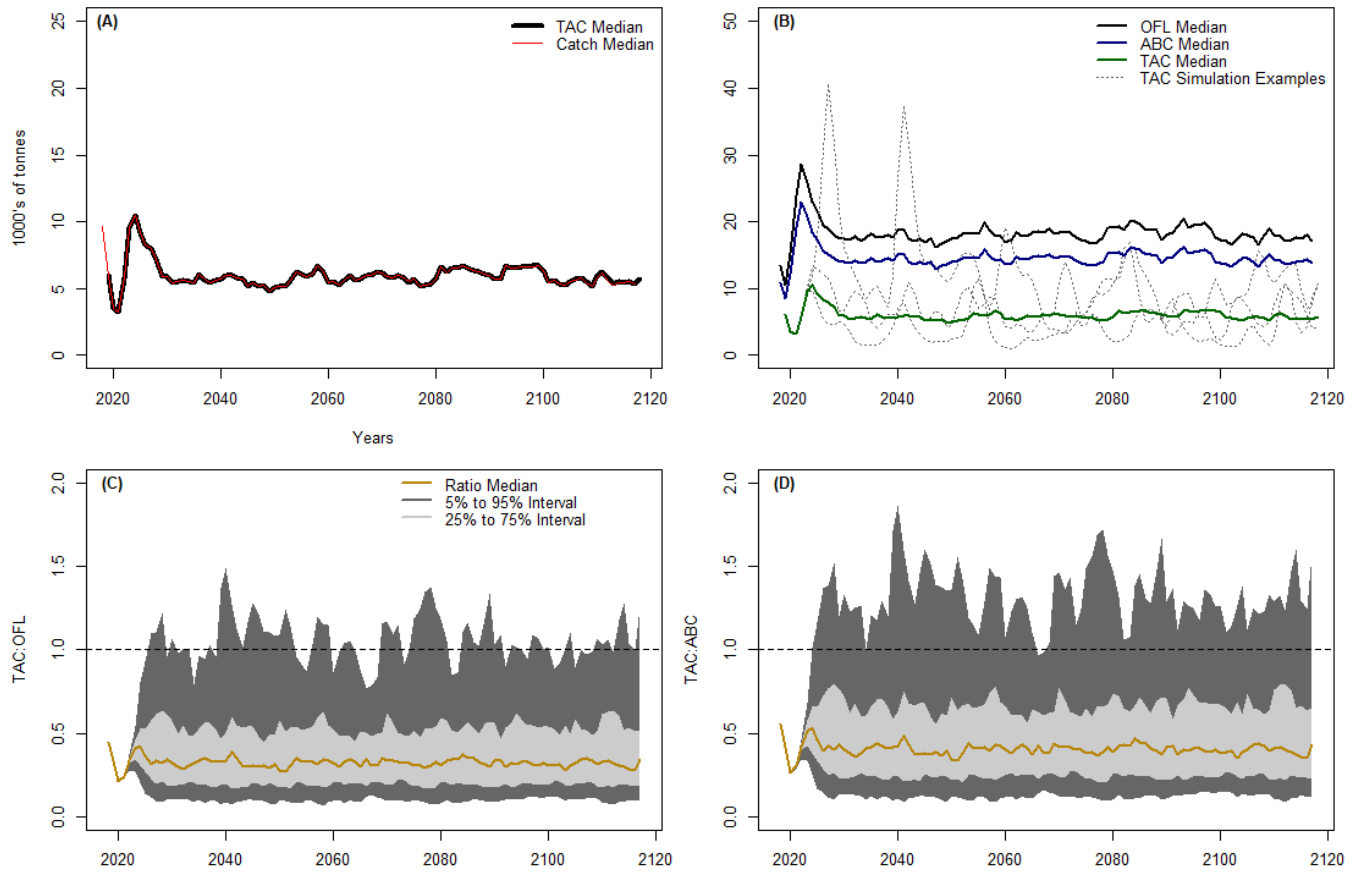


Figure AC. 6 As for Figure A3.2, except for HCR2_2.

HCR2_3

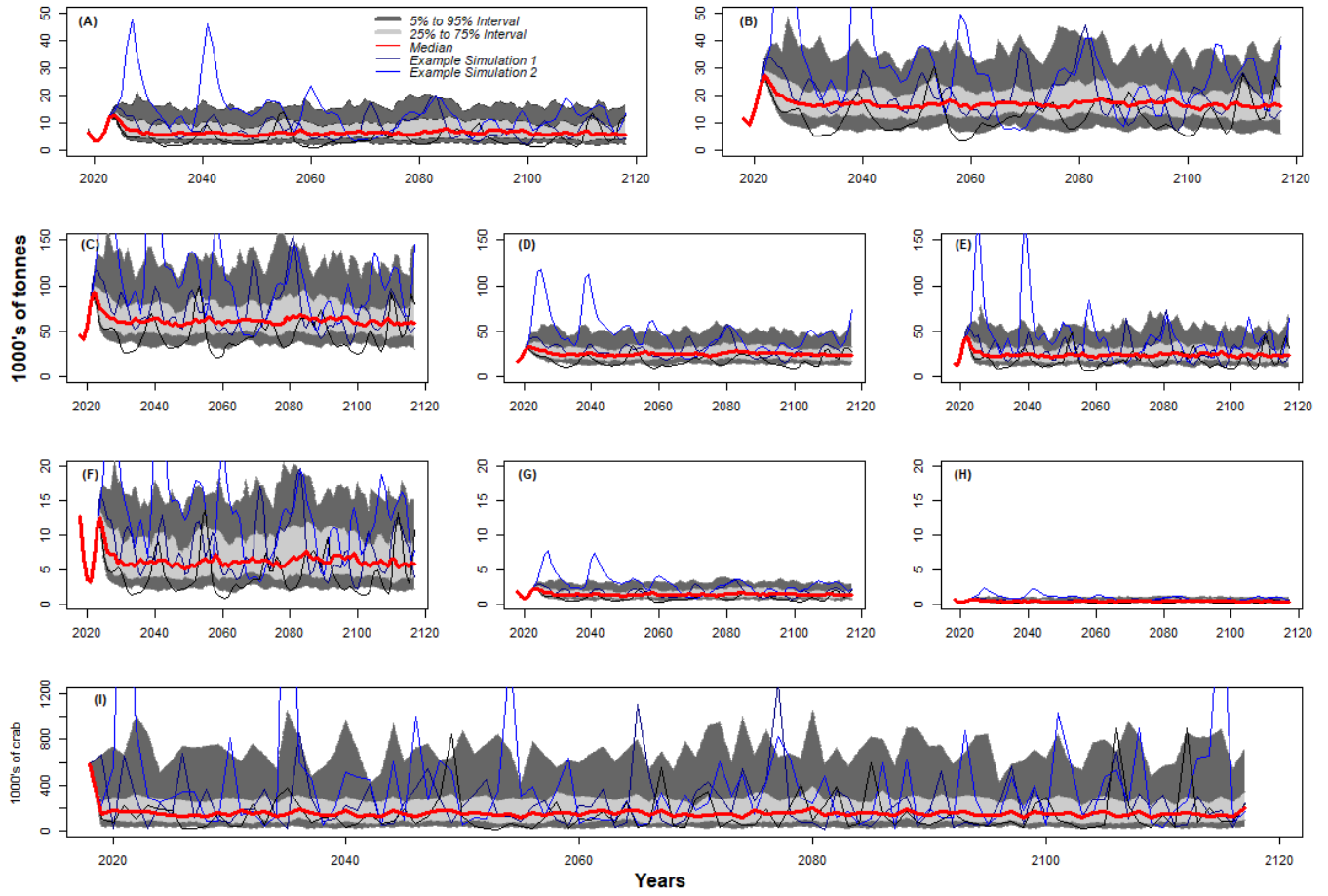


Figure AC. 7 As for Figure A3.1 except for HCR2_3.

HCR2_3

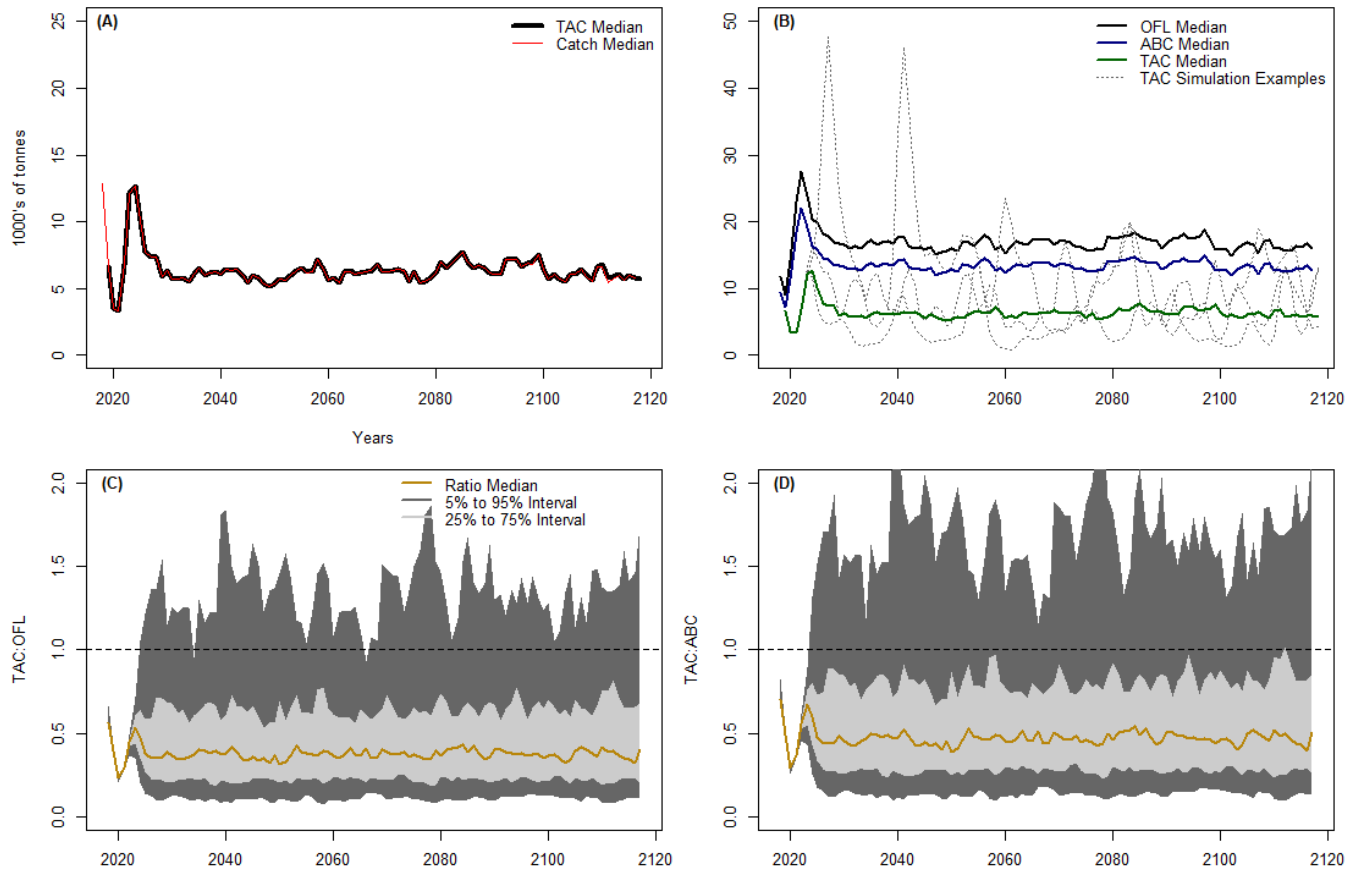


Figure AC. 8 As for Figure A3.2, except for HCR2_3.

HCR2_4

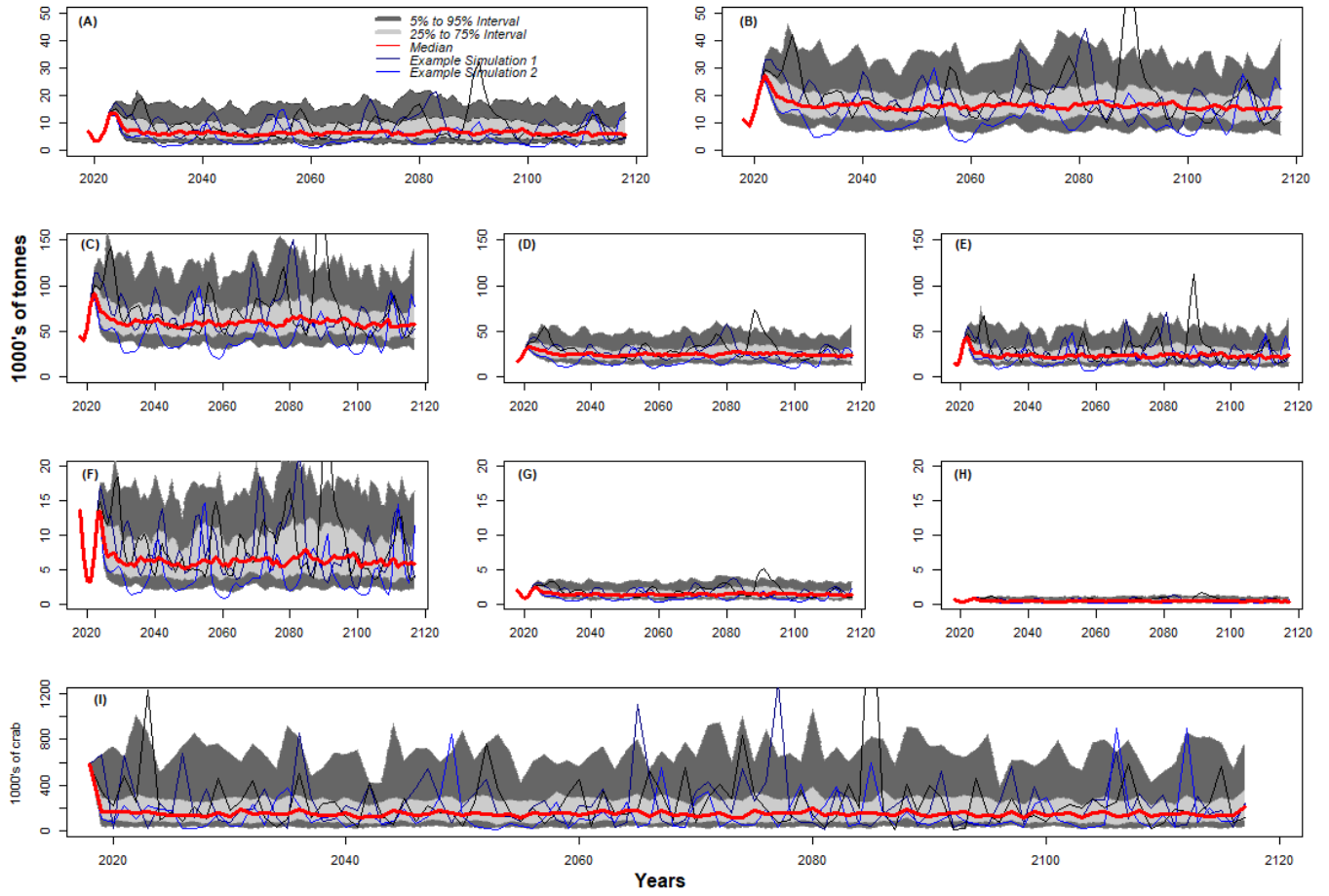


Figure AC. 9 As for Figure A3.1 except for HCR2_4.

HCR2_4

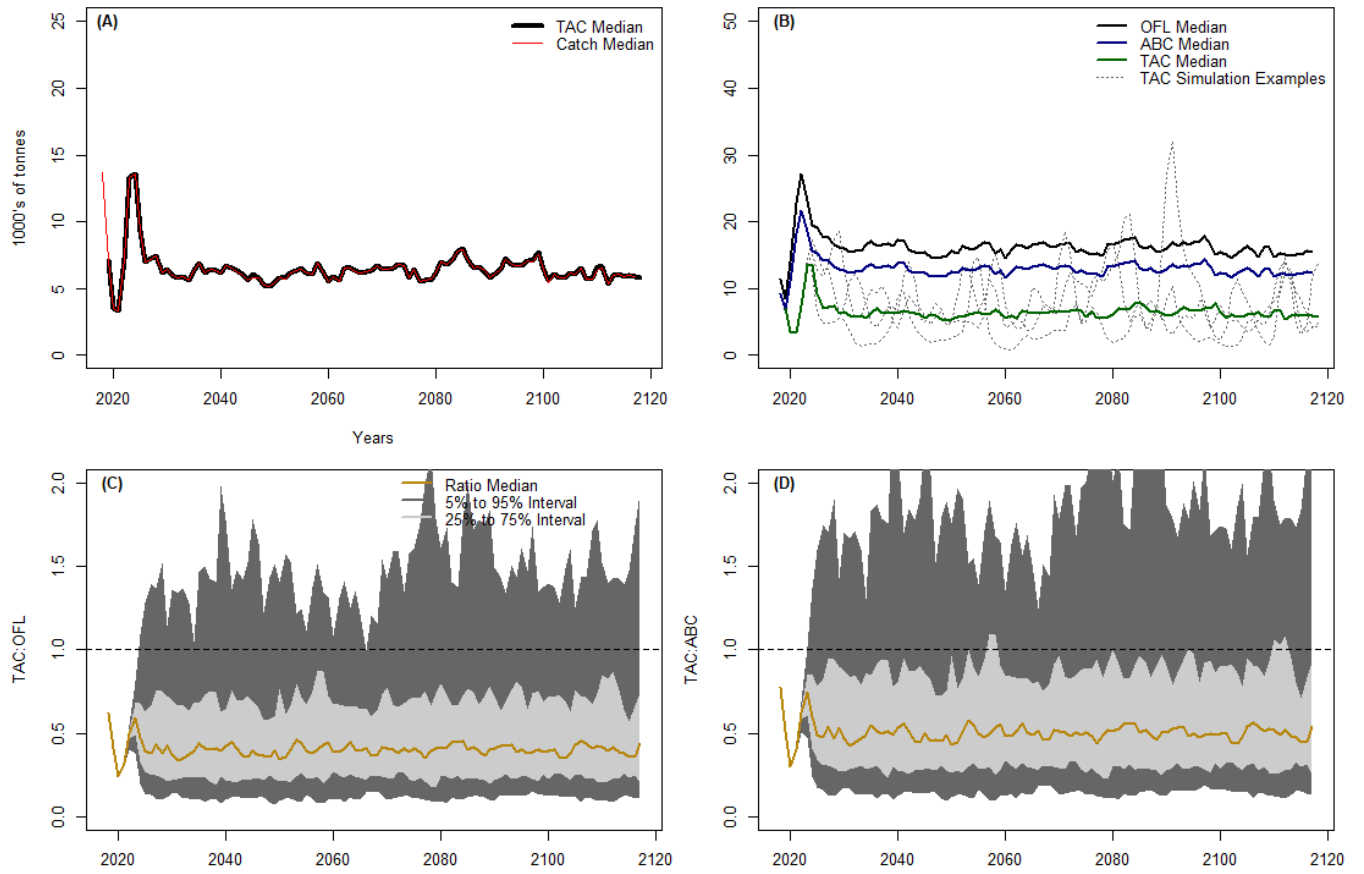


Figure AC. 10 As for Figure A3.2, except for HCR2_4.

HCR3

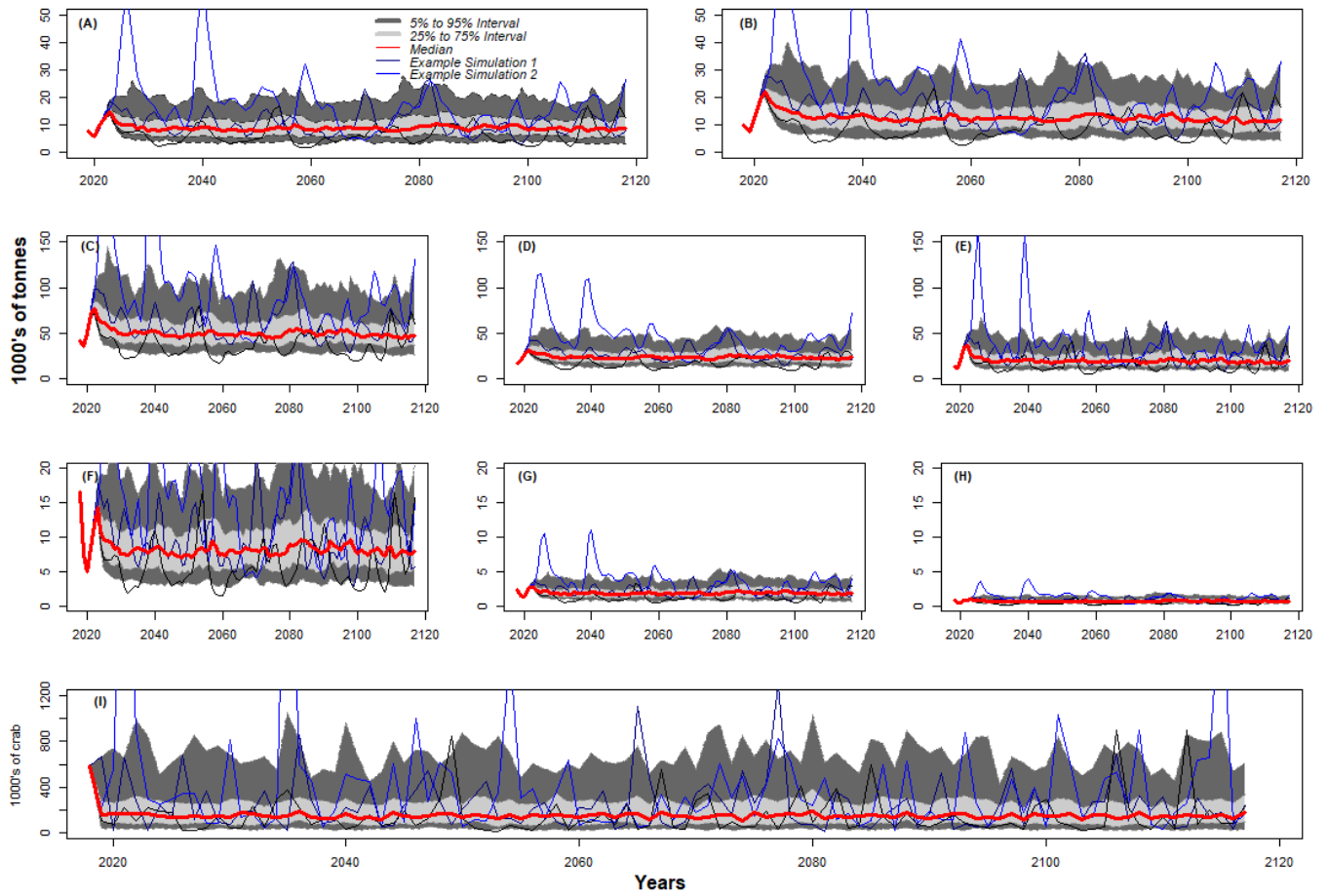


Figure AC. 11 As for Figure A3.1 except for HCR3.

HCR3

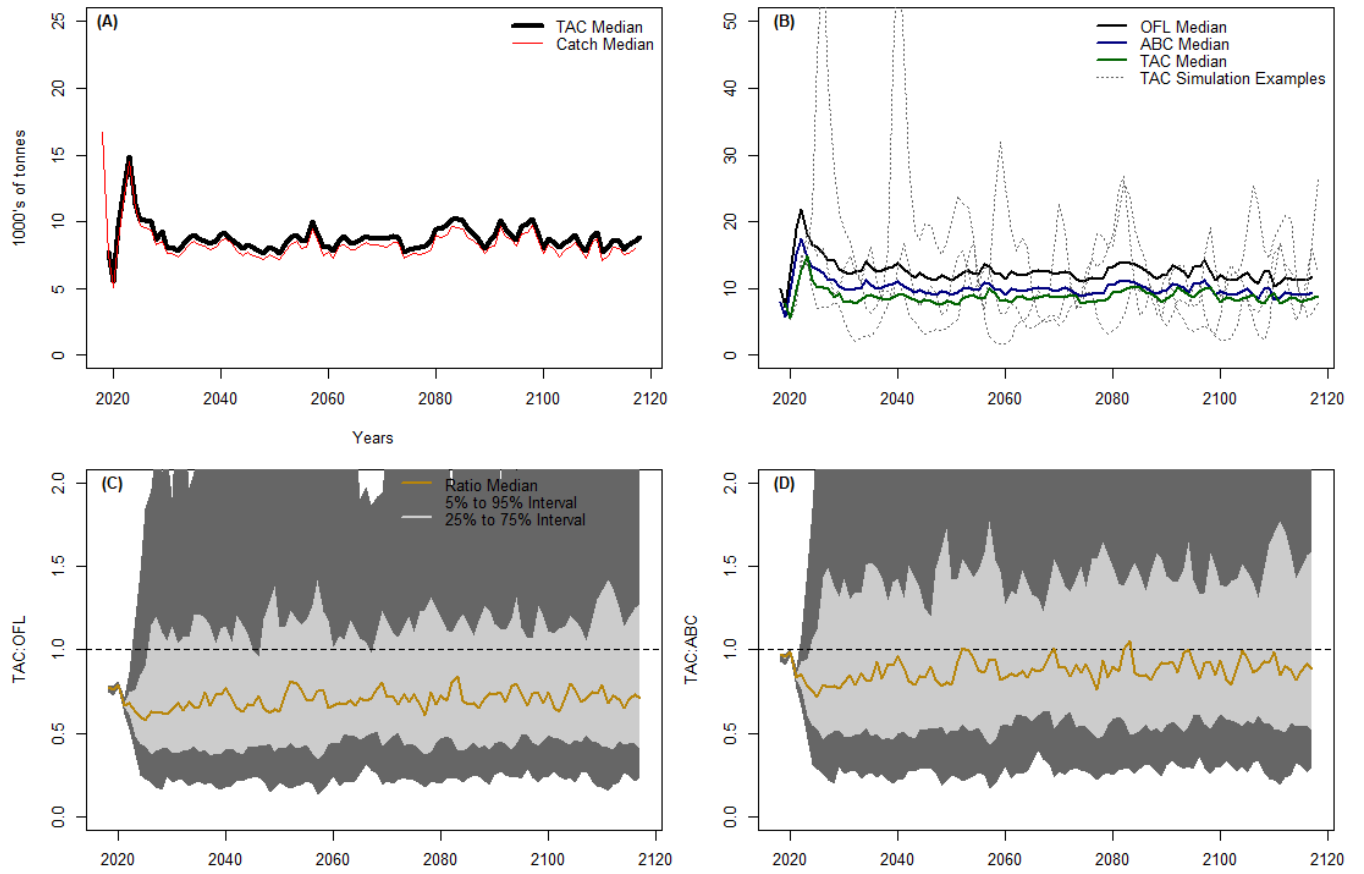


Figure AC. 12 As for Figure A3.2, except for HCR3.

HCR4_1

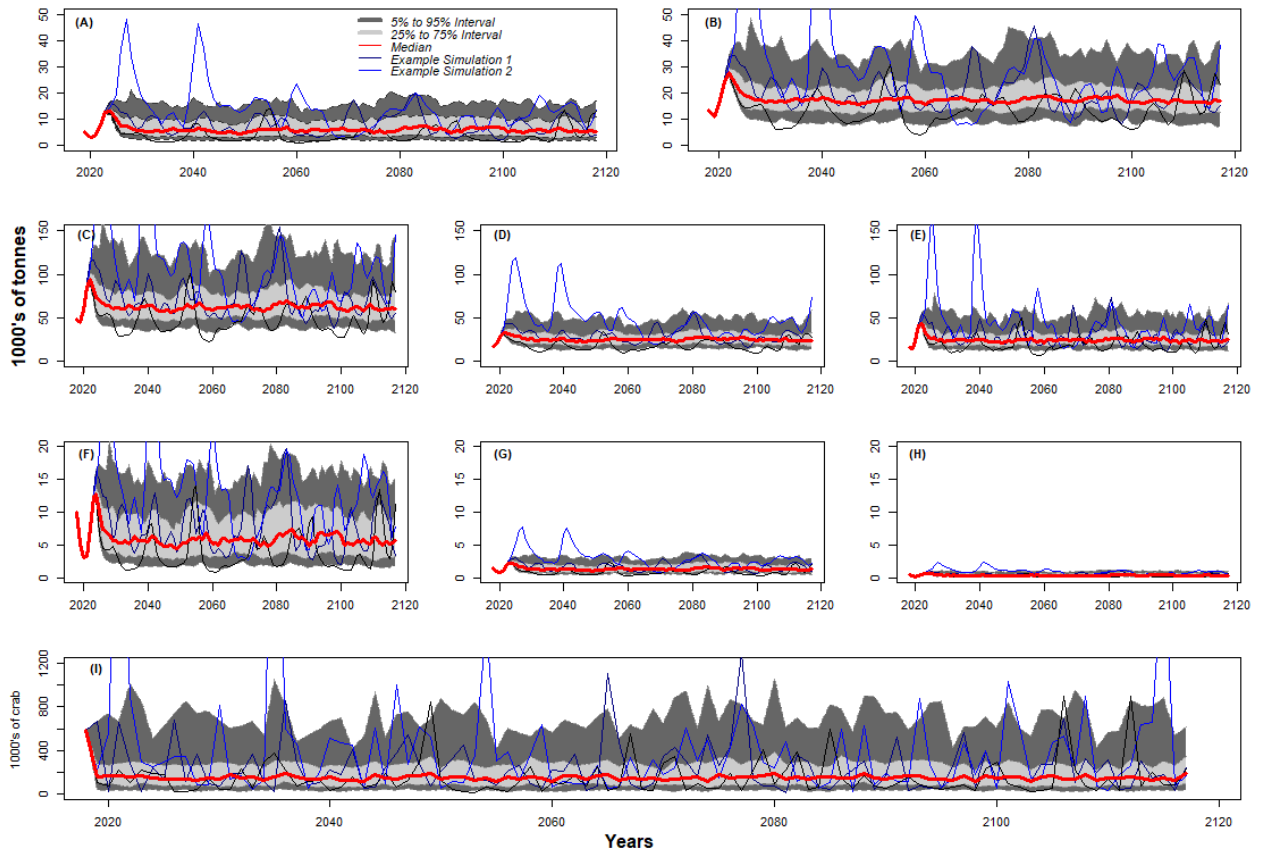


Figure AC. 13 As for Figure A3.1 except for HCR4_1.

HCR4_1

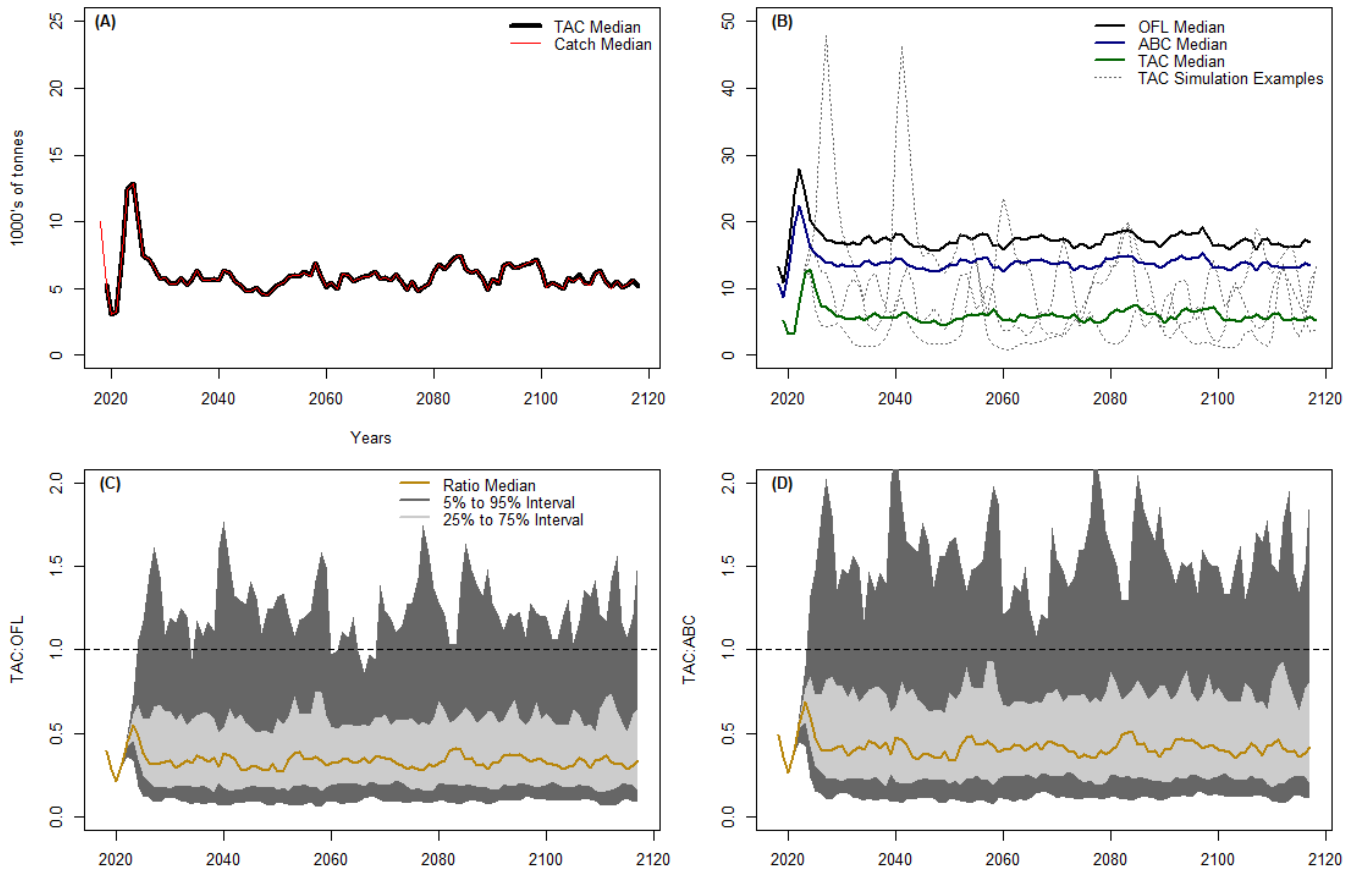


Figure AC. 14 As for Figure A3.2, except for HCR4_1.

HCR4_2

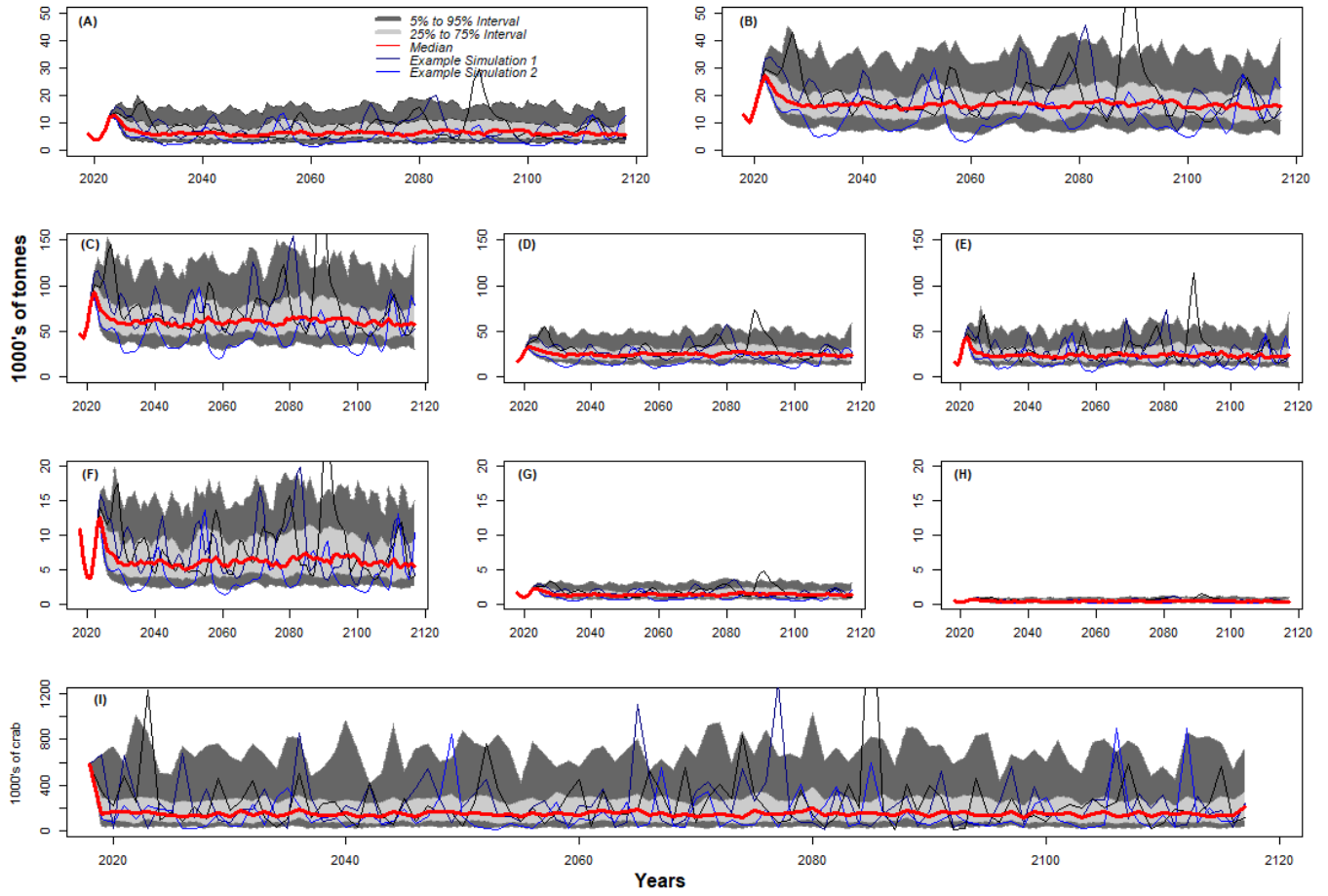


Figure AC. 15 As for Figure A3.1 except for HCR4_2.

HCR4_2

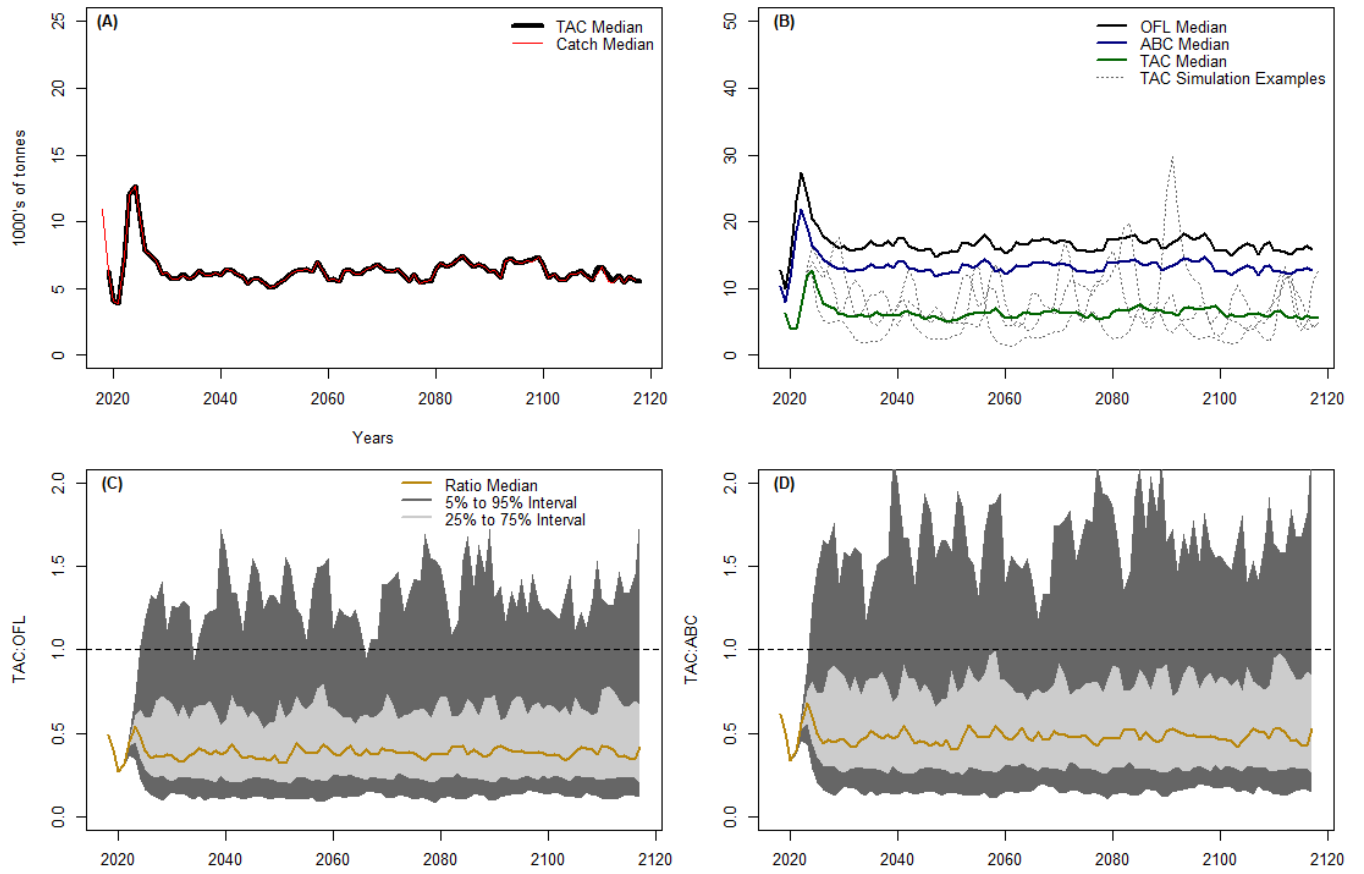


Figure AC. 16 As for Figure A3.2, except for HCR4_2.

HCR4_3

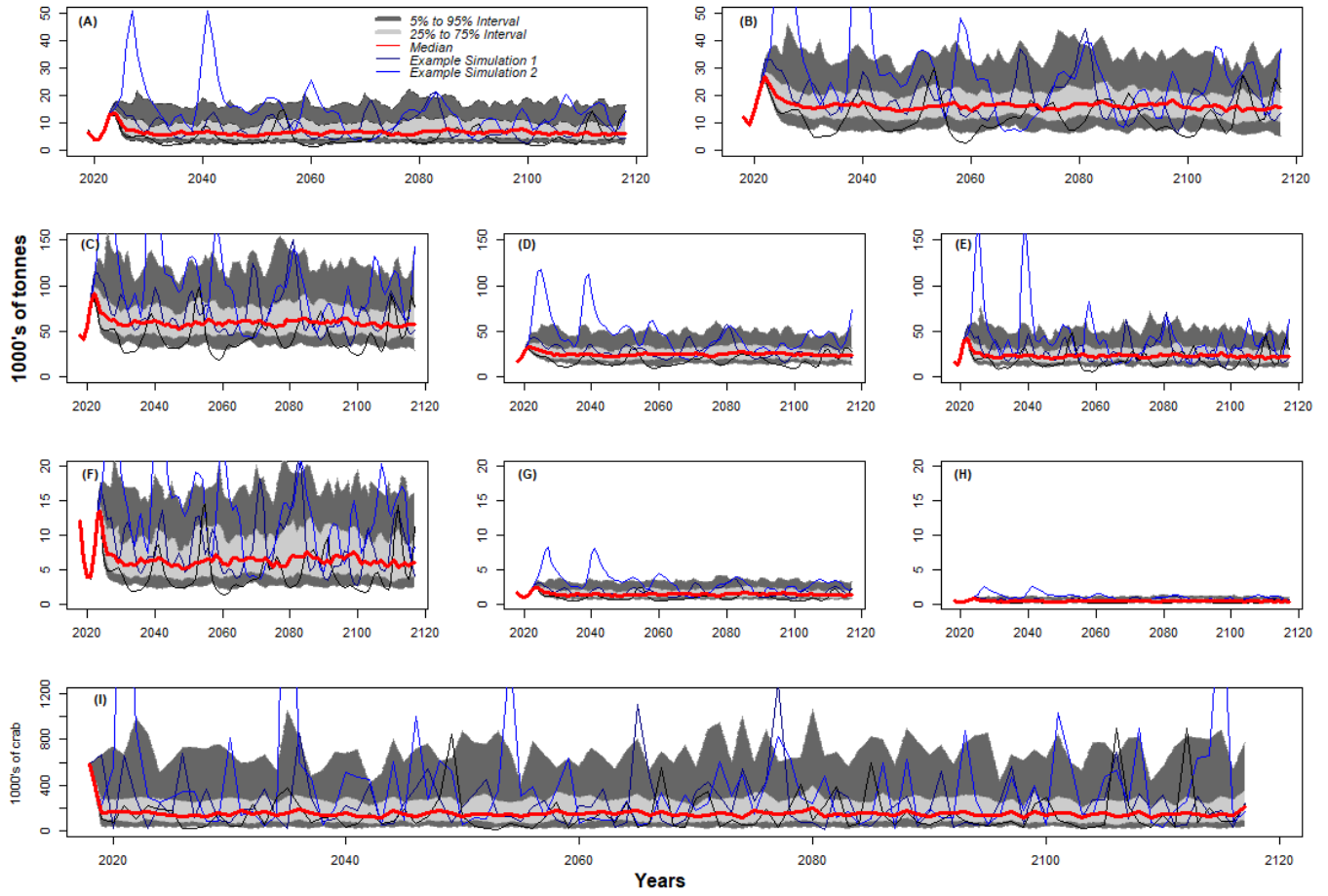


Figure AC. 17 As for Figure A3.1 except for HCR4_3.

HCR4_3

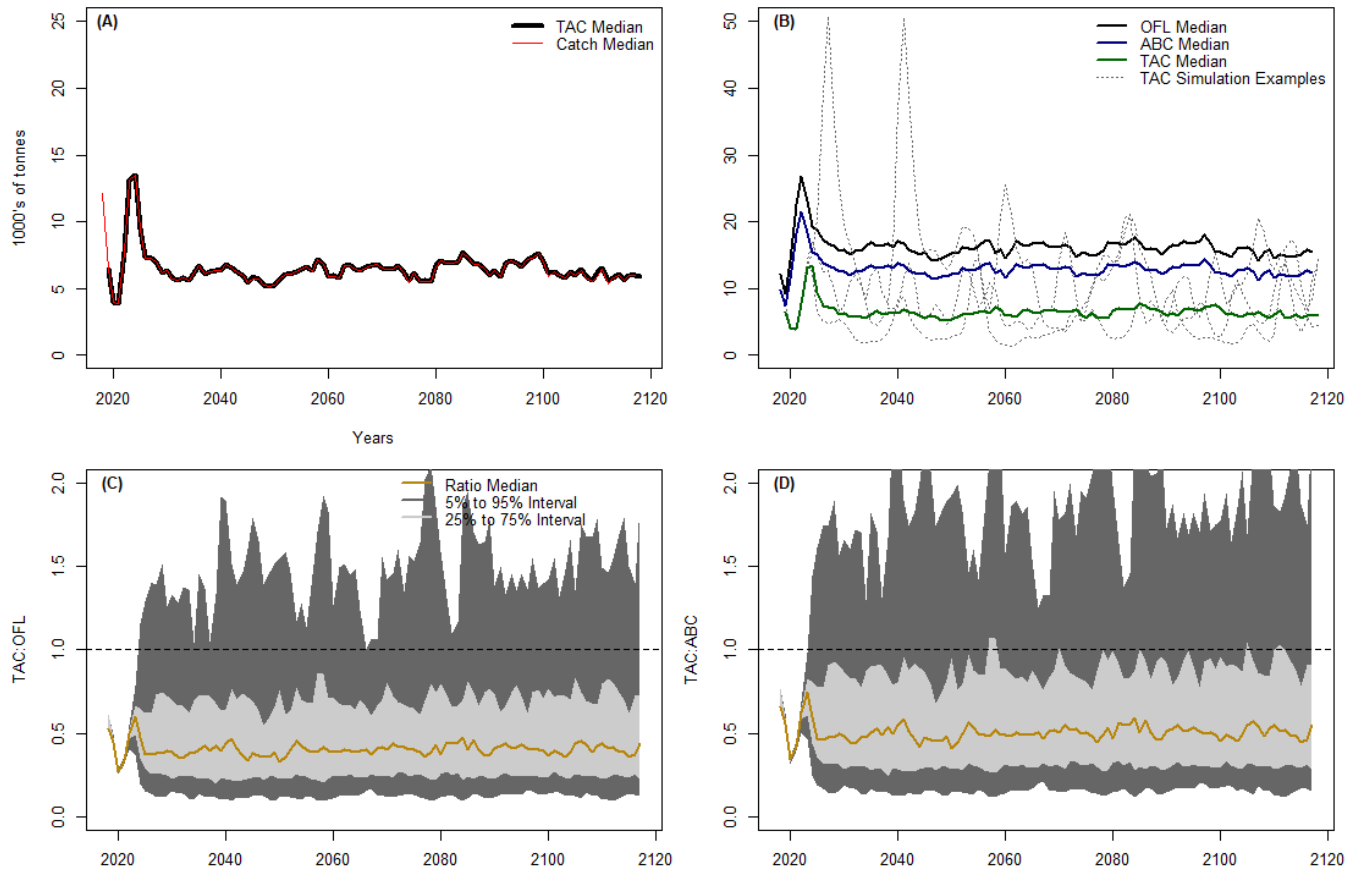


Figure AC. 18 As for Figure A3.2, except for HCR4_3.

HCR4_4

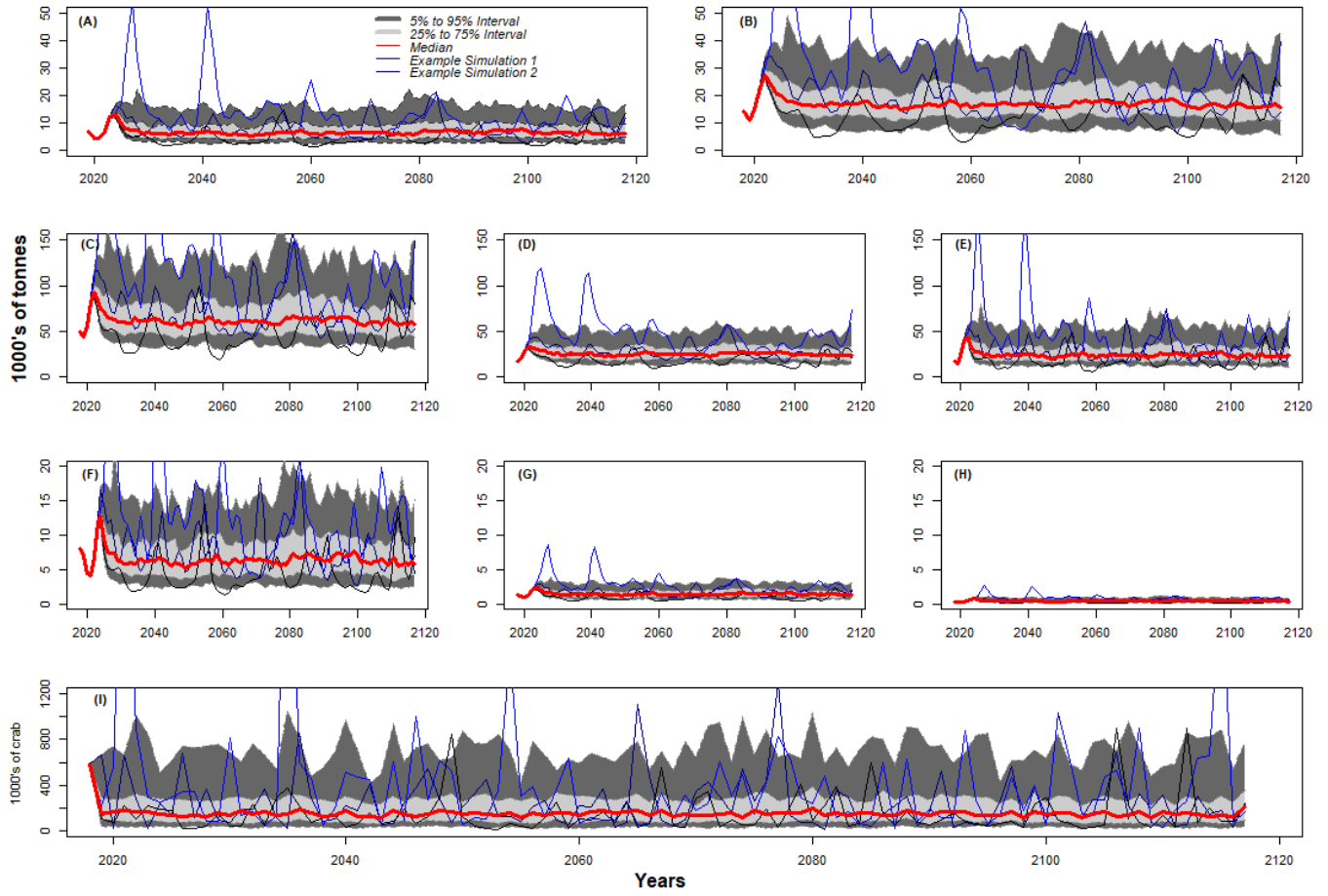


Figure AC. 19 As for Figure A3.1 except for HCR4_4.

HCR4_4

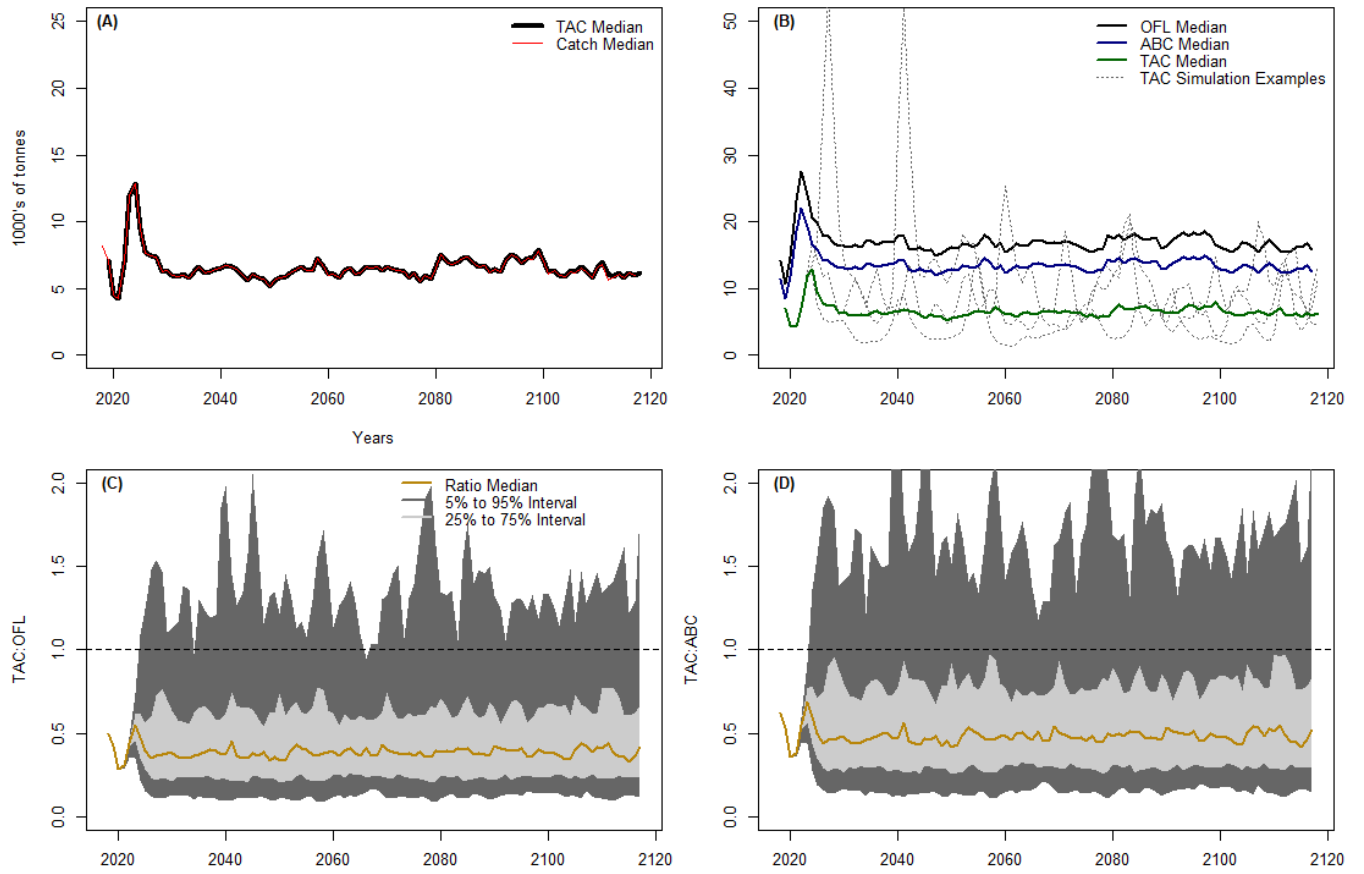


Figure AC. 20 As for Figure A3.2, except for HCR4_4.

HCR5

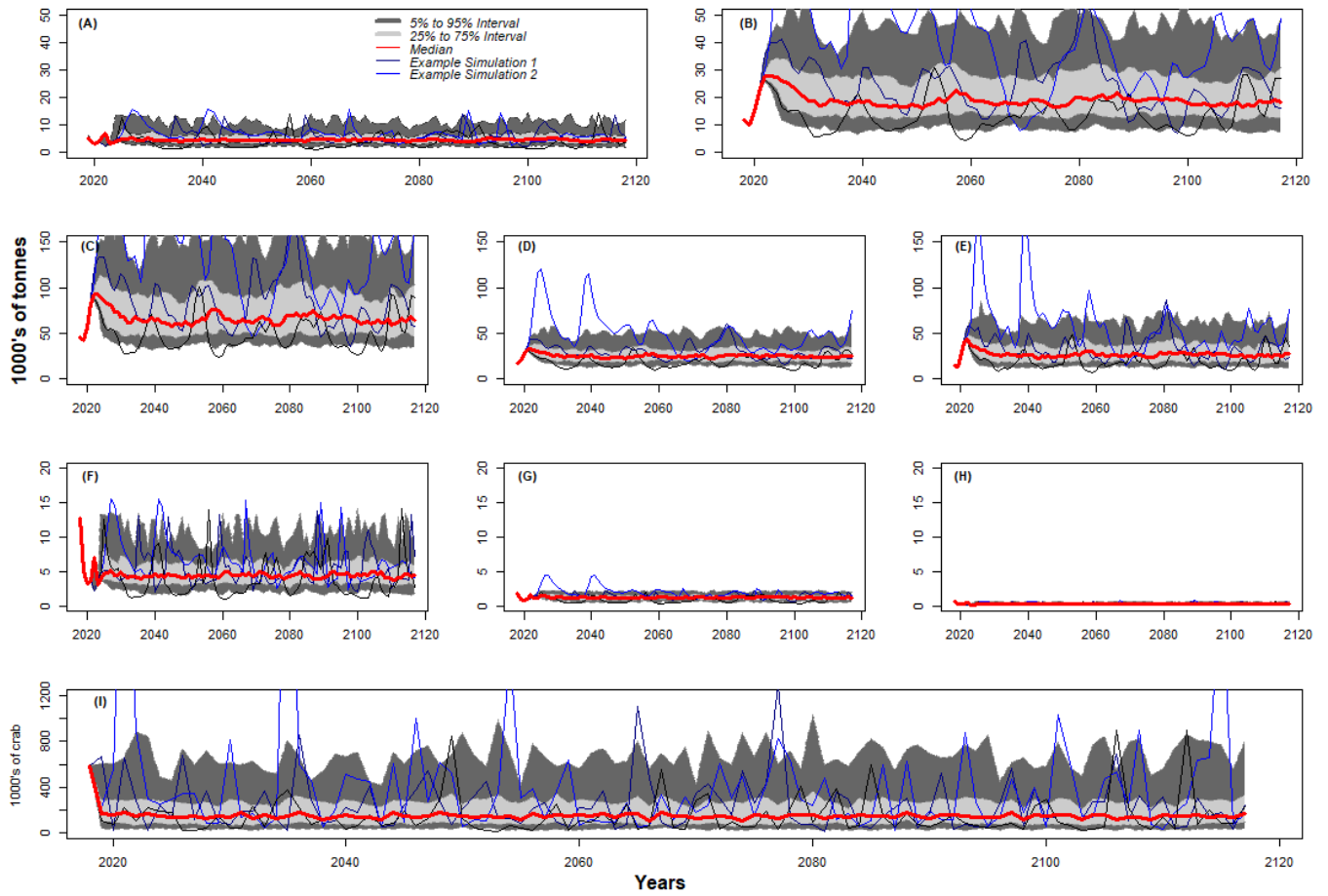


Figure AC. 21 As for Figure A3.1 except for HCR5.

HCR5

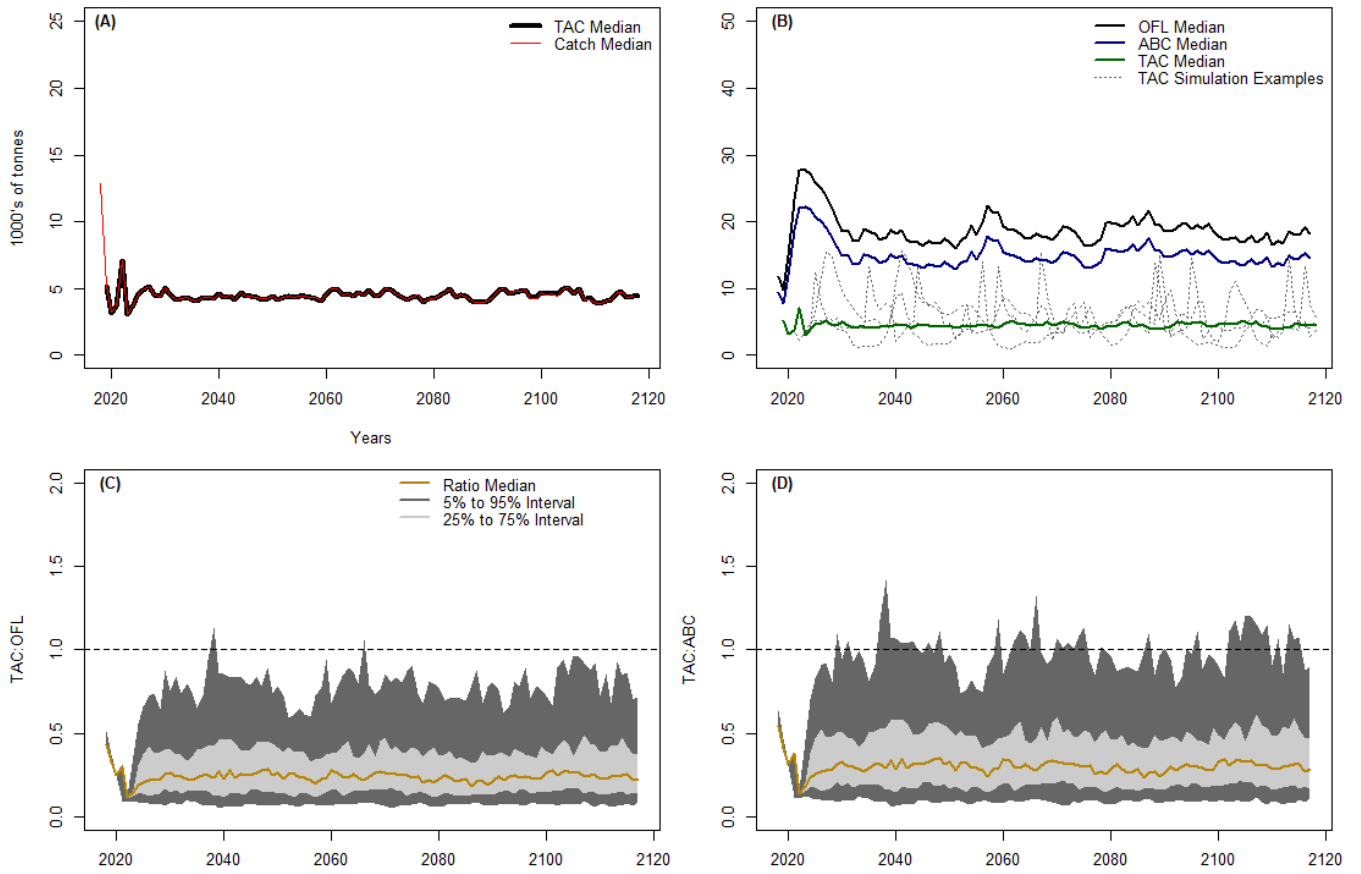


Figure AC. 22 As for Figure A3.2, except for HCR5.

HCR6_3

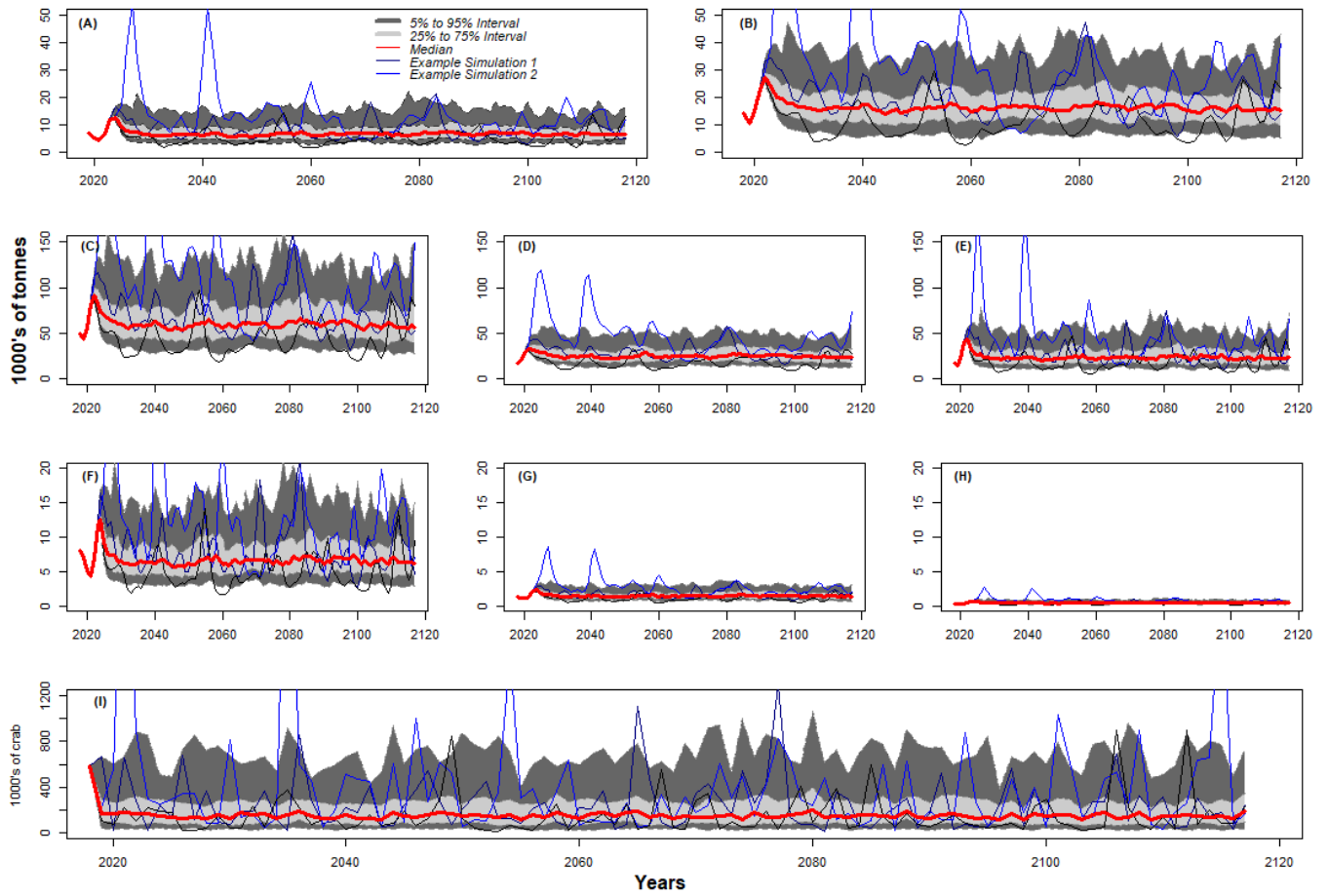


Figure AC. 23 As for Figure A3.1 except for HCR6_3.

HCR6_3

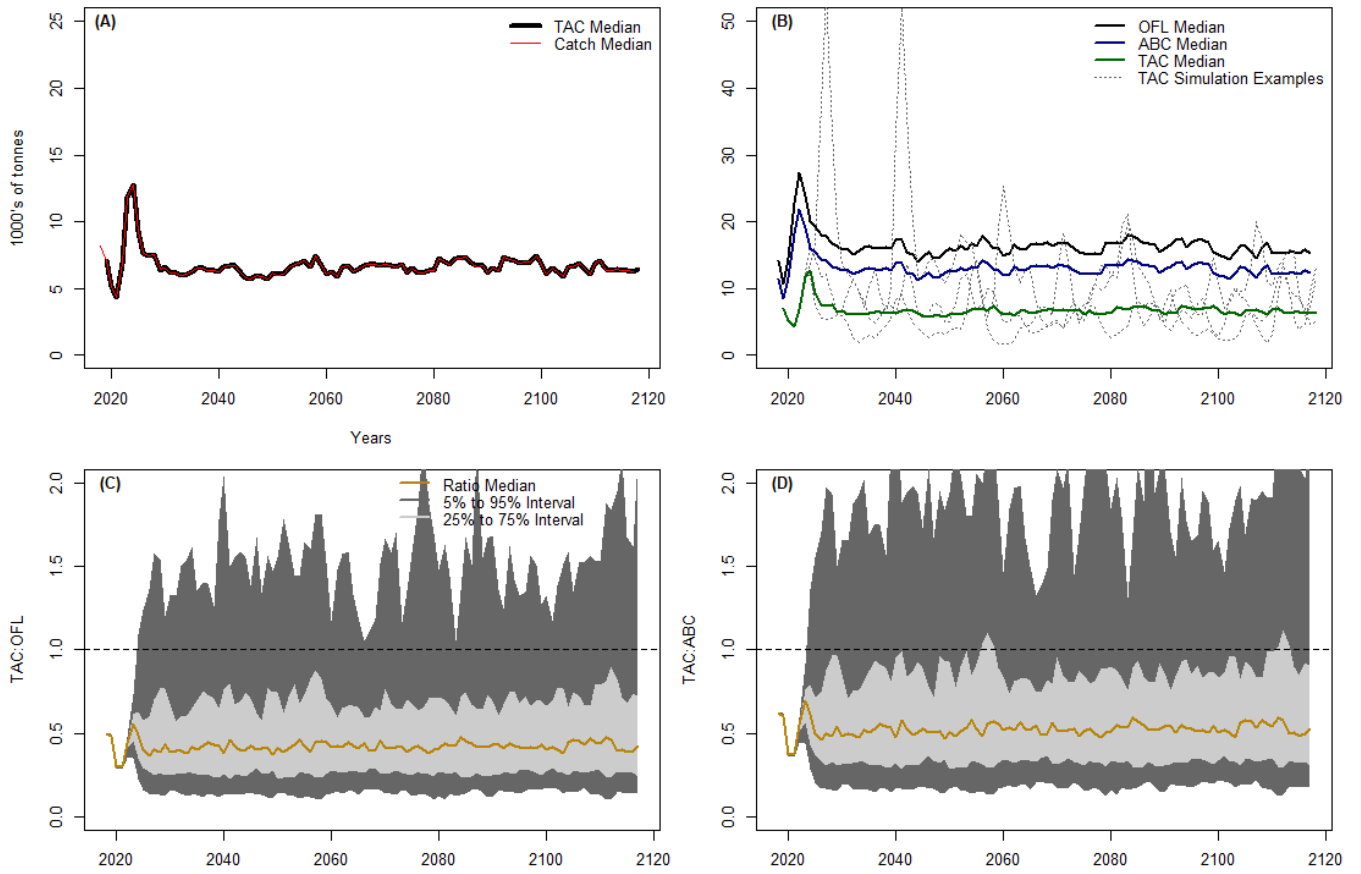


Figure AC. 24 As for Figure A3.2, except for HCR6_3.

HCR6_4

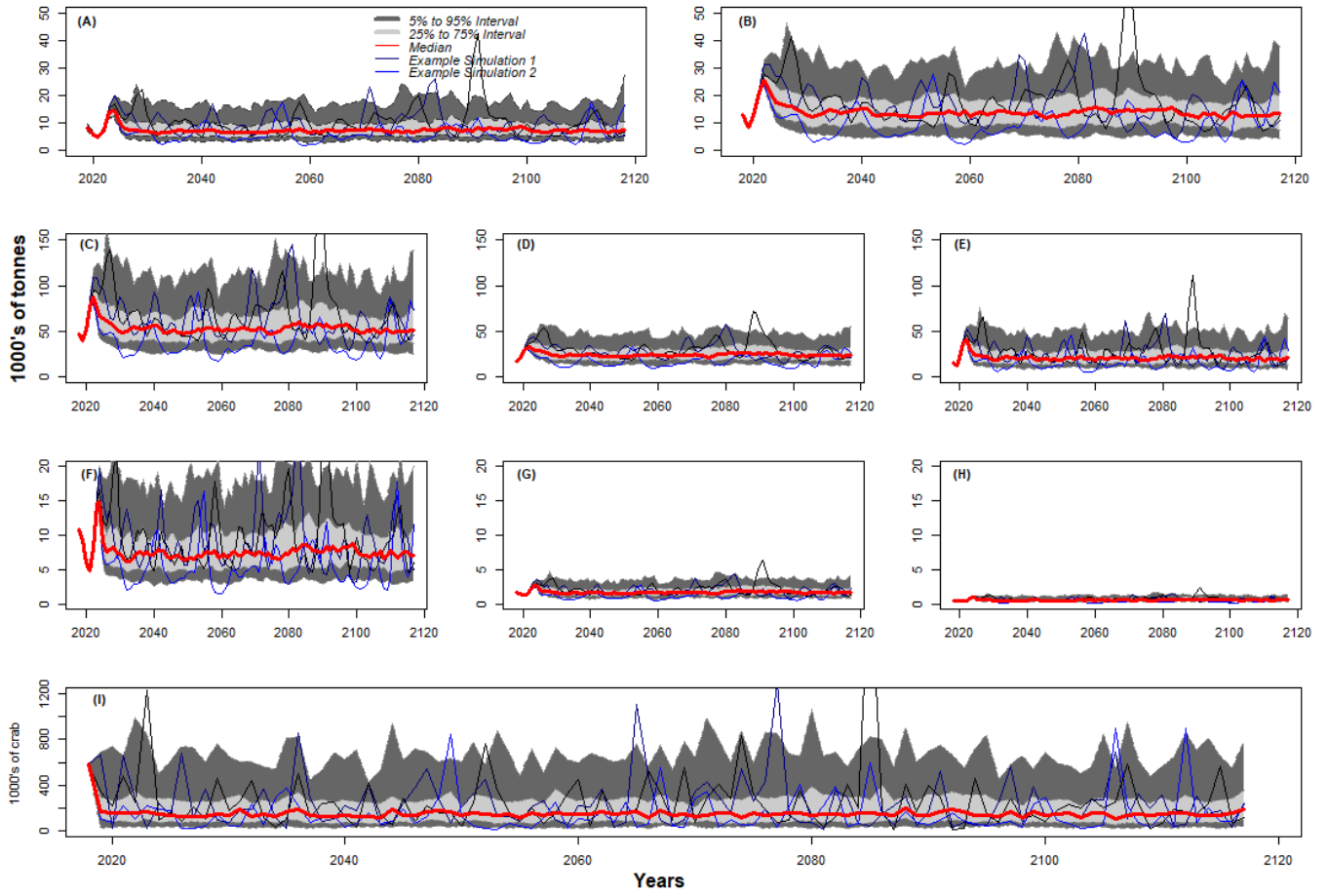


Figure AC. 25 As for Figure A3.1 except for HCR6_4.

HCR6_4

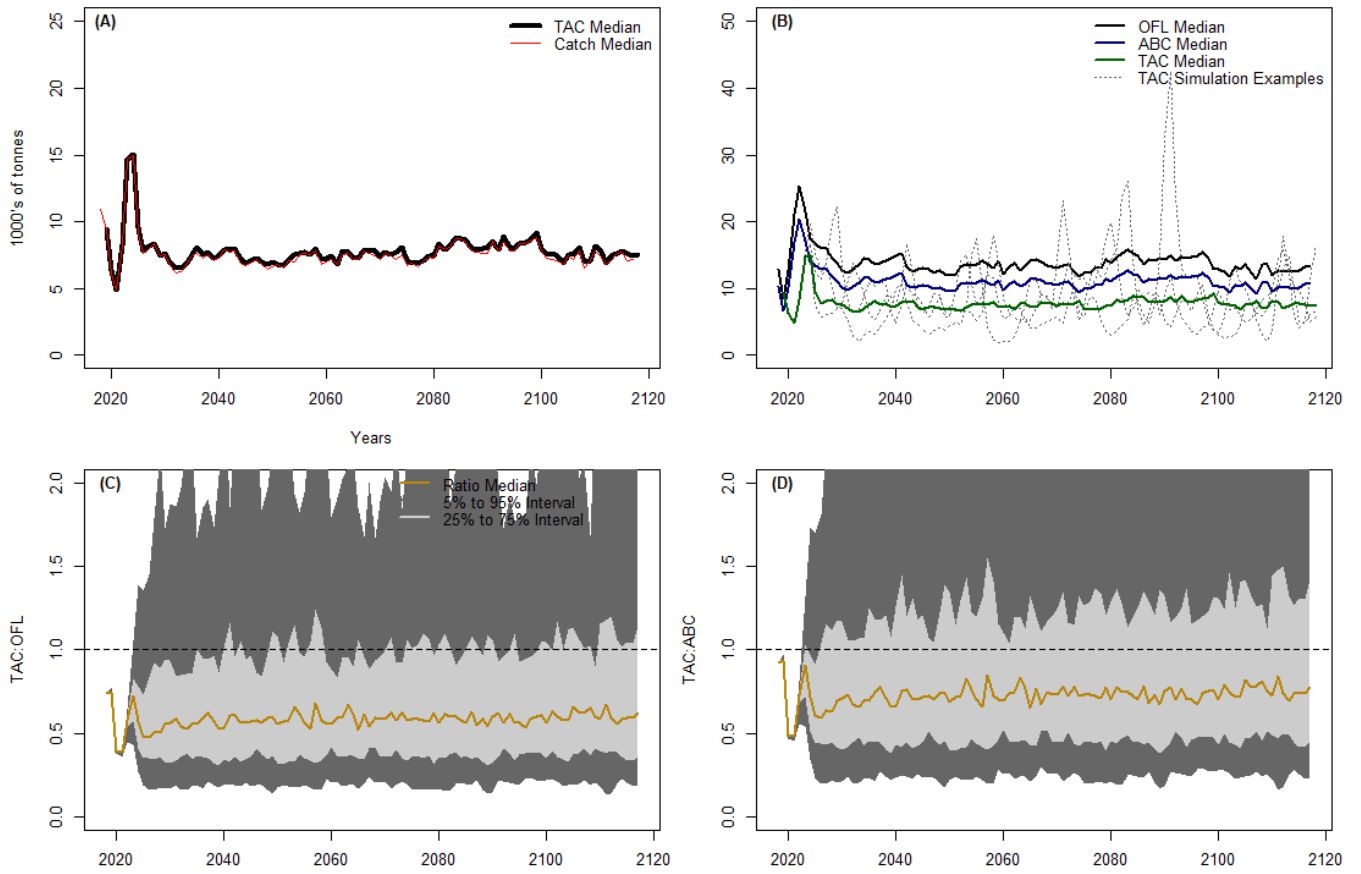


Figure AC. 26As for Figure A3.2, except for HCR6_4.

HCR6_5

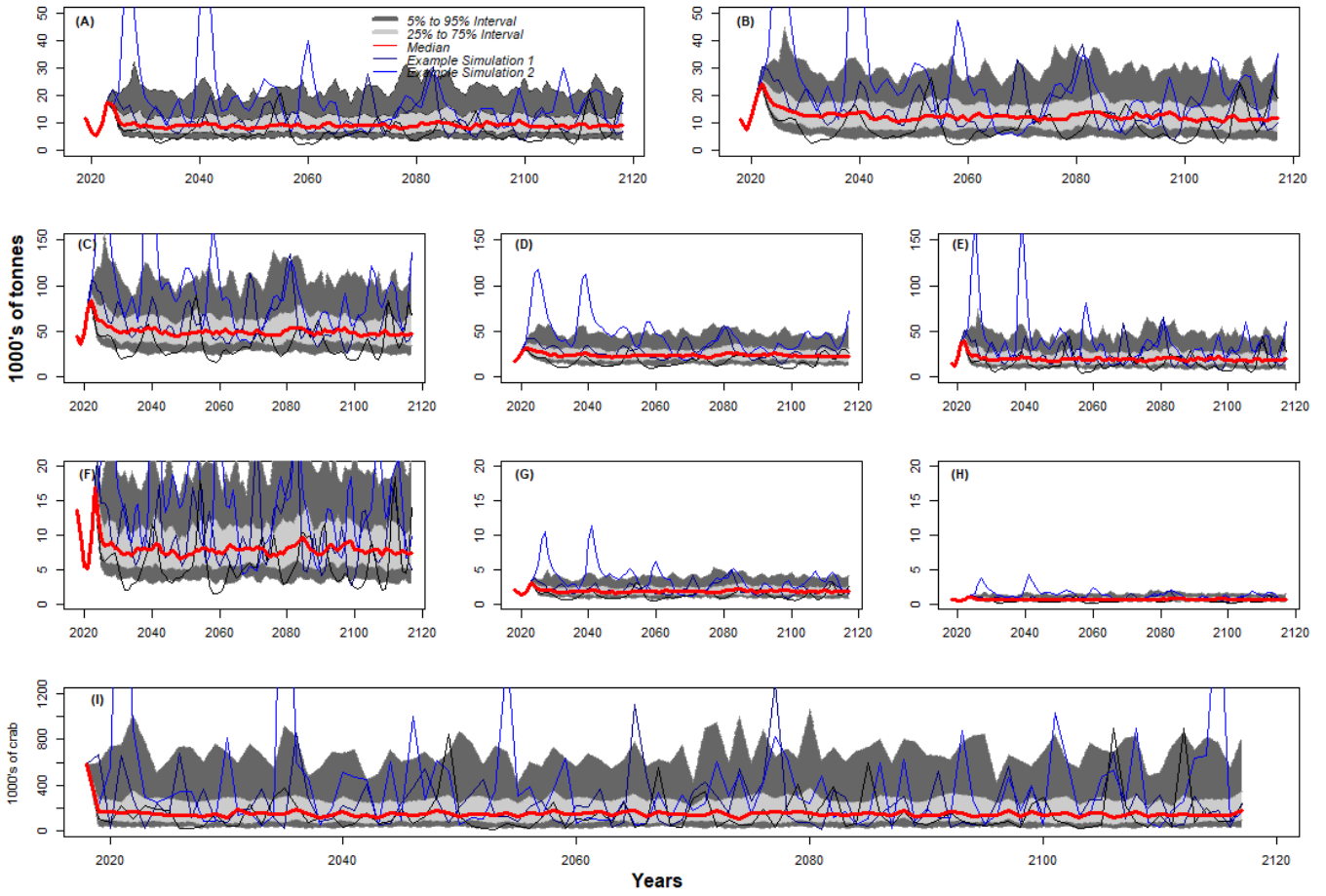


Figure AC. 27 As for Figure A3.1 except for HCR6_5.

HCR6_5

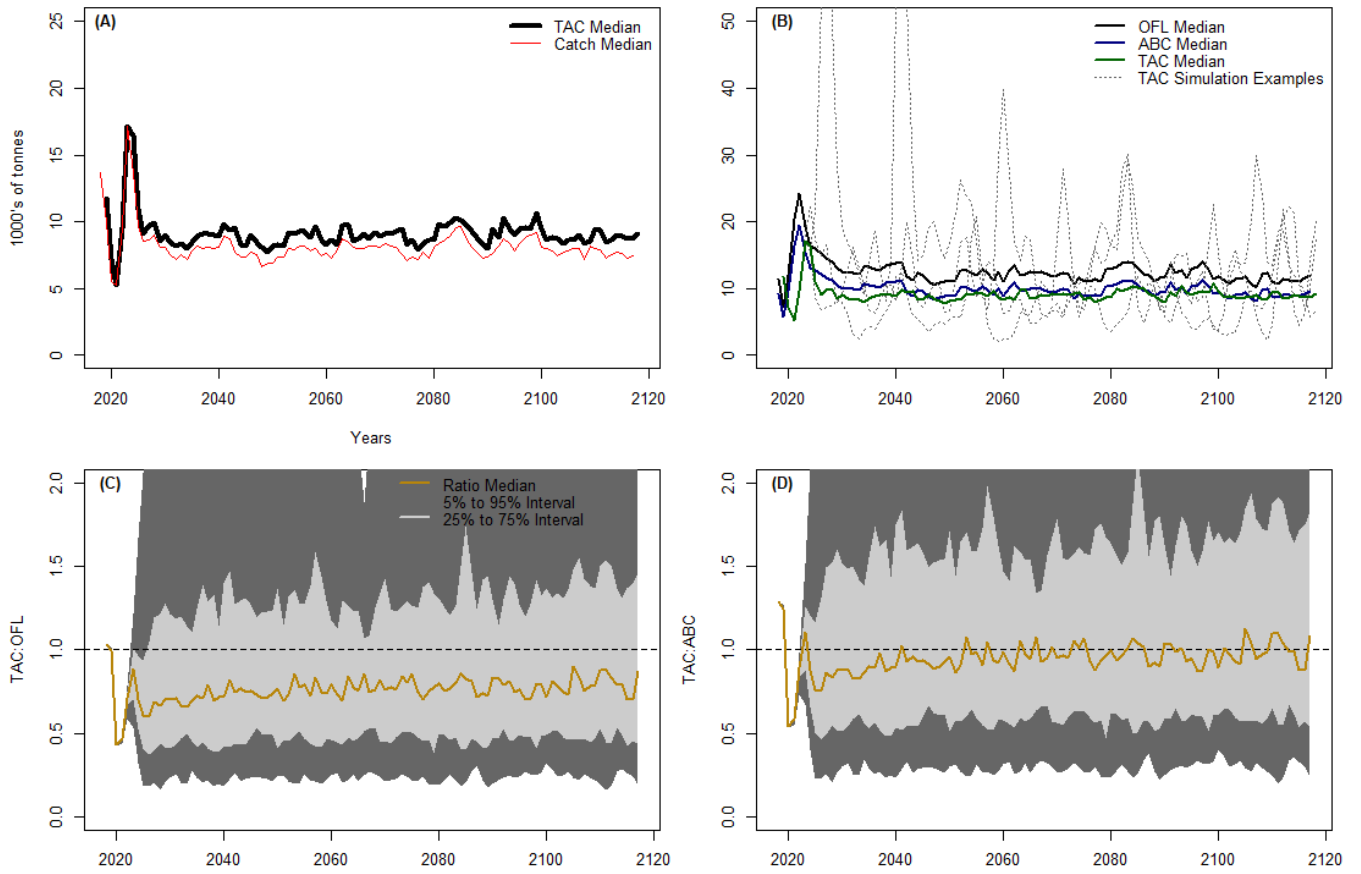


Figure AC. 28 As for Figure A3.2, except for HCR6_5.

HCR7

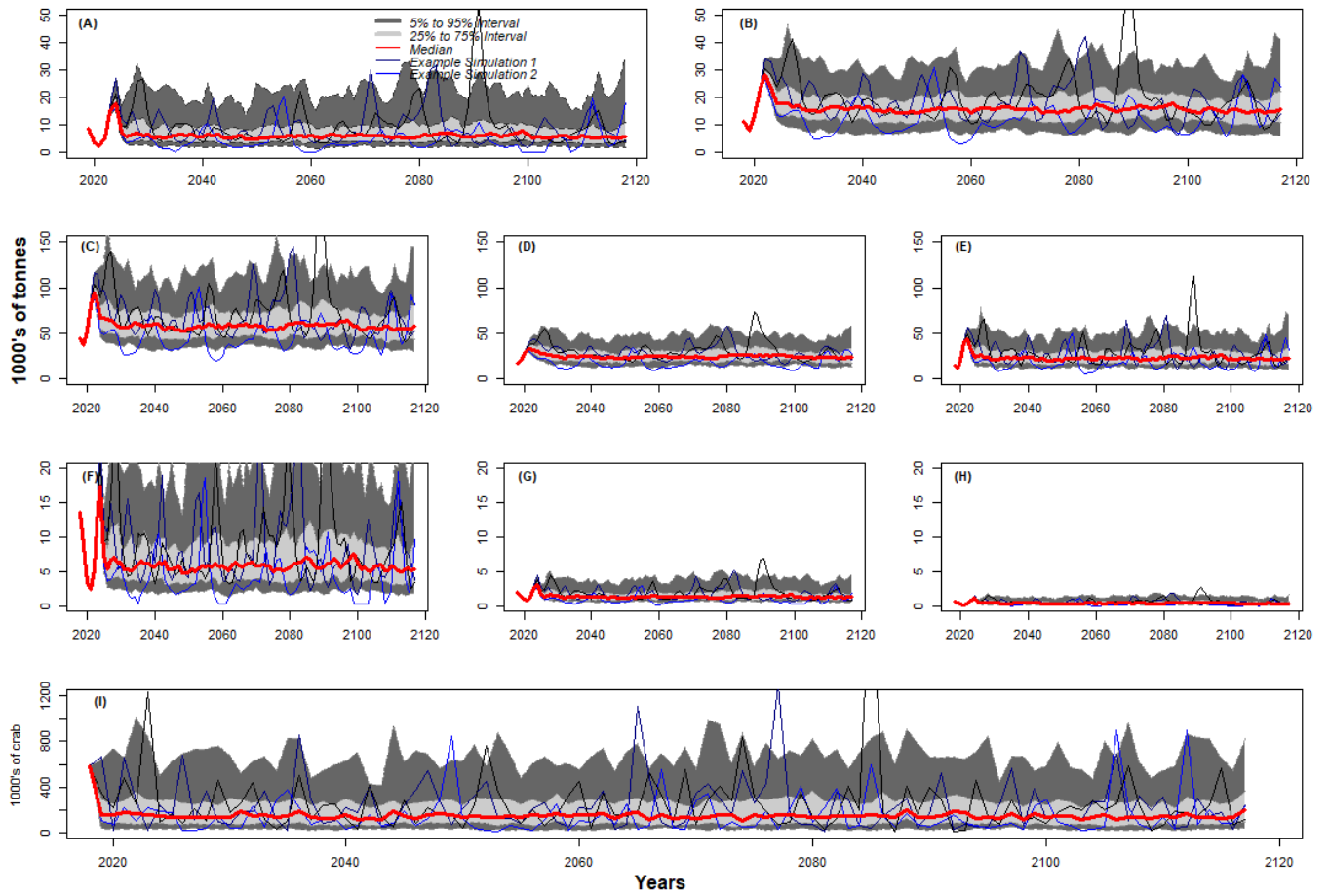


Figure AC. 29 As for Figure A3.1 except for HCR7.

HCR7

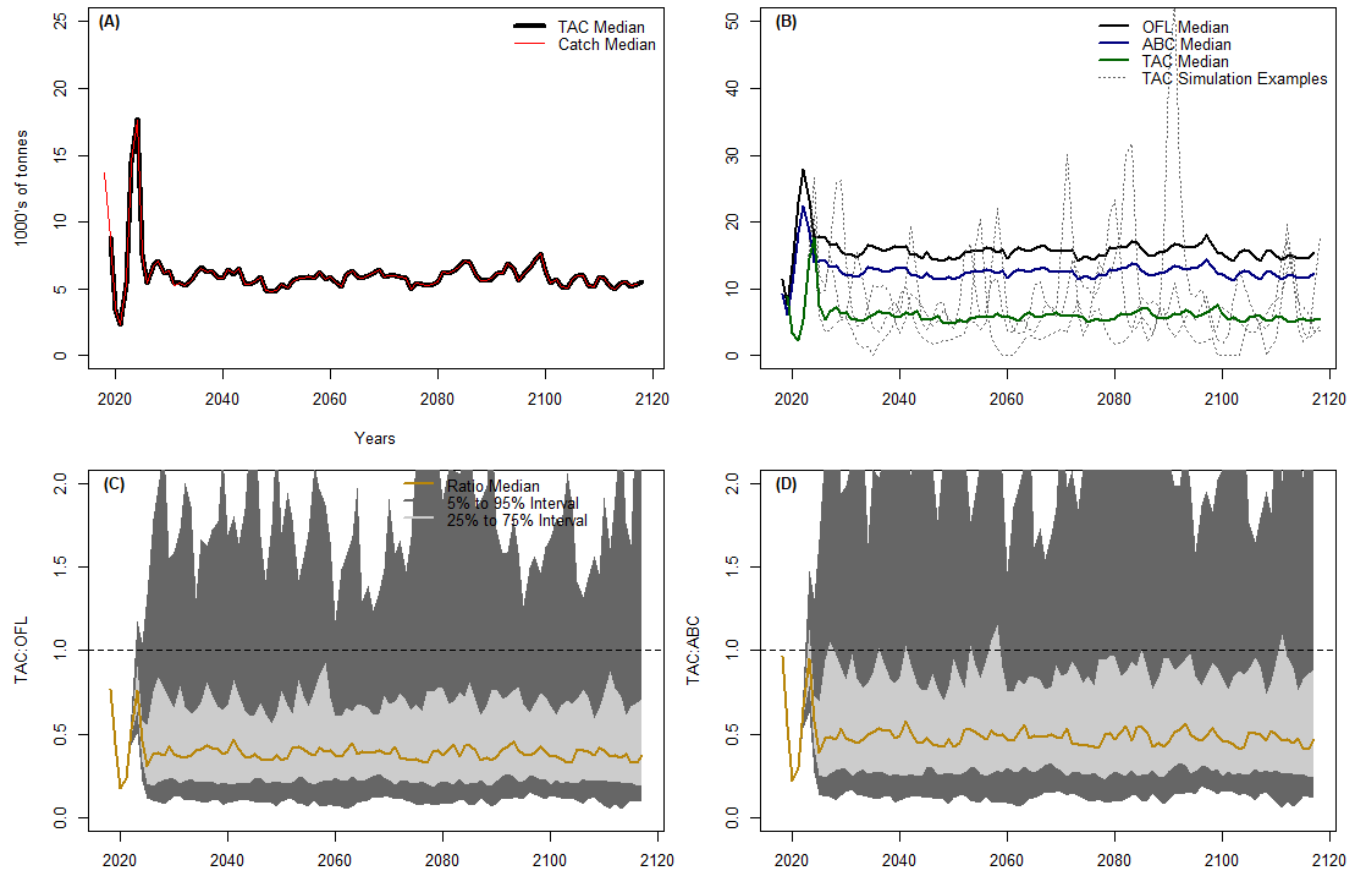


Figure AC.30 As for Figure A3.2, except for HCR7.

BIBLIOGRAPHY

- ADF&G (Alaska Department of Fish and Game). (1990). Policy on king and Tanner crab resource management. *ICES Document* 90-04-FB.
- ADF&G (Alaska Department of Fish and Game). (2017a). 2017-2019 King and Tanner Crab Commercial Fishing Regulations.
- ADF&G (Alaska Department of Fish and Game). (2017b). Tanner crab harvest strategy substitute language. [In] Record Copy 8 (RC8) from Alaska Board of Fisheries May 2017 meeting.
- Beverton, R. J. H., and S. J. Holt. (1957). On the dynamics of exploited fish populations. *Fisheries Investigations* (Series 2).
- Connors, M. E., Hollowed, A. B., & Brown, E. (2002). Retrospective analysis of Bering Sea bottom trawl surveys: Regime shift and ecosystem reorganization. *Progress in Oceanography*, 55(1–2 SPEC ISS.), 209–222.
- Daly, B. (2018, September). *Update: ADF&G Bering Sea Tanner crab harvest strategy revision*. Alaska Department of Fish and Game presentation at Crab Plan Team Meeting, Seattle, WA.
- Daly, B., Heller-Shipley, M., Stichert, M., Stockhausen, W., Punt, A., & Goodman, S. (2020). Recommended Harvest Strategy for Bering Sea Tanner Crab.
- Donaldson, W. E., R. T. Cooney, and J. R. Hilsinger. (1981). Growth, age and size at maturity of Tanner crab, *Chionoecetes bairdi* M. J. Rathbun, in the northern Gulf of Alaska (Decapoda, Brachyura). *Crustaceana* 40(3): 286-302.
- Francis, R. I. C. C., & Shotton, R. (1997). “Risk” in fisheries management: a review. *Can. J. Fish. Aquat. Sci.*, 54(8), 1699-1715.
- Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. (2012). AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optim. Methods Softw.* 27:233-249.
- Goodman, S. (2018). Summary information for the December 2017 workshop for *bairdi* Tanner crab, hosted by the Bering Sea Fisheries Research Foundation (BSFRF), Juneau, AK.
- Lang, C. A., Richar, J. I., & Foy, R. J. (2018). The 2017 eastern Bering Sea continental shelf and northern Bering Sea bottom trawl surveys: results for commercial crab species.
- Mapstone, B. D., Little, L. R., Punt, A. E., Davies, C. R., Smith, A. D. M., Pantus, F., McDonald, A.D., Williams, A.J., & Jones, A. (2008). Management strategy evaluation for line fishing in the Great Barrier Reef: balancing conservation and multi-sector fishery objectives. *Fisheries Research*, 94(3), 315-329.

- Narula, S., Jain, A., & Prachi. (2015). "Cloud Computing Security: Amazon Web Service," 2015 Fifth International Conference on Advanced Computing & Communication Technologies, Haryana. 501-505.
- North Pacific Fishery Management Council (NPFMC). (2007). Stock Assessment and Fishery Evaluation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fishery Management Council, Anchorage, AK.
- North Pacific Fishery Management Council (NPFMC). (2011). Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner Crabs. North Pacific Fishery Management Council, Anchorage, AK.
- Paul, A. J. (1984). Mating frequency and viability of stored sperm in the Tanner crab *Chionoecetes bairdi* (Decapoda, Majidae). *Journal of Crustacean Biology*, 4(3), 375-381.
- Punt, A. E., Butterworth, D. S., de Moor, C. L., De Oliveira, J. A. A., & Haddon, M. (2016). Management strategy evaluation: best practices. *Fish and Fisheries*, 17, 303–334.
- Ricker, W. E. (1954). Stock and recruitment. *Journal of the Fisheries Research Board of Canada* 11(5): 559-623.
- Siddeek, M.S.M., Daly, B., Punt, A.E., Martel, S., Zheng, J., Stritch, M. (In press). Development of threshold management strategies for hard-to-age crab stocks: The example of the eastern Aleutian Islands, Alaska, golden king crab (*Lithodes aequispinus*). *Fish Bull.* US 00, 00-00.
- Smith, A. D. M., Sainsbury, K. J., & Stevens, R. A. (1999). Implementing effective fisheries-management systems—management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science*, 56(6), 967-979.
- Stevens, B. G., Donaldson, W. E., Haaga, J. A., & Munk, J. E. (1993). Morphometry and maturity of paired Tanner crabs, *Chionoecetes bairdi*, from shallow- and deepwater environments. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(7), 1504-1516.
- Stockhausen, W. T., (2018). 2018 Stock Assessment and Fishery Evaluation Report for the Tanner crab Fisheries of the Bering Sea and Aleutian Islands Regions. In: Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands: 2018 Final Crab SAFE. North Pacific Fishery Management Council. Anchorage, AK
- Somerton, D. A. (1981). Regional variation in the size of maturity of two species of Tanner crab (*Chionoecetes bairdi* and *C. opilio*) in the eastern Bering Sea, and its use in defining management subareas. *Canadian Journal of Fisheries and Aquatic Sciences*, 38(56080), 163–174.

- Tamone, S. L., Taggart, S. J., Andrews, A.G., Mondragon, J., & Nielsen, J.K. (2007). The Relationship between circulating ecdysteroids and chela allometry in male Tanner crabs: Evidence for a terminal molt in the genus *Chionoecetes*, *Journal of Crustacean Biology*, 27(4): 635–642
- Wahle, R. A. (2003). Revealing stock-recruitment relationships in lobsters and crabs: is experimental ecology the key? *Fisheries Research* 65: 3-32.
- Webb, J. B., L. M. Slater, G. L. Eckert, and G. H. Kruse. (2016). The contribution of fecundity and embryo quality to reproductive potential of eastern Bering Sea snow crab (*Chionoecetes opilio*). *Canadian Journal of Fisheries and Aquatic Sciences* 73(12): 1800-1814.
- Zacher, L. S., Richar, J. I., & Foy, R. J. (2020). The 2019 eastern and northern Bering Sea continental shelf trawl surveys: results for commercial crab species.
- Zheng, J., and G. H. Kruse. (2003). Stock-recruitment relationships for three major Alaskan crab stocks. *Fisheries Research* 65: 103-121.
- Zheng, J., Murphy, M. C., & Kruse, G. H. (1997). Analysis of harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences*, 54(5), 1121-1134.
- Zheng, J., & Pengilly, D. (2011). Overview of Proposed Harvest Strategy and Minimum Size Limits for Bering Sea District Tanner Crab Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries Symbols and Abbreviations.