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Development of harvest control rules for hard-to-age crab stocks: the example of the golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands in Alaska

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Abstract—The golden king crab (*Lithodes aequispinus*) has traditionally been managed in the Aleutian Islands by using a constant catch strategy but interest in abundance-based management has emerged with the recent adoption of a size-based stock assessment model. Management strategy evaluation (MSE) is commonly used to quantify conservation and economic trade-offs of alternative management strategies, but computational constraints can impede the representation of all sources of uncertainty. We conducted a simplified MSE for the golden king crab that focused on what we regarded as the major uncertainties, including initial stock abundance, future recruitment, estimation of mature male biomass and abundance, and catch implementation error, while capturing the existing unique federal and state cooperative management framework for crab stocks in the Bering Sea and Aleutian Islands. The simplified MSE identified recruitment variability as the most important factor in determining overall fishery performance, and conservation and economic metrics highlight benefits of a 15% over a 30% exploitation rate. We feel this simplified approach results in a robust analysis despite the reduced computational demands compared with those of a full MSE. Similar approaches can be used for other stocks, but managers must define management objectives, consider stock dynamics, and identify factors likely to have the greatest effect on expected performance.

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Strategies for calculating catch limits have evolved from the use of constant catch, constant exploitation rate, and fixed escapement to a focus on threshold harvest control rules (HCRs). The latter are considered superior because they include limits and targets for sizes of the stock and modify exploitation levels to rebuild stocks to, or sustain them at, healthy levels (Quinn et al., 1990; Zheng et al., 1993; Caddy and Mahon, 1995; Restrepo and Powers, 1999; Punt et al., 2008). However, it is necessary to specify parameter values for HCR formulas (for HCRs, see Figure 1 and Supplementary Figure 1) because each set of parameter values will lead to different outcomes. Management strategy evaluation (MSE) is becoming an increasingly common tool for quantification of trade-offs among conservation and economic goals for management strategies (Punt et al., 2016). Management strategy evaluation involves identifying management objectives, identifying the key uncertainties and representing them in a mathematical model of the system (hereafter referred to as the *operating model*), identifying the candidate management strategies (the combination of a method for estimating stock status and an HCR), projecting the population forward in the operating model for each candidate management strategy, and summarizing the results through the use of performance metrics.

Because MSE is computationally intensive, addressing all major uncertainties, including modeling, estimation, observation, process, and implementation, can be impractical. As such, if MSE is to be a practical management tool, it must accurately represent the management framework and narrow sources of uncertainty down to a key subset and represent them in the operating model. Here, we describe how to employ MSE in a simplified form in a unique federal and state cooperative management framework, using the stock of golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands as an example. The data-poor nature and complexity of the assessment of this stock necessitated employment of a simplified MSE in which the stock assessment process is simulated stochastically rather than modeled explicitly (for a similar approach, see Punt et al., 2008).

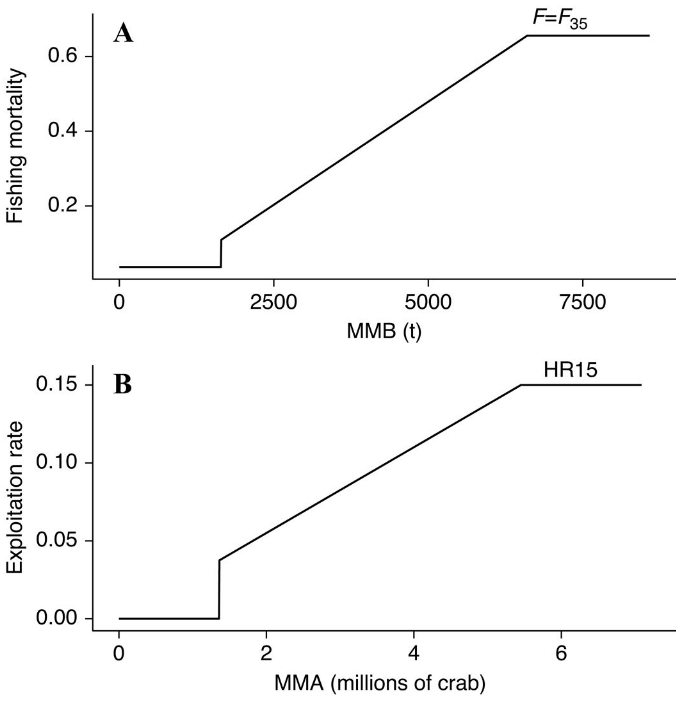

Figure 1

Graphs of the currently implemented (**A**) federal and (**B**) state harvest control rules (HCRs) for golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands. The federal stock assessment establishes the overfishing level on the basis of an HCR that is a function of instantaneous fishing mortality (F), shown in decimal form per year, and mature male biomass (MMB), shown in metric tons (t). The state HCR (HR15) determines a discrete exploitation rate, shown in decimal form, as a function of mature male abundance (MMA). The directed pot fishery closes when MMA or MMB reaches a proportion of 0.25 of average MMA or a proportion of 0.25 of MMB_{35}, which is 35% of the unfished level of MMB (i.e., MMB given F=F_{35}, which is 35% of the unfished spawning biomass per recruit), indicated by the vertical drops in the lines for the HCRs. The vertical drop in panel A does not reach zero because F attributable to bycatch can still occur in the groundfish fishery when the directed fishery is closed.

The rest of this section provides a background of the stock of golden king crab in the eastern Aleutian Islands and its associated management system, which is used to determine which aspects are included in the operating model. We then outline the candidate management strategies (those currently implemented and alternative choices for HCRs), including some with lower and higher target fishing mortality rates than those previously considered appropriate, and compare them by using conservation and economic performance metrics.

Background and fishery

Golden king crab in the Aleutian Islands inhabit relatively deep water (at depths of 300–1000 m) on structurally complex habitat, such as rock and coral. They are caught by using rectangular crab pots ranging in length from 1.2 to 3.0 m. Because of deep habitats, pots are deployed with longlines, with each string having 30–40 pots, each approximately 200 m apart from the next pot. Golden king crab in the Aleutian Islands compose what is considered one stock but are managed in 2 areas: east and west of the longitude 174°W. The fishery is male-only with a minimum size limit. The fishery has been managed by using a constant catch management strategy since the 1996–1997 fishing season. Rationalization of crab stocks in the Bering Sea and Aleutian Islands in the 2005–2006 fishing season resulted in dramatic changes in fishing practices, including those for golden king crab in the Aleutian Islands: most notably, reduced fleet size and increased average pot soak time (Fina, 2005). Although the directed fishery accounts for most of the total fishery mortality, a small amount of bycatch occurs in other crab fisheries and the groundfish trawl and pot fisheries (<1% of the total number of removed animals; Leon et al., 2017). There was a belief by industry members that the stock could sustain higher levels of fishing intensity because no adverse effects to the population were detected through the use of fishery-dependent data under the constant catch management strategy (Siddeek et al., 2020).

Assessment and management system

A stock assessment provides inputs to HCRs (i.e., annual population abundance estimates and measures of productivity) and evaluates whether overfishing has occurred (i.e., whether total fishing mortality exceeds the corresponding overfishing level [OFL]) or whether the stock is in an overfished state (i.e., whether the stock size is below the minimum stock size threshold [MSST], which can be no lower than one half of the biomass [B] corresponding to maximum sustainable yield [MSY] or $0.5B_{\mathrm{MSY}}$). The stock assessment for golden king crab in the Aleutian Islands has been based on a male-only, size-structured population dynamics model, which was adopted for management by the North Pacific Fishery Management Council in 2016. Unlike for other major crab stocks in the Bering Sea and Aleutian Islands, area-swept abundance estimates are not available for this stock because of the lack of a bottom trawl survey (NPFMC, 2018). Consequently, the assessment for the stock in the Aleutian Islands is based on fishery-dependent data (catch per unit of effort [CPUE] and catch size composition) and accounts for changes in fishing behavior due to crab fishery rationalization by fitting the operating model to separate sets of CPUE indices and by estimating fishery selectivity patterns for the pre- and post-rationalization periods (Siddeek et al., 2020).

The North Pacific Fishery Management Council fishery management plan for the king and Tanner crabs in the Bering

Sea and Aleutian Islands established a state and federal cooperative management regime that defers crab management to the state of Alaska with federal oversight (NPFMC[1]). As part of the federal process, status determination criteria, including OFLs and acceptable biological catches (ABCs), are calculated annually for crab stocks on the basis of a 5-tier system that accommodates varying levels of uncertainty, in which stocks with more biological information and greater assessment richness fall into lower tiers (NPFMC[1]). Annual catch levels (i.e., total allowable catches [TACs]) are determined by the state of Alaska according to fishery regulations established by the Alaska Board of Fisheries, but catch levels and management actions need to be consistent with the provisions of the fishery management plan of the North Pacific Fishery Management Council, the national standards of the Magnuson-Stevens Conservation and Management Act, and other applicable federal regulations (NPFMC[1]). As such, it is necessary to consider the federal and state HCRs to adequately represent the management system.

The federal stock assessment establishes the OFL on the basis of an HCR (Fig. 1A) that is a function of instantaneous fishing mortality and mature male biomass (MMB), includes a proxy for F_{MSY} (F_{35}, the fishing mortality rate corresponding to 35% of the unfished spawning biomass per recruit; Clark, 1991, 2002) and a proxy of B_{MSY} (B_{35}, the spawning biomass corresponding to F_{35}). The ABC is then computed as 75% of the OFL. The directed fishery closes when MMB is $<0.25B_{\mathrm{MSY}}$.

The state HCR (Fig. 1B, Suppl. Fig. 1B) determines a (discrete) exploitation rate as a function of mature male abundance (MMA), involves a target level of average MMA (MMA_{ave}), a threshold for opening and closing the directed fishery ($0.25MMA_{\mathrm{ave}}$), and a maximum exploitation rate on MMA (Daly et al., 2019). The outcomes from this HCR may be constrained by a maximum number of legal-sized males that are allowed to be removed, or they may be unconstrained.

The final TAC is the minimum of the outcomes of the state HCR (when expressed as a catch) and the ABC. We investigated only options for the state HCR in this study but simulated both federal and state HCRs because, for example, increasing the target exploitation rate in the state HCR may have no effect on stock dynamics if the resulting catch is less than the federal ABC (i.e., is a lower level to prevent catch exceeding OFL). Historically, the outcome of the state HCR has been substantially lower than that of the ABC (Suppl. Fig. 2).

Materials and methods

The recently developed stock assessment model for golden king crab in the Aleutian Islands provides the input required to support a state HCR that scales the target exploitation rate by using population abundance. However, the shift to abundance-based management needs to be evaluated by using analyses tailored to the management framework for golden king crab in the Aleutian Islands. We evaluated 5 HCRs (Table 1) for the stock of gold king crab in the eastern portion (i.e., east of 174°W) of the Aleutian Islands by projecting the population (in the operating model) forward in time with catches determined by the state HCRs (constrained by the federal ABCs). For the initial year of 2018, stock abundance by size class and operating model parameter values were estimated by using an integrated size-structured assessment model based on data for 1981–2018 (Siddeek et al., 2020; Suppl. Materials). The 30-year projections were replicated 1000 times. The fishing mortality rate for the groundfish fishery was set to the average during 1999–2018. We chose a 30-year period for the projections because survival for animals in the population in 2018 would be <1% by 30 years, assuming an instantaneous natural mortality rate of 0.21/year. The trajectories of selected performance metrics appear to stabilize within ~20 years (for example, for trends in MMB and MMA, see Figure 2).

Selection of uncertainties

It is computationally impossible to consider all possible sources of uncertainty associated with a stock and fishery. Rather, the sources of uncertainty considered in analyses were selected because they were thought to be those most likely to substantially affect performance of management strategies (following table 3 in Punt et al., 2016):

- Uncertainty in stock productivity and recruitment variability: captured with alternative values for the steepness (h) of the stock–recruitment relationship in the Ricker model (Ricker, 1954) and with the extent of variation and autocorrelation in recruitment in the stock–recruitment relationship;
- Estimation uncertainty: captured with the extent of variation and autocorrelation in estimates of biomass and abundance and with linear and nonlinear relationships between CPUE and stock abundance;
- Initial stock size uncertainty: captured with alternative specifications for initial stock abundance by size class and with the extent of variation and correlations in initial stock abundance among size classes; and
- Implementation uncertainty: accounted for with the extent of variation in realized catch with regard to TAC.

There are many other possible uncertainties that could have been but were not included in the simplified MSE, owing to a lack of evidence for such factors based on historical data and a lack of data with which to parameterize them in the operating model:

- Process error: depensation in the stock–recruitment relationship and occasional catastrophic mortality or recruitment events;

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[1] NPFMC (North Pacific Fishery Management Council). 2008. Final environmental assessment for Amendment 24 to the fishery management plan for Bering Sea/Aleutian Islands king and Tanner crabs to revise overfishing definitions, 177 p. [Available from website.]

Table 1

Summary of the 5 harvest control rules (HCRs) of the U.S. government and state of Alaska evaluated for golden king crab (*Lithodes aequispinus*) in the eastern portion of the Aleutian Islands. The management strategy with zero exploitation rate (HR0) is the reference HCR; HR10 has a maximum 10% exploitation rate with a 0.25 catch proportion cap on legal-sized male abundance, HR15 has a maximum 15% exploitation rate with a 0.25 catch proportion cap on legal-sized male abundance, HR15U has a maximum 15% exploitation rate without a cap on the proportion of legal-sized male abundance that can be caught, and HR30 has a maximum 30% exploitation rate with a 0.25 catch proportion cap on legal-sized male abundance. Average mature male abundance (MMA_{ave}) was estimated for the period from the 1985–1986 fishing season through the 2018–2019 fishing season. The HCR currently implemented by the state of Alaska for golden king crab in the eastern portion of the Aleutian Islands is HR15. F=fishing mortality rate; MMB=mature male biomass; OFL=overfishing level; and ABC=allowable biological catch.

Government	Harvest control rule	Maximum F	Minimum MMB for a fishery to take	ABC	Minimum MMA for a fishery to take	Maximum exploitation rate	Catch limit	Catch proportion cap on legal-sized male abundance
Federal		F_{35}	$0.25MMB_{35}$	$0.75OFL$				
State	HR0				$0.25MMA_{ave}$	0.00		0.25
	HR10				$0.25MMA_{ave}$	0.10		0.25
	HR15				$0.25MMA_{ave}$	0.15	≤ABC	0.25
	HR15U				$0.25MMA_{ave}$	0.15	≤ABC	None
	HR30				$0.25MMA_{ave}$	0.30	≤ABC	0.25

- Non-stationarity: changes over time in the form and parameters of the stock–recruitment relationship and time-varying natural mortality, growth, and selectivity; and
- Other factors: spatial and stock structure and time-varying movement.

Key features of the operating model

The basic dynamics are governed by this equation:

$$N_{t+1,j} = \sum_{i=1}^{j}\left[N_{t,i}e^{-M} - (\widehat{C}_{t,i} + \widehat{D}_{t,i} + \widehat{Tr}_{t,i})e^{(y_t-1)M}\right]X_{i,j} + R_{t+1,j} \quad (2018 \le t \le 2047), \tag{1}$$

where $N_{t+1,j}$ = the number of male golden king crab in size class j at the start (1 July, the start of fishing year) of year t+1;

$\widehat{C}_{t,i}$ = the number of individuals retained in catch of the directed pot fishery for size class i during year t;

$\widehat{D}_{t,i}$ = the number of individuals discarded or dead in the pot fishery catch for size class i during year t;

$\widehat{Tr}_{t,i}$ = the number of individuals discarded or dead in the groundfish fishery catch for size class i during year t;

$X_{i,j}$ = the probability of animals in size class i growing into size class j during the year;

y_t = the time from 1 July to the midpoint of the fishery period during year t;

M = the instantaneous rate of natural mortality (assumed to be 0.21/year for all size classes and over time; Siddeek et al., 2020); and

$R_{t+1,j}$ = the recruitment to size class j during year t+1.

The equations used to compute future retained and discarded catches are provided in Equations A1–A4 in Supplementary Materials.

Future recruitment is an essential part of the operating model. However, fitted stock–recruitment models often fail to show the link between spawning individuals and recruits for many species (Subbey et al., 2014), including for most commercially important crab stocks in the Bering Sea and Aleutian Islands. Biomass of mature females is a general choice for an index of egg production for finfish species (e.g., Martell et al., 2008; Punt et al., 2008; Subbey et al., 2014). However, MMB has been adopted as a proxy for reproductive output for stocks of golden king crab in the Aleutian Islands, largely as a result of uncertainties related to identifying the component of the mature population that participates in mating and to defining optimal sex ratios and because fisheries have a male-only retention requirement (NPFMC[1]). The MMB is computed by using this equation:

$$MMB_t = \sum_{j=m}^{n}\left\{N_{t,j}e^{-y'M} - (\widehat{C}_{t,j} + \widehat{D}_{t,j} + \widehat{Tr}_{t,j})e^{(y_t-y')M}\right\}w_j, \tag{2}$$

where y' = the time from 1 July to 15 February in the following year (NPFMC[1]);

w_j = the weight for size class j (Siddeek et al., 2020);

m = the lowest size class with mature animals (i.e., maturity is assumed to be a knife-edged function of size at the carapace length [CL] of 111 mm; Daly et al., 2019); and

n = number of size classes.

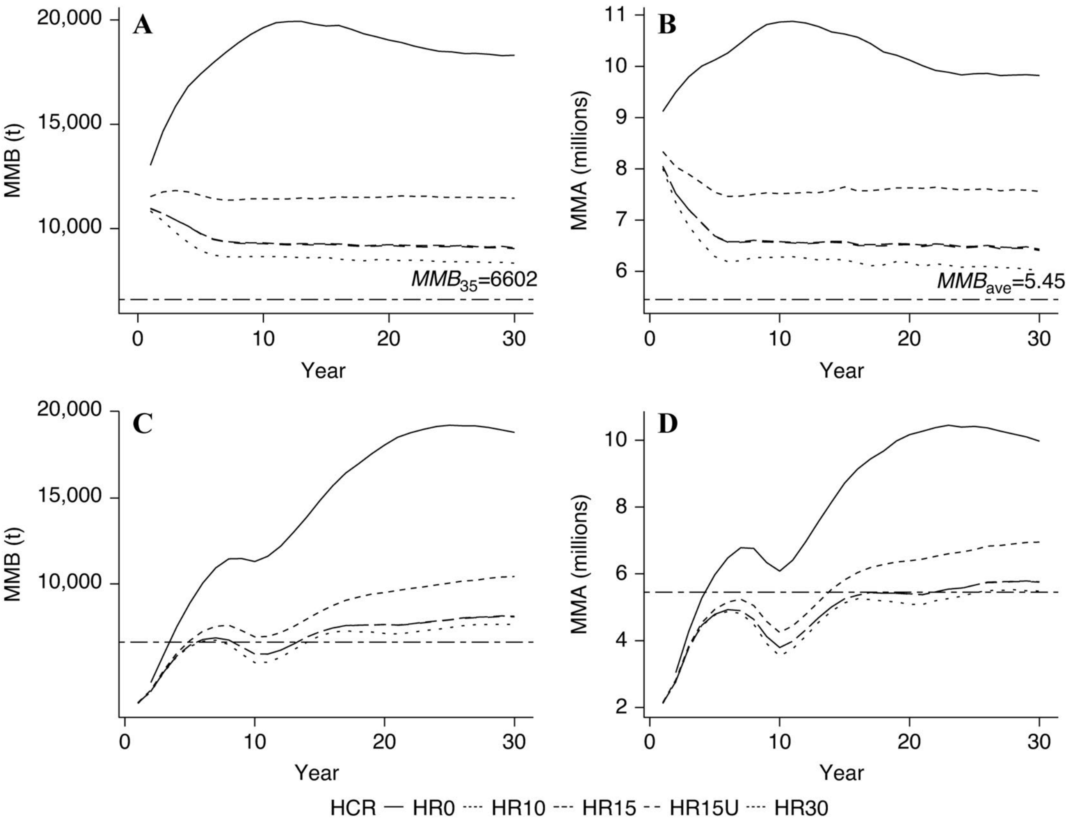

Figure 2

Median mature male biomass (MMB) and median mature male abundance (MMA) of golden king crab (*Lithodes aequispinus*) in the Aleutian Islands under 5 harvest control rules (HCRs), with the initial state of the stock set at (**A** and **B**) healthy or (**C** and **D**) overfished, for scenario 1 of the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Metric tons (t) is the unit for MMB, and number of crab is the unit for MMA. Values are based on a 30-year projection period that begins with 2018. The stock is projected from 2 initial levels of abundance: a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB) and an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). Horizontal dashed lines indicate the MMB_{35} and average MMA (MMA_{ave}) thresholds. The HCRs include HR0, the reference HCR with a zero exploitation rate; HR10, with a maximum 10% exploitation rate and a 0.25 catch proportion cap on legal-sized male abundance; HR15, with a maximum 15% exploitation rate and a 0.25 catch proportion cap on legal-sized male abundance; HR15U, with a maximum 15% exploitation rate and no cap on the proportion of legal-sized male abundance that can be caught; and HR30, with a maximum 30% exploitation rate and a 0.25 catch proportion cap on legal-sized male abundance. Data used in the model are for golden king crab in 1981–2018.

Mature male abundance is determined from Equation 2 without w_j.

Parameterization of the operating model

The population dynamics model has seventeen 5-mm size classes over the size range of 101–185 mm CL. The last size class (181–185 mm CL) is a plus group that includes all golden king crab larger than 185 mm CL. The values for the parameters of the model were estimated on the basis of fitting the model to available data (Siddeek et al., 2020; for some of the estimated parameters, see Supplementary Figure 3). Although Bayesian or Monte Carlo methods could have been used to estimate distributions for the parameters of the operating model, these methods were not pursued because they were found to be computationally infeasible. The parameters of the operating model differed depending on whether CPUE was assumed to be proportional to selected abundance or the square root of selected abundance because the operating model was fitted to the available monitoring data for golden king crab in the Aleutian Islands (for the results for linear relationship [hereafter referred to as the *linear choice*], see Tables 2 and 3 and Supplementary Tables 1 and 2; for the results for the nonlinear relationship [hereafter referred to as the *nonlinear choice*], see Supplementary Tables 3–6). Tables and figures for the linear choice are provided (selected tables and figures for the nonlinear choice are given in Supplementary Materials).

The value of h was determined through the use of a 2-step procedure. The first step was to calculate F_{35} by using an analysis of spawning biomass per recruit (for a plot of spawning potential ratio [SPR] versus fishing mortality [F], where the SPR for a given level of fishing mortality is the ratio of the spawning biomass per recruit at that level of fishing mortality to the spawning biomass per recruit in an unfished state, see Supplementary Figure 4A). The value of F is related to the total fishing mortality for the directed pot fishery when computing SPR, with fishing mortality attributable to bycatch in the groundfish fishery set to the estimated average during 1999–2018 (although this source of mortality is negligible). The second step was to calculate MMB for various h values by projecting the population model forward deterministically given $F=F_{35}$ and to find h such that $MMB=0.35\times MMB_0$ (where MMB_0 is the virgin mature male biomass; Suppl. Fig. 4B).

Table 2

The factors considered during the evaluation of the performance of harvest control rules for golden king crab (*Lithodes aequispinus*) in the eastern portion of the Aleutian Islands. The 3 values are lower limits; the model estimates for 2018, indicated with asterisks (*); and upper limits considered in the evaluation of the performance of harvest control rules. The values are based on the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Data used in the model are for golden king crab in 1981–2018. MMB=mature male biomass; MMA=mature male abundance.

Factors	Values
Steepness (h)	0.600, 0.729*, 1.200
Recruitment variation (σ_R)	0.100, 0.274*, 0.800
Autocorrelation in recruitment (ρ_R)	0.000, 0.455*, 0.900
Extent of annual catch implementation error (σ_C)	0.000, 0.039*, 0.100
Extent of MMB estimation error (σ_B)	0.000, 0.214*, 0.300
Autocorrelation in MMB estimation error (ρ_B)	0.000, 0.700, 0.900
Extent of MMA estimation error (σ_N)	0.000, 0.216*, 0.300
Autocorrelation in MMA estimation error (ρ_N)	0.000, 0.700, 0.900

The selected value of h ensures that fishing at F_{35} produces MMB_{35}, which is equivalent to $0.35\times MMB_0$ (a proxy for B_{MSY}), and a proxy MSY (see Supplementary Figure 5). Figure 3 shows the fitted (deterministic) Ricker stock–recruitment relationship when h was set by using this procedure (h=0.729, R_0=2.528 million crab, MMB_0=18,862 metric tons) along with the MMB_{t-8} (MMB estimated 8 years prior to year t) and recruit (R_t) pairs of data points from the stock assessment model. Figure 4 depicts the estimated number of recruits from the model, along with a 95% confidence interval, indicating that uncertainty in these estimates increased over time.

Harvest control rules

Federal harvest control rule The federal HCR is based on MMB and is needed to determine the OFL and the ABC for each year of the projection period. The OFL fishing mortality (F_{OFL}) is determined by using this equation (NPFMC[1]):

$$F_{\text{OFL,t}} = \begin{cases} F_{35} & \text{if } MMB_t > MMB_{35}, \\ F_{35}\left(\dfrac{\dfrac{MMB_t}{MMB_{35}} - \alpha}{1-\alpha}\right) & \text{if } 0.25MMB_{35} < MMB_t \ll MMB_{35}, \text{ and} \\ 0 & \text{if } MMB_t \ll 0.25MMB_{35}, \end{cases} \tag{3}$$

where $\alpha = 0.1$ (a preset value).

The OFL of total catch is calculated by applying $F_{\text{OFL,t}}$ to male stock abundance through the use of Equations A1–A3 in Supplementary Materials and by summing over the

Table 3

The reference points used in the evaluation of candidate harvest control rules for golden king crab (*Lithodes aequispinus*) from the eastern portion of the Aleutian Islands: a proxy for biomass corresponding to maximum sustainable yield (35% of the unfished level of mature male biomass [MMB_{35}]), the fishing mortality rate corresponding to 35% of the unfished spawning biomass per recruit (F_{35}), mean catch, average mature male abundance (MMA_{ave}), and mean catch per unit of effort (CPUE). The estimates are based on the operating model in which a linear relationship between CPUE and selected abundance is assumed. Data used in the model are for golden king crab in 1981–2018.

Reference point	Estimate	Basis of estimation
MMB_{35}	6601.61 t	Assessment model
F_{35}	0.656/year	Assessment model
Mean catch	1492.82 t	Period from the 2005–2006 fishing season through the 2018–2019 fishing season (post-rationalization period)
MMA_{ave}	5.45 million crab	Period from the 1985–1986 fishing season through the 2018–2019 fishing season (estimation period)
Mean CPUE	31.70 crab/pot lift	Period from the 2005–2006 fishing season through the 2018–2019 fishing season (post-rationalization period)

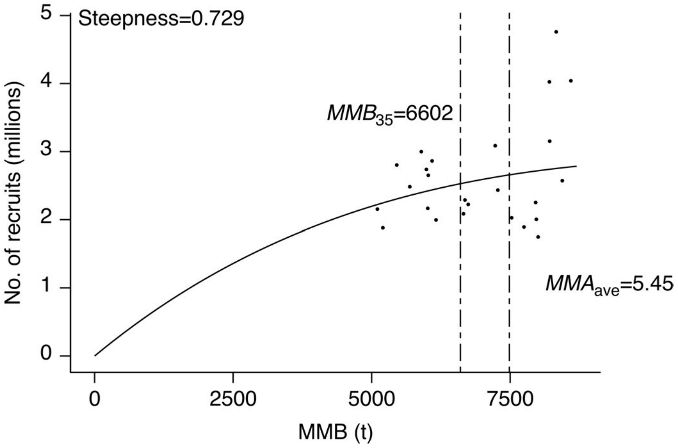

Figure 3

The stock–recruitment relationship from the Ricker model fitted to the stock and recruitment data for golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands during 1981–2018. The vertical dashed lines indicate the respective reference points: 35% of the unfished level of mature male biomass (MMB_{35}), which is a proxy for biomass corresponding to maximum sustainable yield, and average mature male abundance (MMA_{ave}). The steepness value is the estimate for 2018. In the operating model used in this analysis, catch per unit of effort is assumed to be proportional to selected abundance. t=metric tons.

predicted catches in weight by source of mortality, in other words, by using this equation:

$$OFL_t = \sum_{j=1}^{n} \left(\widehat{C}'_{t,j} w_j + \widehat{D}'_{t,j} w_j + \widehat{Tr}'_{t,j} w_j \right), \tag{4}$$

where the prime symbols indicate that the catch and bycatch are calculated by using $F{=}F_{OFL,t}$. The ABC (which applies to all sources of fishery-related mortality) is calculated (NPFMC, 2018) with this equation:

$$ABC_t = 0.75 \times OFL_t. \tag{5}$$

State harvest control rule options We compared 5 candidate state HCRs, with the aim to maintain consistency with state of Alaska commercial fishery regulations, the Alaska Board of Fisheries policy on king and Tanner crab resource management (ABF[2]), the North Pacific Fishery Management Council fishery management plan (NPFMC[1]), and National Standards 1 and 2 of the Magnuson-Stevens Fishery Conservation and Management Act (NPFMC[1]). The candidate HCRs were informed by catch policies for other stocks of king crab species in the Bering Sea and Aleutian Islands, historical exploitation rate estimates for the fishery for golden king crab in the Aleutian Islands, and stakeholder input.

The currently adopted state HCR is HR15, with a maximum exploitation rate of 15% and a 0.25 catch proportion cap on abundance (number) of legal-sized males. An alternative HCR is HR10, with a maximum exploitation rate of 10% and a 0.25 catch proportion cap on legal-sized male abundance; HR15U is an alternative HCR with a maximum exploitation rate of 15% without any cap on the proportion of legal-sized male abundance that can be caught, HR30 is an alternative HCR with a maximum exploitation rate of 30% and a 0.25 catch proportion cap on legal-sized male abundance, and HR0 is a reference HCR with no directed fishery (i.e., zero exploitation rate) (Table 1, Fig. 1, Suppl. Fig. 1). The state HCR is based on MMA and computes the catch proportion for year t, HR_t, as follows:

$$HR_t = \begin{cases} x & \text{if } MMA_t > MMA_{ave}, \\ x\left(\dfrac{MMA_t}{MMA_{ave}}\right) & \text{if } 0.25MMA_{ave} < MMA_t \ll MMA_{ave}, \text{ and} \\ 0 & \text{if } MMA_t \ll 0.25MMA_{ave}, \end{cases} \tag{6}$$

where x = the maximum exploitation rate; and MMA_{ave} = the average MMA during 1985–2018.

The exploitation rate from Equation 6 is converted into an instantaneous fishing mortality rate (F_t in year t) by solving this equation:

$$HR_t = \frac{F_t \times S^T}{Z_t}\left(1.0 - e^{-Z_t}\right), \tag{7}$$

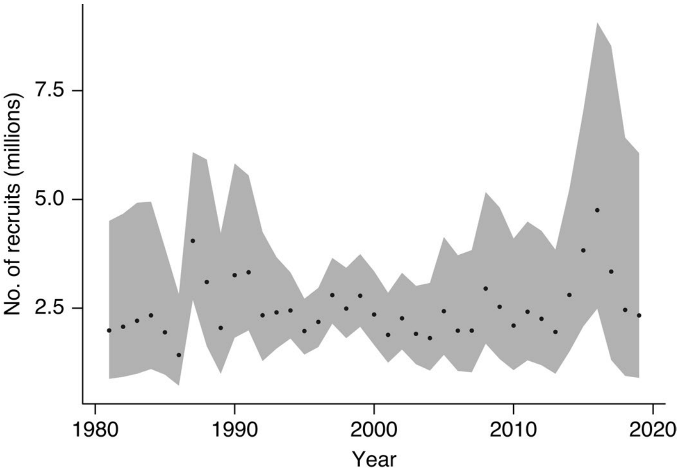

Figure 4

The number of recruits of golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands for 1981–2019 estimated with the stock assessment model. The gray shaded area indicates the 95% confidence interval. In the operating model used in this analysis, catch per unit of effort is assumed to be proportional to selected abundance.

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[2] ABF (Alaska Board of Fisheries). 1990. Policy on king and Tanner crab resource management. Policy no. 90-04-FB. [Available from website.]

where S^{T} = the total selectivity (a curve for selection of all susceptible sizes of retained and discarded crab to pot gear, fixed at the assessment model estimates); and

Z^{T} = the instantaneous total mortality during year *t* (including components for the directed pot fishery and bycatch in the groundfish fishery).

A cap on the proportion of legal-sized male abundance that can be caught is included in the state HCRs for several Alaska crab stocks, such as the stock of red king crab (*Paralithodes camtschaticus*) in Bristol Bay (Zheng et al., 1995). The $\mathrm{HR_t}$ may therefore be further modified for conservation purposes by constraining the predicted catch (in numbers) by the directed pot fishery to not exceed 25% of the legal-sized male abundance (crab size ≥136 mm CL; Siddeek et al., 2020), in other words,

$$\sum\nolimits_{\mathrm{j=L}}^{\mathrm{n}} \widehat{C}_{\mathrm{t,j}} \le 0.25 \sum\nolimits_{\mathrm{j=L}}^{\mathrm{n}} N_{\mathrm{t,j}},$$

where L = the legal minimum size of golden king crab in the Aleutian Islands.

The predicted catch (in weight) by the directed pot fishery cannot exceed the retained component of the ABC (currently adopted precautionary state management policy is to avoid exceeding the federal fishery management limit, the OFL), in other words,

$$\sum\nolimits_{\mathrm{j=1}}^{\mathrm{n}} \widehat{C}_{\mathrm{t,j}} w_{\mathrm{j}} \le 0.75 \times \sum\nolimits_{\mathrm{j=1}}^{\mathrm{n}} \widehat{C}'_{\mathrm{t,j}} w_{\mathrm{j}}.$$

Representing uncertainties

Uncertainty about future recruitment Many types of stock–recruitment relationships can be fitted to the results from an assessment, but the Ricker model (Ricker, 1954) was chosen for this study given its previous use for king crab species (*Lithodidae* spp.) (e.g., Zheng et al., 1995; Bechtol and Kruse, 2009). Future recruitment is generated with variation and temporal autocorrelation, with this equation:

$$R_{\mathrm{t+1,j}} = R_0 \frac{MMB_{\mathrm{t-k}}}{MMB_0} e^{-1.25\ln\left(5\mathrm{h}\right)\left[\frac{\mathrm{MMB_{t-k}}}{\mathrm{MMB_0}}-1\right]} e^{\varepsilon_{\mathrm{t}}-\frac{\sigma_{\mathrm{R}}^2}{2}} \Omega_{\mathrm{j}}, \tag{8}$$

$$\varepsilon_{\mathrm{t}} = \rho_{\mathrm{R}}\varepsilon_{\mathrm{t-1}} + \sqrt{1-\rho_{\mathrm{R}}^2}\, e_{\mathrm{t}}, \text{ and}$$

$$e_{\mathrm{t}} \sim N\left(0, \sigma_{\mathrm{R}}^2\right),$$

where R_0 = the number of recruits at unfished equilibrium;

$MMB_{\mathrm{t-k}}$ = the MMB (in metric tons) in year *t–k* given a *k*-year lag between spawning and recruits entering the model (*k*=8; Daly et al., 2019);

MMB_0 = the unfished MMB;

h = the steepness parameter;

ρ_{R} = the extent of autocorrelation in the recruitment deviations;

σ_{R} = the standard deviation of recruitment; and

Ω_{j} = a normalized gamma function that determines the distribution of recruits to each size class:

$$\Omega_{\mathrm{j}} = \frac{\int_{\mathrm{l_j-2.5}}^{\mathrm{l_j+2.5}} gamma(\mathrm{x}|\,\alpha_{\mathrm{r}}, \beta_{\mathrm{r}})\,d\mathrm{x}}{\sum\nolimits_{\mathrm{j=1}}^{\mathrm{n}} \int_{\mathrm{l_j-2.5}}^{\mathrm{l_j+2.5}} gamma(\mathrm{x}|\,\alpha_{\mathrm{r}}, \beta_{\mathrm{r}})\,d\mathrm{x}} \text{ and} \tag{9}$$

$$gamma\left(\mathrm{x}\,|\,\alpha_{\mathrm{r}}, \beta_{\mathrm{r}}\right) = \frac{\mathrm{x}^{\alpha_{\mathrm{r}}-1} e^{\frac{\mathrm{x}}{\beta_{\mathrm{r}}}}}{\beta_{\mathrm{r}}{}^{\alpha_{\mathrm{r}}} \Gamma_{(\alpha_{\mathrm{r}})}},$$

where α_{r} = a parameter of the gamma distribution;

β_{r} = a parameter of the gamma distribution;

l_{j} = the midpoint of size class *j*; and

n = the number of recruiting size classes, fixed to 5.

Uncertainty about the state of the stock in 2018 For simplicity, most parameter values were fixed at their best estimates. However, uncertainty was introduced to the size composition for the first projection year (2018), according to the following equation:

$$N_{\mathrm{2018,j}} = \widehat{N}_{\mathrm{2018,j}} e^{\vartheta_{\mathrm{i,j}}-\frac{\sigma_{\mathrm{2018,j}}^2}{2}}, \tag{10}$$

$$\vartheta_{\mathrm{i,j}} \sim MN\left(\underline{0}, V\right),$$

where $\widehat{N}_{\mathrm{2018,j}}$ = the estimate of the number of males in size class *j* at the start of 2018;

$\sigma_{\mathrm{2018,j}}$ = the standard error of the logarithm of the estimate of $\widehat{N}_{\mathrm{2018,j}}$; and

V = the variance–covariance matrix for the numbers by size class at the start of 2018.

Estimates of $\widehat{N}_{\mathrm{2018,j}}$ and V were obtained from the assessment model. Stock status in each projection was determined by using the best estimates from the assessment model rather than by sampling parameter vectors from a posterior or a bootstrap distribution, as would commonly be done in a full MSE.

Uncertainty when applying the federal and state harvest control rules Uncertainty in the estimates of MMB and MMA are accounted for by replacing MMB and MMA in Equations 3 and 6 as follows:

$$MMB_{\mathrm{t}}^{\mathrm{estimated}} = MMB_{\mathrm{t}} e^{\delta_{\mathrm{t}}-\frac{\sigma_{\mathrm{B}}^2}{2}}, \tag{11}$$

$$\delta_{\mathrm{t}} = \rho_{\mathrm{B}}\delta_{\mathrm{t-1}} + \sqrt{1-\rho_{\mathrm{B}}^2}\,\varphi_{\mathrm{t}}, \text{ and}$$

$$\varphi_{\mathrm{t}} \sim N\left(0, \sigma_{\mathrm{B}}^2\right); \text{ and}$$

$$MMA_{\mathrm{t}}^{\mathrm{estimated}} = MMA_{\mathrm{t}} e^{\omega_{\mathrm{t}}-\frac{\sigma_{\mathrm{N}}^2}{2}}, \tag{12}$$

$$\omega_{\mathrm{t}} = \rho_{\mathrm{N}}\omega_{\mathrm{t-1}} + \sqrt{1-\rho_{\mathrm{N}}^2}\,\varnothing_{\mathrm{t}}, \text{ and}$$

$$\varnothing_{\mathrm{t}} \sim N\left(0, \sigma_{\mathrm{N}}^2\right),$$

where $MMB_{\mathrm{t}}^{\mathrm{estimated}}$ = the estimate of MMB for year *t*;

$MMA_t^{\text{estimated}}$ = the estimate of MMA for year t;

MMB_t and MMA_t = the true MMB and MMA during year t in the operating model;

ρ_B and ρ_N = the extents of autocorrelation in stock status estimation error; and

σ_B and σ_N = the extents of estimation error.

The values for σ_B and σ_N are set to the standard deviations of the logarithms of the estimates of MMB and MMA for 2018 rather than those of MMB/MMB_{35} and MMA/MMA_{ave} because the estimates of average MMB and MMA are precise. The autocorrelation in estimation error cannot be obtained from the assessment model; therefore, a range of plausible values are considered in the analyses.

Implementation error

The fishery does not catch the TAC exactly; therefore, implementation error is introduced as follows:

$$C_{t,j}^{\text{actual}} = \hat{C}_{t,j} + \tau_{t,j} \text{ and} \qquad (13)$$

$$\tau_{t,j} \sim N\left(0, \sigma_{C,t,j}^2\right),$$

where $C_{t,j}^{\text{actual}}$ = the true catch for animals in size class j during year t;

$\hat{C}_{t,j}$ = the expected catch of animals in size class j during year t based on the simulated fishing mortality from the HCR; and

$\sigma_{C,t,j}$ = the standard deviation of the differences between TACs and actual catches for size class j based on the standard deviation of the differences between the TAC and total landed catches, σ_C, in other words,

$$\sigma_{C,t,j} = \frac{\sigma_{Cj}}{\sum_{j=1}^{n} \hat{C}_{t,j}}, \qquad (14)$$

where $\sum_{j=1}^{n} \hat{C}_{t,j}$ = the sum of the expected retained catches of all size classes during year t.

Simulation design

The design of the simplified MSE involved combining levels for each of the uncertainties. In total, 53 scenarios based on the selected uncertainties were considered for each relationship between CPUE and selected abundance (Table 2; Suppl. Tables 1–5).

Scenario 1 was based on the best estimates of the parameters, and the specifications of this scenario are indicated by asterisks in Table 2 and Supplementary Table 5. Scenario 1 was also based on the middle level of autocorrelation in error when MMB and MMA were estimated (for the full list of scenarios and specifications, see Supplementary Tables 1 and 2 [linear choice] and Supplementary Tables 3 and 4 [nonlinear choice]). Scenarios 2–17 involved changing the value of one of the parameters of scenario 1, and scenarios 18–53 changed the value of more than one parameter. The scenarios did not explore all possible combinations of parameters owing to computational and presentational limitations.

Two options (applied separately for each of the linear and nonlinear choices) were considered for the size structure at the start of the projection period (1 July 2018): 1) estimate in the assessment model (i.e., MMB/MMB_{35}=1.55; Siddeek et al., 2020) and 2) the MSST ($0.5MMB_{35}$). The second option was implemented by increasing the fishing mortality rate on the size structure for 2018 such that MMB approached $0.5MMB_{35}$. Performances of candidate HCRs were evaluated by projecting the stock from the initial abundance levels from these 2 options, in other words, a healthy state ($MMB>MMB_{35}$) and an overfished state ($MMB=0.5MMB_{35}$).

Performance metrics

We considered conservation and economic criteria when evaluating the candidate HCRs. The conservation criteria were 1) the probability (across simulations and the entire 30-year period) of the stock being below MSST (i.e., a threshold for being overfished), 2) the probability of total catch being greater than OFL (i.e., a threshold for overfishing occurring), 3) the probability of total catch being greater than ABC, and 4) the probability that MMB is less than MMB_{35}. The economic criteria were 1) the probability of fishery closure, 2) the average annual catch (across simulations) for the directed fishery, 3) the annual variability of catch in the directed fishery, 4) the probability of retained catch being less than mean retained catch during 2005–2018 (post-rationalization period), 5) the average CPUE, 6) the probability of CPUE being less than mean CPUE for the period 2005–2018, 7) fishing effort (number of pot lifts, as approximated by using $Catch/[CPUE \times 0.00195]$, where mean crab weight is assumed to be 0.00195 metric tons on the basis of unpublished data [Ben[3]] on the retained catch in 2018), and 8) the probability of MMA being less than MMA_{ave} (an average value for the period 1985–2018), an indication of whether the exploitation rate for a given management strategy reaches the maximum allowable exploitation rate in expectation. The reference points for comparison with simulation results are listed in Table 3 (linear choice) and Supplementary Table 6 (nonlinear choice).

In addition, the time series of MMB, MMA, catch, effort, and catch variation were summarized as follows:

- Time trends in median (over simulations) MMB, MMA, catch, and effort over the projection period;
- Rebuilding time from the overfished level ($0.5MMB_{35}$) to MMB_{35} and the rebuilding time from the corresponding MMA to MMA_{ave}; and
- Median (over simulations) annual catch variability (AAR) computed with this equation:

$$AAR = \frac{\sum_t |C_t - C_{t-1}|}{\sum_t C_t}. \qquad (15)$$

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[3] Ben, D. 2018. Unpubl. data. Div. Commer. Fish., Alaska Dep. Fish Game, 351 Research Ct., Kodiak, AK 99615.

The 5 HCRs were ranked within each conservation and economic performance criteria leading to a risk matrix that involved grouping these performance metrics into 3 categories: conservation, catch, and catch stability. Overall ranks within each category were based on average ranks across all criteria.

Results

Performance of harvest control rules (scenario 1)

The time trajectories of MMB and MMA for scenario 1 (i.e., the best estimates of the parameters when CPUE was assumed to be linearly proportional to selected abundance; Suppl. Table 1) stabilized toward the end of the 30-year projection period in median terms for the 5 HCRs. As expected, HR10, HR15, HR15U, and HR30 led to much lower MMB and MMA than HR0. The alternative policy of HR30 resulted in slightly lower MMB (Fig. 2, A and C) and MMA (Fig. 2, B and D) than HR10, HR15, and HR15U, with the latter 2 HCRs having very similar trajectories of MMB and MMA. The MMB and MMA trajectories remained above MMB_{35} and MMA_{ave}, respectively, throughout the projection period when the simulation started above MMB_{35} and reached the respective reference points toward the end of the projection period when the simulation started in an overfished state (Fig. 2). The estimates of MMB and MMA are qualitatively similar, a result that was expected given MMB is MMA multiplied by average weight, which did not change much over time. The results are similar for scenario 1 when CPUE was assumed to be proportional to the square root of abundance (Suppl. Tables 7–9).

Catch and effort stabilized (in median terms) toward the end of the 30-year projection period for HR10, HR15, HR15U, and HR30. However, the time trajectories of catch and effort differed depending on the initial state. The median catch declined over time when MMB_{2018} was greater than MMB_{35} (Fig. 5A) but increased over time for when MMB_{2018} was equal to $0.5MMB_{35}$ (Fig. 5C). Effort was almost constant over the projection period when

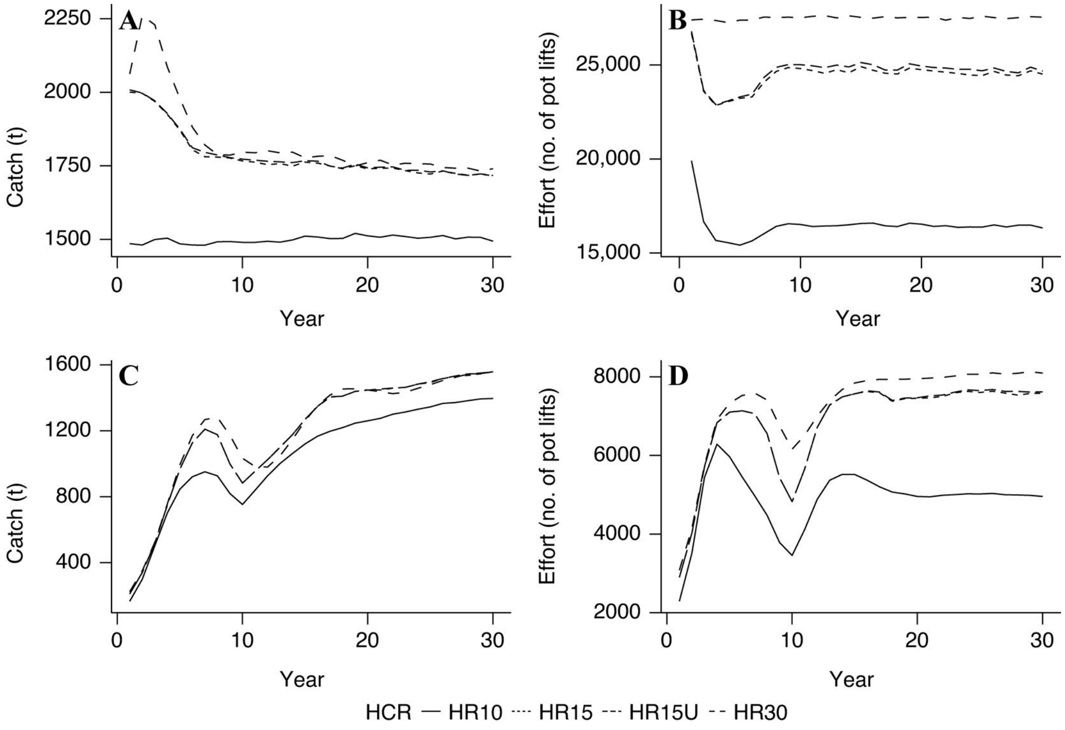

Figure 5

Median catch and median effort of the directed pot fishery for golden king crab (*Lithodes aequispinus*) in the eastern Aleutian Islands under 4 harvest control rules (HR10, HR15, HR15U, and HR30), with the initial state of the stock set at (**A** and **B**) healthy or (**C** and **D**) overfished, for scenario 1 of the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Values are based on a 30-year projection period that begins with 2018. The stock is projected from 2 initial levels of abundance, measured in mature male biomass (MMB): a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB) and an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). Data used in the model are for golden king crab in 1981–2018. For details about the harvest control rules, see Table 1. t=metric tons.

MMB_{2018} was greater than MMB_{35} (Fig. 5B) but increased over time when MMB_{2018} was equal to $0.5MMB_{35}$ (Fig. 5D). The alternative of HR30 led to slightly higher catches but substantially higher effort when MMB_{2018} was greater than MMB_{35}. The alternative of HR10 led to lower catches than HR15, HR15U, and HR30. The alternative of HR15U led to negligibly higher catches than HR15 (Fig. 5A). Results were similar for scenario 1 when CPUE was assumed to be proportional to the square root of abundance (Suppl. Table 8).

The probabilities of the stock of golden king crab in the Aleutian Islands being overfished ($MMB<MSST$) and severely overfished ($MMB<0.5MSST$) and of overfishing occurring (i.e., catch exceeding OFL) were zero, and the probability of this stock being below MMB_{35} was <0.02 for all policies when MMB_{2018} was greater than MMB_{35} when CPUE was assumed to be linearly proportional to abundance (Table 4). The probability of this stock of golden crab being below MMB_{35} was higher for HR15, HR15U, and HR30 when CPUE was proportional to the square root of selected abundance, but the trends were similar to those with the linear relationship of CPUE to abundance (Suppl. Table 7). The fact that the probability of overfishing occurring was zero across policies was expected, given the constraint that the predicted catch (in weight) in the directed fishery could not exceed the retained catch component of the ABC. Interestingly, the probabilities of the stock of golden king crab in the Aleutian Islands being severely overfished and of overfishing occurring were also zero when the stock was initially overfished. Probabilities of this stock being below MMB_{35} were greater for all policies when it was initially in an overfished state, yet probabilities of this stock staying overfished during the projection period were <0.031 for all policies, indicating a resiliency of this population in the simulations.

Results from consideration of economic criteria for HR0 were largely moot; therefore, only HR10, HR15, HR15U, and HR30 were ranked for these metrics. The alternative of HR10 resulted in lower catch in comparison with that of the rest of the HCRs but led to improved performance for other economic metrics, such as reduced effort (i.e., fewer pot lifts needed to achieve a low TAC; see Tables 4 and 5 for the linear choice and Supplementary Tables 7 and 8 for the nonlinear choice). Most economic criteria were similar between HR15 and HR15U for both initial conditions, indicating that the catch limit on legal-sized male abundance had little overall effect (see Table 5 for the linear choice and Supplementary Table 8 for the nonlinear choice). The alternative

Table 4

Conservation performance metrics for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands, with the initial state of the stock set at healthy or overfished, for scenario 1 (based on best parameter estimates) of the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Values for the 5 harvest control rules (HCRs) evaluated by conservation criteria, HR0, HR10, HR15, HR15U, and HR30, are probabilities that the estimated quantity, such as mature male biomass (MMB) or total catch, is above or below the associated reference point, such as minimum stock size threshold (MSST), overfishing level (OFL), allowable biological catch (ABC), or 35% of the unfished level of MMB (MMB_{35}), calculated for the last 10 years of the 30-year projection period, which begins with 2018. For example, values for $MMB<MSST$ are the probabilities that MMB is below MSST. Harvest control rules were ranked among each other for each performance metric (ranks are given in parentheses; ranks are the same for HCRs if probabilities are the same for those HCRs). Total catch is the catch retained in the directed pot fishery plus the discard mortality in the directed fishery and the bycatch mortality in the groundfish fishery. The stock is projected from 2 initial levels of abundance, measured in MMB: a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018) and an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). For details about the HCRs, see Table 1. B_{MSY}=the biomass corresponding to maximum sustainable yield.

Metric	Description	HR0	HR10	HR15	HR15U	HR30
Healthy						
Overfished	$MMB<MSST$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Severely overfished	$MMB<0.5MSST$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Overfishing (OFL)	Total catch>OFL	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Overfishing (ABC)	Total catch>ABC	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Below B_{MSY}	$MMB<MMB_{35}$	0.000 (1)	0.000 (1)	0.001 (3)	0.001 (3)	0.016 (5)
Overfished						
Overfished	$MMB<MSST$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Severely overfished	$MMB<0.5MSST$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Overfishing (OFL)	Total catch>OFL	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Overfishing (ABC)	Total catch>ABC	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Below B_{MSY}	$MMB<MMB_{35}$	0.000 (1)	0.000 (1)	0.063 (3)	0.063 (4)	0.141 (5)

Table 5

Economic performance metrics for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands, with the initial state of the stock set at healthy or overfished, for scenario 1 (based on best parameter estimates) of the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Values for the 4 harvest control rules (HCRs) evaluated by economic criteria, HR10, HR15, HR15U, and HR30, are probabilities that the estimated quantity is above or below the associated reference point (e.g., $MMA<0.25MMA_{\mathrm{ave}}$ indicates the probability that mature male abundance [MMA] is below 25% of average MMA [MMA_{ave}]), calculated for the last 10 years of the 30-year projection period, which begins with 2018. The exceptions are for values of catch (mean in metric tons), CPUE_1 (given as the number of crab per pot lift), and effort (given as the number of pot lifts). Harvest control rules were ranked among each other for each performance metric (ranks are given in parentheses; ranks are the same for HCRs if probabilities are the same for those HCRs). Catch is the catch retained in the directed pot fishery. The stock is projected from 2 initial levels of abundance, measured in mature male biomass (MMB): a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB) and an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). For details about the HCRs, see Table 1. $\mathrm{Catch}_{\mathrm{AveHist}}$=historical average catch; $\mathrm{CPUE}_{\mathrm{AveHist}}$=historical average CPUE; and MMA_{AveHist}=historical average MMA.

Metric	Description or unit	HR10	HR15	HR15U	HR30
Healthy					
Fishery closure	$MMA<0.25MMA_{\mathrm{ave}}$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Catch	Mean	1508 (4)	1732 (3)	1735 (2)	1770 (1)
Catch variability	Annual proportional change in catch	0.049 (1)	0.052 (3)	0.055 (4)	0.052 (2)
Relative catch	$\mathrm{Catch}<\mathrm{Catch}_{\mathrm{AveHist}}$	0.468 (4)	0.140 (2)	0.141 (3)	0.101 (1)
CPUE_1	Mean number	47.4 (1)	36.7 (2)	36.4 (3)	33.0 (4)
CPUE_2	$\mathrm{CPUE}<\mathrm{CPUE}_{\mathrm{AveHist}}$	0.000 (1)	0.153 (2)	0.174 (3)	0.408 (4)
Effort	Number of pot lifts	16,315 (1)	24,202 (2)	24,444 (3)	27,506 (4)
Stock status	$MMA<MMA_{\mathrm{AveHist}}$	0.002 (1)	0.075 (2)	0.078 (3)	0.196 (4)
Overfished					
Fishery closure	$MMA<0.25MMA_{\mathrm{ave}}$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Catch	Mean	1354 (4)	1510 (2)	1512 (1)	1508 (3)
Catch variability	Annual proportional change in catch	0.048 (1)	0.050 (3)	0.052 (4)	0.049 (2)
Relative catch	$\mathrm{Catch}<\mathrm{Catch}_{\mathrm{AveHist}}$	0.807 (4)	0.477 (2)	0.475 (1)	0.503 (3)
CPUE_1	Mean number	139.6 (1)	103.8 (2)	103.5 (3)	96.7 (4)
CPUE_2	$\mathrm{CPUE}<\mathrm{CPUE}_{\mathrm{AveHist}}$	0.000 (1)	0.000 (1)	0.000 (1)	0.000 (1)
Effort	Number of pot lifts	4974 (1)	7460 (2)	7492 (3)	7997 (4)
Stock status	$MMA<MMA_{\mathrm{AveHist}}$	0.037 (1)	0.396 (2)	0.398 (3)	0.535 (4)

of HR30 was the most aggressive policy, but with only marginally higher catches than HR15 and HR15U, and HR15U had the most variable catches (see Table 5 for the linear choice and Supplementary Table 8 for the nonlinear choice).

Performance of harvest control rules (all scenarios)

Catch variability was high for the highest value of σ_R (scenarios 3, 20–21, and 27–29) and very high when σ_R and ρ_R were at their maxima (scenarios 35–37 and 52–53 in Figure 6). In contrast, catch variability was insensitive to the other factors considered and to the choice of management strategy (Fig. 6). The probabilities of catch being less than mean catch and CPUE being less than mean CPUE were very high when σ_R and ρ_R were at their maxima (scenarios 35–37 and 52–53) (see Figure 7 for the linear choice and Supplementary Figure 6 for the nonlinear choice). The probability of not achieving mean CPUE was higher for HR30 (Fig. 7H, Suppl. Fig. 6H) than for HR10, HR15, and HR15U for all scenarios, with probability levels lower for the nonlinear choice than for the linear choice.

Figure 8 and Supplementary Figure 7 show the probabilities of MMA being less than MMA_{ave} and of MMB being less than MMB_{35} for the linear and nonlinear choices, respectively, when MMB_{2018} was greater than MMB_{35} for the 5 HCRs. Spawning biomass and abundance declined even under HR0 (i.e., F=0) for scenarios 35–37 and 52–53 because of high recruitment variability for the base level of the steepness parameter (Fig. 8, A and F; Suppl. Fig. 7, A and F). The probabilities of MMB being less than MSST and of MMA being less than $0.25MMA_{\mathrm{ave}}$ were closer to zero for all scenarios and HCRs across simulations and for the entire projection period (results not shown).

The median rebuilding time for all HCRs under the linear choice increased for scenarios 35–37 and 52–53 because of high recruitment variability (Fig. 9). As expected, HR0 had the shortest rebuilding time. The

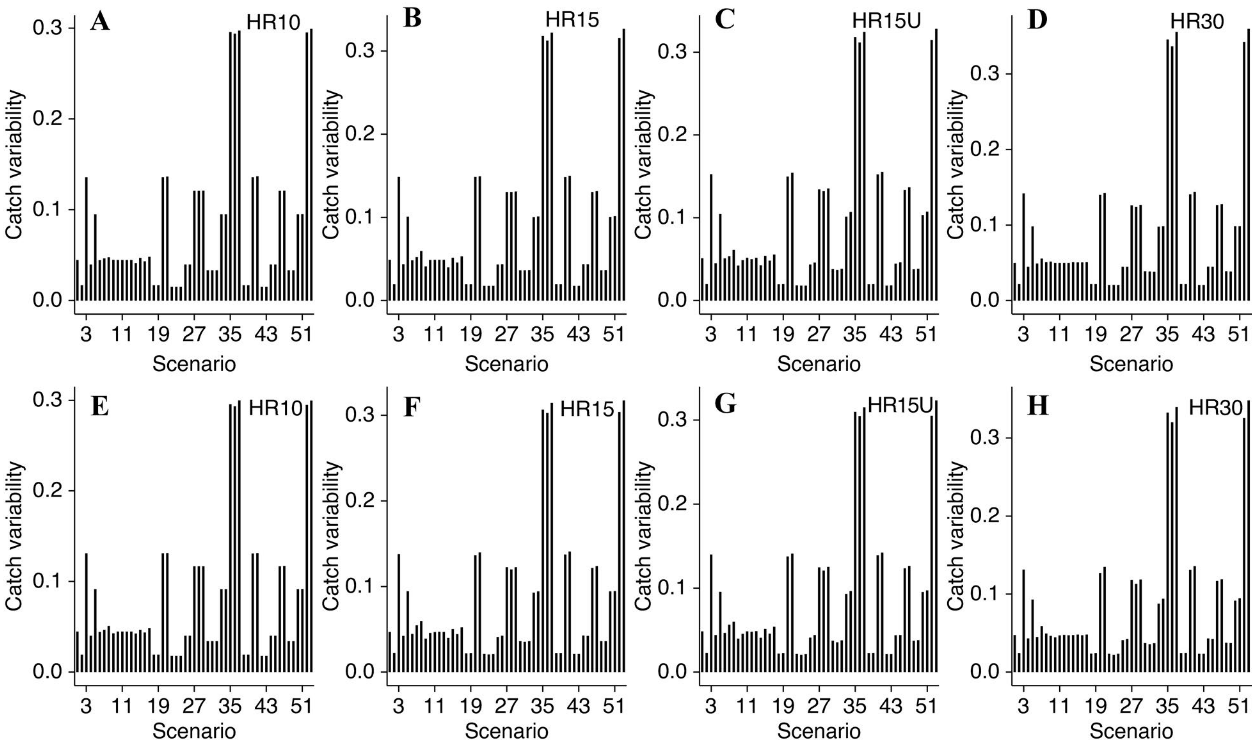

Figure 6

Median catch variability in the directed pot fishery for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands during the last 10 years of a 30-year projection period, which begins in 2018, for 53 scenarios of an operating model used to evaluate harvest control rules (HCRs). The stock is projected from 2 initial levels of abundance, measured in mature male biomass (MMB). Values are given in numbers without a unit for HCRs (**A**) HR10, (**B**) HR15, (**C**) HR15U, and (**D**) HR30, with the stock set initially at a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB), and for HCRs (**E**) HR10, (**F**) HR15, (**G**) HR15U, and (**H**) HR30, with the stock set initially at an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). In the model used in this analysis, a linear relationship between catch per unit of effort and selected abundance is assumed. Data used in the model are for golden king crab in 1981–2018. For details about the HCRs, see Table 1.

rebuilding time is short when values for steepness are higher (e.g., scenario 9) and is longer for HR30 than for HR10, HR15, and HR15U for most scenarios. The rebuilding times necessary to achieve MMA_{ave} are longer than those necessary to achieve MMB_{35} for all non-zero exploitation rates. The results for the nonlinear choice are similar (results not shown).

The MMA and CPUE distributions for scenario 1 (with parameters estimated through the use of the assessment model) indicate that HR10, HR15, and HR15U performed better than HR30. Fewer instances of MMA being lower than MMA_{ave} and more frequent values of higher CPUE were observed for HR10, HR15, and HR15U than for HR30 (Fig. 10). Catch distributions were similar for HR15 and HR30 and for the equilibrium state; size compositions of crab in total catch as well as in retained catch did not differ significantly from those for HR15 and those for HR30 (Suppl. Fig. 8). This result occurred because the stock was projected from a healthy state (MMB>MMB_{35}) and because the effective F under both HR15 and HR30 was dampened because of reduction in abundance over the years.

The results for the conservation and economic performance criteria of HR15 and HR15U for the last 10 years of the 30-year projection period were very similar for the linear and the nonlinear relationships of CPUE to abundance (Tables 4–6, Suppl. Tables 7–9). When compared with HR10 and HR30, HR15 may optimize the balance between conservation and economic criteria (Tables 4–6). Conservation metrics were similar among all HCRs except for HR30 (nonlinear choice; Suppl. Table 7). Probabilities of fishery closures were zero, and catch variability was similar for all HCRs, yet relative stock status was lower under HR30. Relative to HR15, HR10 required substantially lower effort (~48% lower) to achieve the TAC, yet the TAC itself was lower (~15% lower); in contrast, HR30 required higher effort (~14% higher) to achieve only a marginally higher (~2% higher) TAC (Table 5).

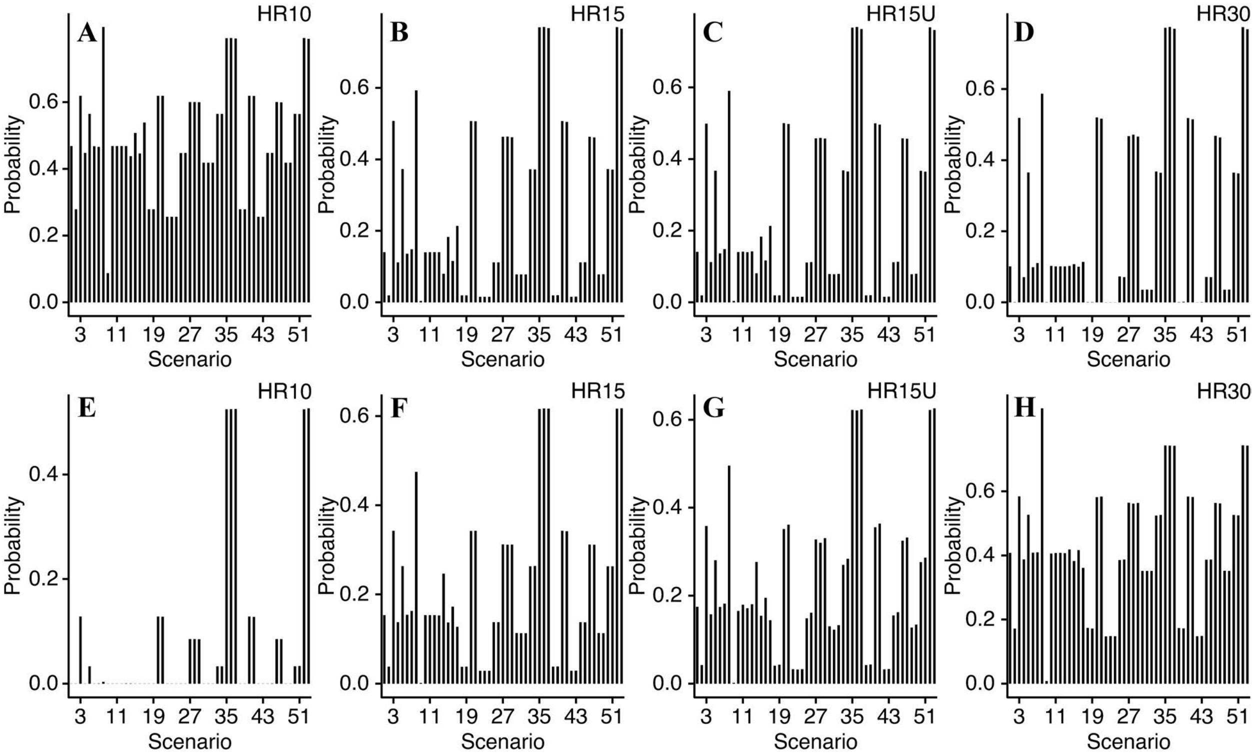

Figure 7

The probability of (**A**–**D**) catch and (**E**–**H**) catch per unit of effort (CPUE) being below their mean values for the period after crab stocks were rationalized, from the 2005–2006 fishing season through the 2018–2019 fishing season, in the directed pot fishery for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands, by model scenario, under harvest control rules (HCRs) HR10, HR15, HR15U, and HR30. Estimates are based on the last 10 years of a 30-year projection period for 53 scenarios of an operating model used to evaluate HCRs. The stock is projected from an initial level of abundance, measured in mature male biomass (MMB): $1.55MMB_{35}$, where MMB_{35} is 35% of the unfished level of MMB. In the model used in this analysis, a linear relationship between CPUE and selected abundance is assumed. For details about the HCRs, see Table 1.

Discussion

We have demonstrated the utility of the simplified MSE for evaluating HCRs through consideration of conservation and economic trade-offs. Our results indicate that HR15 and HR15U are preferable to HR10 and HR30, given the desire to balance the trade-off between sustainability and economic viability, and this notion was supported under both the linear and nonlinear assumptions about the relationship between CPUE and selected abundance. Although HR30 yielded the highest catch, it performed poorest in terms of other economic and conservation criteria. Specifically, HR30 had the highest relative probabilities of MMB being below MMB_{35} and of MMA being below the historical average MMA, had the lowest CPUE, and required substantially more effort to realize marginally higher (~2% higher) catches compared with HR10, HR15, and HR15U. Relative to HR10, HR30 required 69% more effort to achieve 17% more catch (Table 5). Therefore, criteria beyond projected average TAC are important from an economic viewpoint because costs required to make excessive numbers of fishing trips when fishing effort is high may outweigh modest increases in TAC.

Although we suggest that HR15 is the optimal HCR, given the trade-offs between conservation, catch, and catch stability, we acknowledge that the preferred HCR may differ depending on management and stakeholder priorities. Although HR10 yielded improved performance in terms of some conservation and economic criteria (e.g., higher CPUE, MMA, MMB, and reduced effort), it yielded lower catch compared with that from HR15, HR15U, and HR30. Our analysis is meant to provide managers and stakeholders with a tool to evaluate the trade-offs between various fishery management criteria relative to risk.

The conservation and economic criteria were very similar for HR15 and HR15U. Although the catch limit on legal-sized male abundance did not meaningfully affect the performance of the management strategy, it is likely

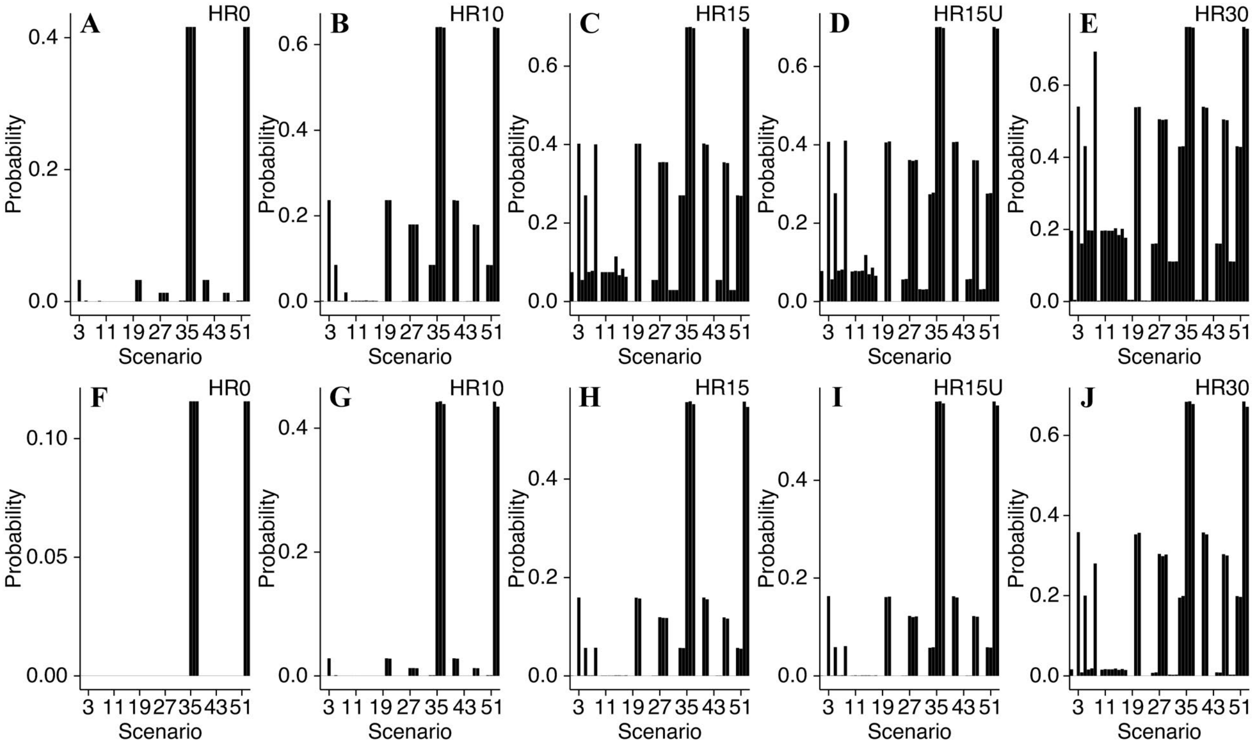

Figure 8

The probability (**A–E**) of mature male abundance (MMA) being less than average MMA (MMA_{ave}) and (**F–J**) of mature male biomass (MMB) being less than 35% of the unfished level of MMB (MMB_{35}) for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands during the period from the 1985–1986 fishing season through the 2018–2019 fishing season, by model scenario, under harvest control rules (HCRs) HR0, HR10, HR15, HR15U, and HR30. Estimates are based on the last 10 years of a 30-year projection period for 53 scenarios of an operating model used to evaluate HCRs. The stock is projected from an initial level of abundance: $1.55MMB_{35}$. In the model used in this analysis, a linear relationship between CPUE and selected abundance is assumed. For details about the HCRs, see Table 1.

an important conservation component of the management strategy given the desire to ensure future recruitment. Realized exploitation rates on abundance of legal-sized male golden king crab is expected to be higher when population abundance is on an increasing trend (i.e., when mature male recruits have yet to reach the legal size) because the exploitation rate is scaled to MMA. The maximum exploitation rate on legal-sized male abundance provides an additional level of protection against overfishing of legal-sized males in years when legal-sized male abundance is low relative to the abundance for the entire size range of mature males and is a commonly adopted step in the HCRs for other crab stocks in the Bering Sea and Aleutian Islands (e.g., red king crab in Bristol Bay; Pengilly and Schmidt[4]; Zheng et al., 1997).

It is important to note that our simulations limited the catch in the directed fishery by the retained catch component of the ABC. As such, the more aggressive HCRs likely performed more conservatively (i.e., there was zero probability of exceeding OFL and ABC) than any of the HCRs that did not constrain the directed fishery catch below the retained catch component of the ABC. However, our simulations best approximate how management for crab stocks occurs in the North Pacific Ocean because TACs would not be set above estimated ABCs in practice.

Incorporating uncertainty is a fundamental challenge in MSE. Parameters, such as natural mortality, catchability, growth, maturity, selectivity, and the stock–recruitment relationship are assumed to be correct and time invariant, and the projections ignore spatial and environmental variability (Somerton and Otto, 1986; Hollowed et al., 2001; Clark and Hare, 2002). However, the ability to use MSE to help achieve management goals depends on how well uncertainty in the system is represented in simulations (Punt et al., 2016). Because it is

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[4] Pengilly, D., and D. Schmidt. 1995. Harvest strategy for Kodiak and Bristol Bay red king crab and St. Matthew Island and Pribilof blue king crab. Alaska Dep. Fish Game, Spec. Publ. 7, 10 p. [Available from website.]

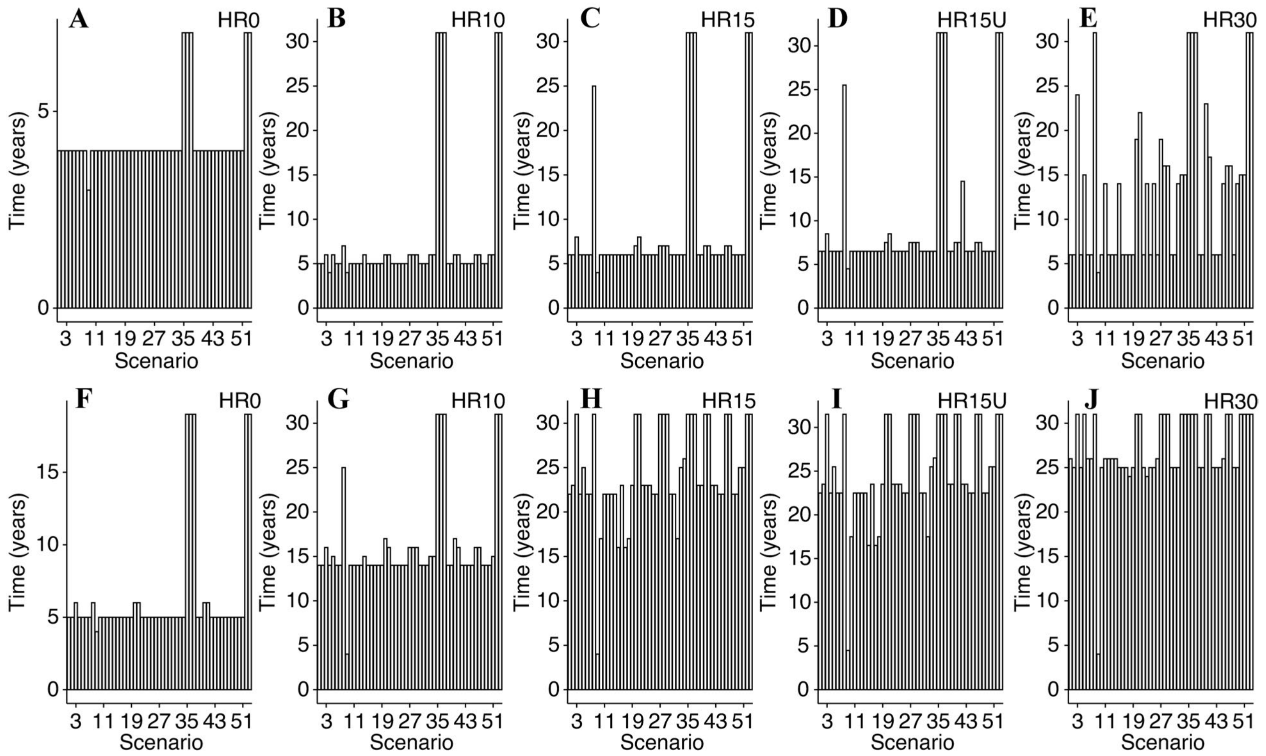

Figure 9

Median time, in years, for a stock of golden king crab (*Lithodes aequispinus*) in the Aleutian Islands (**A**–**E**) to rebuild from an initial overfished state of $0.5MMB_{35}$, where MMB_{35} is 35% of the unfished level of mature male biomass, to a full MMB_{35} and (**F**–**J**) to rebuild from the corresponding mature male abundance to average mature male abundance under harvest control rules (HCRs) HR0, HR10, HR15, HR15U, and HR30, for the 53 scenarios of the operating model in which a linear relationship between catch per unit of effort and selected abundance is assumed. Data used in the model are for golden king crab in 1981–2018. For details about the HCRs, see Table 1.

computationally prohibitive to address all uncertainties by using a projection model, we considered a small set of scenarios focused on those uncertainties most likely to affect the performance of HCRs under the linear and nonlinear choices.

Our findings indicate how projection results respond to changes in steepness, variation, and autocorrelation of the stock–recruitment relationship, error in estimating MMB and MMA, and catch implementation error (Table 2, Suppl. Tables 1–5). Although the values of the performance metrics differ between the linear and nonlinear choices, trends in HCR ranks were largely unchanged between these choices, indicating that our analysis for these choices is robust for evaluating policy trade-offs. The results presented here are based on approximate closed-loop simulations because, although errors in estimating MMB and MMA are considered, the full stock assessment is not simulated because of computational limitations, and our analysis is not a full MSE. Comparison of the full suite of scenarios (i.e., a range of contrasting parameter values) reveals the level of risk related to each source of uncertainty when relying on best estimates of parameters for decision-making.

The projections in our study identify recruitment variability as the most important factor determining the performances of the HCRs, yet understanding causes of recruitment fluctuations is a fundamental challenge in modeling crab population dynamics. The results of our simulations may underestimate recruitment variability or fail to capture the non-stationarity of the nature of recruitment, and such underestimation or failure may bias estimates of HCR performance. Well-defined stock–recruitment relationships are rare for crab and lobster species because the underlying physical and biological processes that influence larval survival to the juvenile stages are difficult to define (Wahle, 2003). For red king crab in Bristol Bay, recruitment trends are consistent with decadal climate shifts (Zheng and Kruse, 2003), indicating the importance of environmental factors (Zheng and Kruse, 2006). Nevertheless, because of uncertainties in the stock–recruitment relationship (or lack thereof) for golden king crab in the Aleutian Islands,

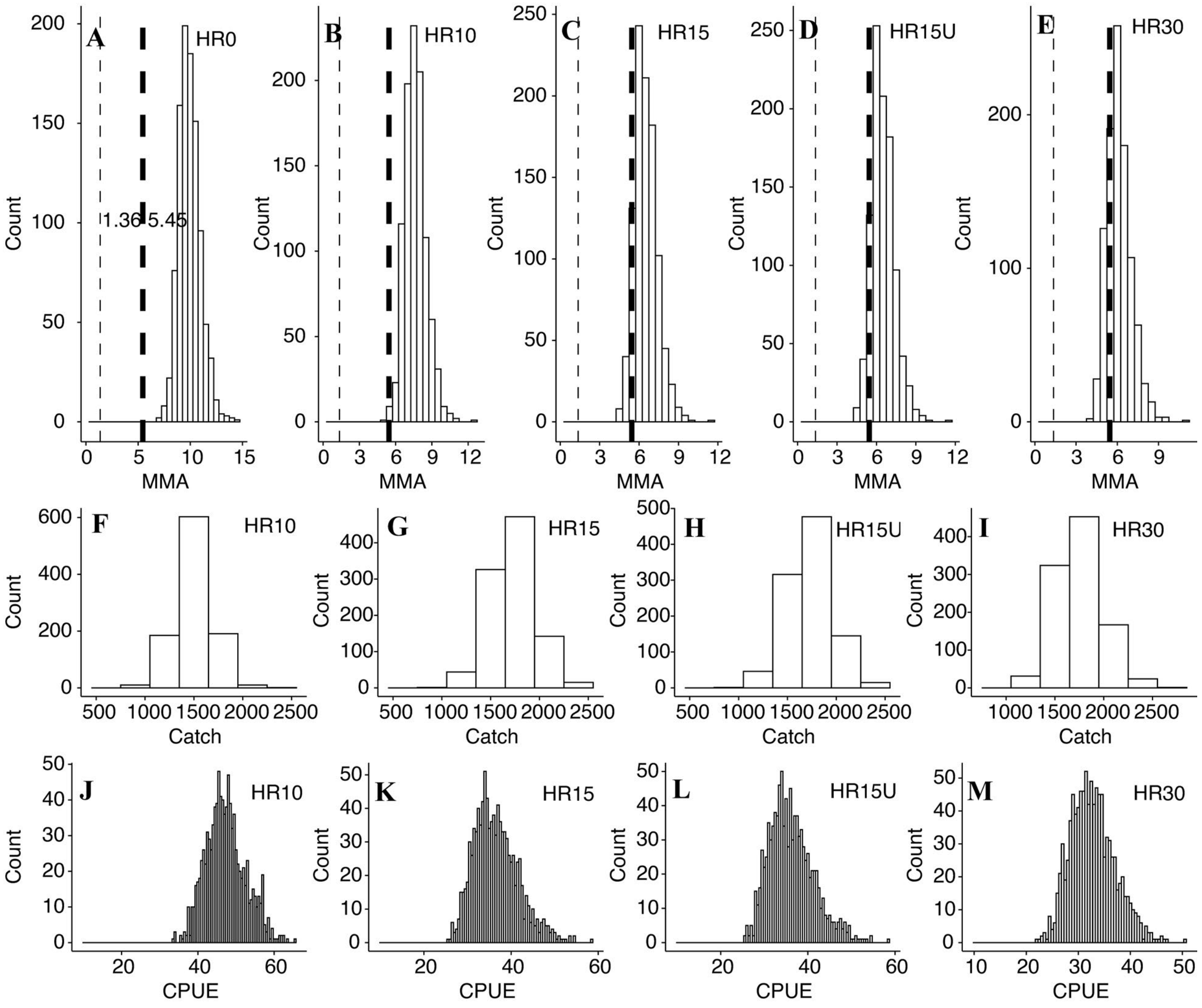

Figure 10

Distributions of (**A–E**) mature male abundance (MMA), (**F–I**) retained catch, and (**J–M**) catch per unit of effort (CPUE), all given in frequency counts, of golden king crab (*Lithodes aequispinus*) in the Aleutian Islands under harvest control rules (HCRs) HR0, HR10, HR15, HR15U, and HR30. Distributions are from 1000 simulations for scenario 1 of the operating model in which a linear relationship between CPUE and selected abundance is assumed. The stock is projected from an initial level of abundance, measured in mature male biomass (MMB): a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB). The vertical thick dashed lines in the top row of panels indicate average mature male abundance (MMA_{ave}), and the vertical thin dashed lines indicate $0.25MMA_{ave}$. Data used in the model are for golden king crab in 1981–2018. For details about the HCRs, see Table 1.

understanding the sensitivity of the performance of candidate HCRs to changes in recruitment parameters will assist managers in decision-making.

We feel that the approach of using a simplified MSE presented here is a fair balance between a robust analysis with reduced computational demands and a full MSE that can be applied to any stock that is hard to age and for which there are several candidate HCRs. Although we highlight the importance of recruitment variability, managers of other stocks should consider their management goals, dynamics of the stock that they manage, uncertainties, and candidate catch policies. The ability to objectively evaluate conservation and economic tradeoffs leads to a level of transparency between managers and fishermen that allows productive dialogue regarding emerging HCRs.

Acknowledgments

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Table 6

Decision matrix based on average policy ranks within each metric used to evaluate harvest control rules (HR0, HR10, HR15, HR15U, and HR30) for golden king crab (*Lithodes aequispinus*) in the Aleutian Islands, when a linear relationship between catch per unit of effort and selected abundance is assumed in the operating model. Values are based on the last 10 years of the 30-year projection period, which begins with 2018. The stock is projected from 2 initial levels of abundance, measured in mature male biomass (MMB): a healthy state (i.e., MMB_{2018}/MMB_{35}=1.55, where MMB_{2018} is MMB in 2018 and MMB_{35} is 35% of the unfished level of MMB) and an overfished state (i.e., MMB_{2018}/MMB_{35}=0.50). Values are average ranks within each metric, with ranks of the average metric ranks given in parentheses. The ranks of the catch metric correspond only to the long-term averages of retained catch; therefore, no average ranks were computed. For details about the harvest control rules, see Table 1.

Metric	Conservation	Catch	Catch stability
Healthy			
HR0	1.00 (1)		
HR10	1.00 (1)	4	1.43 (1)
HR15	1.40 (3)	3	2.00 (2)
HR15U	1.40 (3)	2	2.86 (3)
HR30	1.80 (5)	1	2.86 (3)
Overfished			
HR0	1.00 (1)		
HR10	1.00 (1)	4	1.43 (1)
HR15	1.50 (3)	2	1.86 (2)
HR15U	1.75 (4)	1	2.29 (3)
HR30	2.00 (5)	3	2.71 (4)

suggestions on the projection simulations and stakeholders of the fishery for golden king crab in the Aleutian Islands for suggestions on management strategy scenarios. This manuscript is contribution PP–285 of the Commercial Fisheries Division of the Alaska Department of Fish and Game, Juneau, Alaska.

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