A management strategy evaluation of Pacific Hake: implications of spatial distribution and differentiated harvest control rules.

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Abstract

A key question regarding management of exploited species is how spatial structure influences the estimation and derivation of management quantities. Pacific Hake is the largest groundfish fishery on the Pacific West Coast, with over 300,000 tons annual catch in recent years. The Pacific Hake stock spans Canadian and U.S. exclusive economic zones, and management is directed through a binational treaty, where quotas are based on a harvest control rule and a fixed allocation to each country. There are two pertinent hypotheses regarding how spatial structure of the stock can affect management: 1) demographic distribution shifts - Pacific Hake spawn in the southern California Current (U.S. territory)

and the extent of northward migration (towards and into Canadian territory) is related to individual size, and 2) climate-driven distribution shifts – prevailing ocean conditions, including climate change, cause distributional shifts of the stock. We use management strategy evaluation (MSE) to evaluate how alternative hypotheses about spatial stock structure influence robust management choices. The MSE employs closed-loop simulations with an operating model that represents the complexity of hake biology, an observation model that 'samples' data, an estimation model similar to the stock assessment model used for Pacific Hake, and a management model that interprets stock assessment outputs into total allowable catch. By explicitly modeling spatial structure (i.e., movement and spatial recruitment) in the operating model, we evaluate the accuracy and associated uncertainty of estimated reference points that do not account for spatial differences. The results of the MSE are contextualized in regards to improving current management and assessment of the binational stock.

Introduction

The US-Canada Agreement for Pacific Hake was fully implemented in 2012 when the stock assessment was first conducted by the newly appointed Joint Technical Committee (JTC) and first reviewed by the newly formed Scientific Review Group (SRG). Both the JTC and SRG reports that year highly recommended embarking on a Management Strategy Evaluation (MSE) as a tool to explore a variety of issues associated with management of the hake fishery, including data collection (frequency of acoustic surveys), assessment methods (treatment of selectivity), and management (performance of the harvest control rule) (SRG, 2012; Stewart *et al.*, 2012).The Pacific Hake fishery had also been certified as sustainable by the Marine Stewardship Council in 2010 with the evaluation of the harvest control rule in an MSE framework included as a condition for maintaining the certification (Devitt *et al.*, 2009).

An initial iteration of the MSE was conducted during the period 2012 to 2015, with results presented as appendices to the 2013, 2014, and 2015 stock assessments (Hicks *et al.*, 2013; Taylor *et al.*, 2014, 2015). The SRG reviews of these results were largely supportive of the MSE work, but noted the need for more complexity in the operating model (OM) to provide a more robust test of the performance of the assessment model specifically and the management system more generally. Recommendations from SRG reports during this iteration included the following:

- "The SRG encourages the JTC to consider including structural mismatches in future MSE experiments to evaluate the model uncertainties that are inherent but currently unmeasured in the stock assessment results." (SRG, 2014).
- "The SRG concludes that developing a spatially explicit MSE operating model is necessary to examine issues involving fishing by the US and Canada with spatial dimensions, such as the availability of fish in each country." (SRG, 2015).
- "The SRG concludes that developing an operating model that is structured differently from the assessment model will be a critical element of conducting further MSE work for Pacific Hake. A spatially explicit operating model is likely necessary to examine issues involving fishing by the US and Canada with spatial dimensions, such as the availability of fish in each country. Other areas of fruitful inquiry with an MSE include evaluating alternative approaches to modeling selectivity of the fishery, evaluating juvenile indices, and management approaches and procedures for stocks with episodic strong recruitment events." (SRG, 2016).

Development of this more complex operating model was stalled due to lack of staff time available to do the work. The addition of a MSE coordinator position at NOAA's Northwest Fisheries Science Center in 2017 (filled by K. Marshall) and a postdoctoral research position in 2018 (filled by N. Jacobsen) allowed this next iteration of MSE work to begin and a proposed work plan was presented at the 2018 SRG

meeting. The 2018 SRG report (SRG, 2018) supported implementation of the work plans and repeated the recommendation that "the OM must be structurally different from, and more complex than, the assessment model".

This document describes a new spatially explicit operating model and other aspects of the MSE which have been developed over the past year, incorporating feedback gathered at the Joint Management Committee (JMC) meetings in March and July of 2018 and three phone meetings of a newly formed MSE Working Group that occurred between the two JMC meetings. The 2018-19 U.S. federal government shutdown delayed progress on the MSE, so the results presented here should be considered preliminary and are included to allow the SRG to have a preview of results that will be forthcoming in 2019 and an opportunity to provide feedback on how the results are communicated.

Methods

The simulation component of the management strategy evaluation consists of four individual components: 1) an operating model (OM), 2) data generation from the OM, 3) an estimation model (EM), and 4) a harvest control rule model (Figure 1). Each component is described in detail below.

Operating model.

The operating model is a standard age-based model with movement occurring between two spatial areas. The time scale of the model is four seasons per year, which allows fish to move within a year, and subsequently return to spawn at a given area in the beginning of the following year. We denote years as y and the general time scale as t to distinguish between processes that happen among years (y) and within seasons (t), with the maximum number of seasons t_{end}. We define the equations for the operating model below. The model is programmed in a framework that allows for strategically expanding complexity and adding additional sources of uncertainty (e.g., additional spatial cells or alternative configurations of time varying selectivity), or sensitivity of parameters (e.g., initial conditions, observation errors, or natural mortality).

Equilibrium abundance

To initialize the model we calculate the unfished distribution based on natural mortality and unfished recruitment.

$$N_a = \begin{cases} R_0 e^{-\sum_a M_a} & if\ a < A \\ \frac{N_{A-1} e^{-M_a}}{1-e^{-M_a}} & if\ a = A \end{cases} \qquad (1)$$

Where R_0 is the unfished recruitment, *a* is age, *A* is the plus-group age, and M_a is the natural mortality at age. The unfished age distribution results in unfished spawning biomass as

$$S_0 = 0.5 \sum_a \psi_a N_a \qquad (2)$$

where ψ_a is the age specific fecundity and 0.5 assumes that half of the population is female.

Initial conditions

The initial conditions leading up to the fishery also includes A number of years with recruitment deviations. The first year of the simulation is therefore initialized with the following age distribution

$$N_a = \begin{cases} R_0 e^{-\sum_a M_a} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} & if\ a < A \\ \frac{N_{A-1} e^{\sum_a M_a}}{1-e^{-M_a}} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} & if\ a = A \end{cases} \quad (3)$$

Where N_a is the numbers at age, σ_R is the standard deviation of recruitment deviations, b_y is a bias adjustment factor (Methot *et al.*, 2011). We assume $b_y = 0$ in the years leading up to the fishery. $\tilde{R}_y$is annual recruitment deviations that are assumed to be normally distributed with 0 mean.

Growth

Growth follows the empirical weight at age used in the Pacific Hake stock assessment (Edwards *et al.*, 2018) . In years where the empirical weight at age is unavailable we use the average weight at age. The weight at age is different depending on the source, i.e., there is a weight available for the fishery, the survey, the spawning biomass, and in the middle of the year.

Reproduction

Recruitment is assumed to occur in the beginning of the year and follows a Beverton-Holt stock recruitment curve with annual deviations

$$R_y = \frac{4hR_0 S_y}{S_0(1-h)+S_y(5h-1)} e^{-0.5\sigma_R^2 b_y + \tilde{R}_y} \quad (4)$$

h is steepness of the stock recruitment curve and S_y is the spawning biomass in that year calculated as $S_y = \sum_a N_{a,y} w_a \psi_a$ where ψ_a is the age specific fecundity.

We use bias correction, b, as an input to the model following (Methot *et al.*, 2011)

$$b_y \begin{cases} 0 & y \le y_1^b \\ b_{max}\left(1 - \frac{y-y_1^b}{y_2^b-y_1^b}\right) & y_1^b < y < y_2^b \\ b_{max} & y_2^b < y < y_3^b \\ b_{max}\left(1 - \frac{y_3^b-y}{y_4^b-y_1^b}\right) & y_3^b < y < y_4^b \\ 0 & y_4^b \le y \end{cases} \quad (5)$$

where $y_1^b \ldots y_4^b$ are breakpoints for the change in bias adjustment. While the bias correction is not strictly necessary in the OM, we use it to keep internal consistency in the magnitude of historical recruitment deviations.

We distinguish between seasonal rates with the subscript t and yearly rates with the subscript y. We assume that natural mortality, M, is equally distributed between all seasons. Leading into a new year the model is projected forward in time using the standard population dynamic equations

$$N_{t=1,a} \begin{cases} R_{t,y} & if\ a = 0 \\ N_{y-1,t=t_{end},a-1} e^{-Z_{t,a}} & if\ 1 \le a \le A-1 \\ N_{y-1,t=t_{end},A-1} e^{-Z_{t,a}} + N_{y-1,t=t_{end},A} e^{-Z_{t,a}} & if\ a = A \end{cases} \quad (6)$$

Within a year the fish are subject to the total mortality, $Z = s_{a,y} F_t + M_a$ where s_a is the age and year specific fishing selectivity, and F_t is the fishing mortality occurring in that particular season (in the case

of going in between years from season four to season 1). The number of fish surviving to the next season is then calculated as

$$N_{\mathrm{t,a}} = N_{t-1} e^{-Z_t} \qquad (7)$$

Fishing

We model age-based selectivity for both the fishery and the scientific survey as an approximation of a trawl selectivity curve with four and five parameters for the survey and fishery, respectively. We assume that selectivity does not change within a year, and that the scientific survey selectivity is constant. The fisheries selectivity is constant from the years 1965 to 1991, and from 2018 and onwards. From 1991-2017 fisheries selectivity is furthermore calculated every year as deviations from the constant selectivity. The years where selectivity is constant it is modeled as

$$s_a = \exp(s'_a - s'_{\max}) \qquad (8)$$

Where s'_a is the cumulative sum over ages of the selectivity parameter p

$$s'_a = \sum_{a=a_{min}}^{a_{max}} p_a \qquad (9)$$

Finally, s'_{max} is the maximum value of s'_a. When $a < a_{min} \mid s_a = 0$, and when $a > a_{max} \mid s_a = s_{a_{max}}$.

In the years selectivity is variable, p_i is allowed to vary as

$$p_{a,y} = p_a + \epsilon_{a,y} \qquad (10)$$

where $\epsilon_{a,y}$ is an annual selectivity deviation assumed normally distributed with variance σ_{sel}. a_{min} denotes the age below which $s_a = 0$ and a_{max} denotes the age above which $s_a = s_{a-1}$.

Movement

To model the spatial distribution of Pacific Hake we assume there are n areas, between which the fish can move (2 areas in current OM development). First, we define the first year of the simulation

$$N_{0,a,i} = N_{0,a}\omega_{0,i} \qquad (11)$$

Where ω_0 is an I length vector that sums to 1 that defines the fraction of fish in each of the spatial areas and i denotes the areas from $1 \ldots I$ going from North to South. Currently the model is parameterized with two areas ($I = 2$) representing Canada and the US. When the model is projected forward in time, fish move between areas depending on their age, the season, and which area they are in at the beginning of that season. Specifically, we model the movement as a matrix that determines the number of fish that leave an area. We assume that movement occurs after mortality has occurred (eq 6 and 7), and for clarity we do not denote the mortality in the equations below

$$N_{t,a,i} \begin{cases} N_{t,a}\omega_{t,a,2} - N_{t,a}\omega_{t,a,1} & i = 1 \\ N_{t,a}\omega_{t,a,1} - N_{t,a}\omega_{t,a,2} & i = I \end{cases} \qquad (12)$$

where $\omega_{t,a,i}$ is the movement matrix.

Movement is modeled as a saturating function of age defined as

$$\omega_{a,i} = \frac{\kappa_i}{1+e^{\left(-\gamma(a-a_{50})\right)}} \qquad (13)$$

Where κ is the maximum movement rate, α determines the slope towards the maximum, and a_{50} is the age at 50% of maximum movement rate. There are two other main assumptions to movement

1) 80% of all spawning biomass present in the Northern part move south to spawn in the last season of the year, so they are effectively present to spawn first of January in the following year
2) When the fish have moved North during the year, they only rarely (5%) move South again before the last season, where the spawning biomass migrates.

The movement in between the seasons is visualized in Figure 2.

Catch

We model the catch with the standard Baranov catch equation, but applied to each season, and area

$$C_{t,a,i} = \frac{s_{y,a}F_{t,a,i}}{Z_{t,a,i}}(1 - e^{-Z_{t,a,i}})N_{t,a,i}w_{t,a} \quad (14)$$

where $F_{t,a,i}$ is the instantaneous fishing mortality, $Z_{t,a,i}$ is the total fishing mortality ($F_{t,a,i}$+M_a), and $w_{t,a}$ is the weight at age. The OM uses total catch as an input and dynamically calculates the fishing mortality based on the 'Hybrid' method described in Methot & Wetzel (2013). The catch is distributed among the four seasons as $[0; 0.5,0.30,0.2]$ in both countries (which roughly corresponds to the observed catch distribution), and it is assumed that the US takes 76% of the total catch, while Canada takes the remaining 24% according to the Treaty.

Data generation

The goal of the operating model is to produce output similar to the empirical data available for the fishery. The model outputs every year the total catch

$$C_y = \sum_t \sum_a \sum_i C_{t,a,i} \qquad (15)$$

Both the fishery and the survey report age compositions per year φ_s, φ_F . For the fishery the numbers at age in the catch is found by dividing by the individual weight.

$$\varphi_{a,y} = \frac{N_{y,a,c}}{\sum_{a=1}^{A} N_{y,a,c}} \qquad (16)$$

$N_{y,a,c}$ is the abundance of individuals at age in the catch. All ages over 15 are summed up for both the fishery and the scientific survey.

The survey is reported as the total biomass targeted by the survey, and thus does not report area specific biomass. The survey is biannual.

$$B_y = qs_aN_{y,a}w_{y,a}\epsilon_s \qquad (17)$$

Where q is the catchability coefficient, and s_a is the survey selectivity. We assume that the survey takes part in the second quarter of the year. $\epsilon_s \sim Lognormal\left(0, \sigma^2_{survey}\right)$ is observation error on the survey. The standard deviation is comprised of two different values $\sigma^2_{surv} + \sigma^2_{s,y}$ where σ^2_{surv} is a constant variance, and $\sigma^2_{s,y}$ is a standard deviation specific to the survey years.

Estimation model

The estimation model (EM) is a standard age-based model with the same dynamics as the operating model (i.e., the same equations as above, but excluding equation 11-13). Furthermore, the time step is annual rather than having 4 seasons per year. We estimate 274 parameters in the model (from year 1965-2017) with the number of parameters increasing with two per extra year modeled into the future; fishing mortality and recruitment deviations. We ignore time-varying selectivity in the future to avoid the number of parameters rapidly expanding, and thus impeding calculation times (time varying selectivity is still estimated from year 1991-2018 as in the current assessment model).. The parameters are estimated by minimizing the negative joint log-likelihood function comprised of 8 different components, of which 4 are fit to data and 4 are penalty functions for parameter deviations. Notation where a ~ denotes 'data':

Data fitting

- Fit of the survey data as a log-normal distribution $\tilde{B}_y \sim Lognormal(B_y, \sigma^2_{s,adj})$The adjusted standard deviation is $\sigma^2_{s,adj} = \sigma^2_s + \sigma^2_{s,y}$ where σ^2_s is a constant survey variance term accounting for survey error, and $\sigma_{s,y}$ is an additional time varying variance term calculated externally as a part of the survey krieging and extrapolation only in survey years
- Fit to the natural logarithm of total catches as a lognormal distribution $\tilde{C}_y \sim Lognormal(C, \sigma^2_C)$ with standard deviation $\sigma^2_C = 0.01$ to closely match observed and modeled catches.
- A Dirichlet-Multinomial fit to age composition data from both survey and catches (Thorson *et al.*, 2017; Edwards *et al.*, 2018) $-logL(\varphi, \theta|\widetilde{\varphi}, n) = log\Gamma(n + 1) - \sum((log\Gamma(n\widetilde{\varphi} + 1) + log\Gamma(\theta n) - \log\Gamma(n + \theta n) + \sum(\log\Gamma(n\widetilde{\varphi} + \theta n\varphi) + log\Gamma(\theta n\varphi)$ where *n* is the number of samples in the observations, and θ is the Dirichlet-Multinomial shape parameter

Penalty functions

- Penalty for recruitment deviations away from 0 as $L_R = 0.5\left(\frac{\widetilde{R^2_y}}{\sigma^2_R} + b_y \log(\sigma^2_r)\right)$
- Penalty for selectivity deviations away from 0 as $L_{sel} = 0.5\left(\frac{\epsilon^2_{a,y}}{\sigma^2_{sel}}\right)$
- A penalty on deviations on steepness, *h*, as a beta-function $-\log(L_h) \sim beta(h, \alpha, \beta)$ where $\beta = \tau\mu$ and $\alpha = \tau(1-\mu)$. $\mu = \frac{(h_{prior} - h_{mini})}{h_{maxi} - h_{mini}}$ and $\tau = \frac{\left((h_{prior} - h_{min})(h_{max} - h_{prior})\right)}{\sigma^2_h} - 1$
- A penalty for natural mortality log-normal deviations away from 0.2 $L_M = 0.5\left(\frac{(\log(M) - \log(0.2))}{0.1}\right)^2$

The estimation model is fitted in the software 'TMB' (Kristensen *et al.*, 2016). To fit a model in TMB, a template is constructed where the likelihood function is specified as a function of the biological model. The template is then called from R which uses a gradient based non-linear minimizer to identify the value of the parameters that minimize the likelihood function.

Management model

The default management model is the stepwise $F_{SPR=40\%}$ harvest control rule (HCR) contained within the agreement between the U.S. and Canada governing the fishery that determines the total allowable catch based on the spawning potential ratio (SPR). The spawning potential ratio (SPR) is calculated as

$$N_{a,SPR} = \begin{cases} 1e^{-\sum_a Z_a} & if\ a < A \\ \frac{N_{A-1}e^{\sum_a Z_a}}{1-e^{-Z_a}} & if\ a = A \end{cases} \quad (18)$$

$$SPR = \frac{0.5\sum_a N_{SPR} w_a E_a}{S_0} \quad (19)$$

Where the goal is to reach SPR = 0.4 by adjusting the F component of Z. We then convert the fishing mortality rate that leads to SPR = 0.4, F_{eq} , to a harvest rate as $H = 1 - \exp(-F_{eq})$, and set the total allowable catch (TAC) according to

$$TAC_{y+1,HCR} = \begin{cases} 0 & S_y/S_0 < 0.1 \\ HV_y\left(\left(S_y - 0.1S_0\right)\left(\frac{\frac{0.4S_0}{S_y}}{0.4S_0 - 0.1S_0}\right)\right) & 0.4 \geq \frac{S_y}{S_0} \geq 0.1 \\ HV_y & \frac{S_y}{S_0} > 0.4 \end{cases} \quad (20)$$

Here $V_y$is the biomass available to catch for the fishery (i.e., $\sum N_{a,y} s_a w_a$). The TAC achieved based on this rule is denoted as the default harvest control rule, HCR_0.

We implement two variation on the default harvest control rules based that uses an adjustment factor to buffer the catch 1) default HCR with JMC buffer adjustment (HCR_{JMC})t and 2) default HCR with realized catch buffer adjustment ($HCR_{realized}$) (Figure 3). The two variations on the harvest control rule are used such that they scale down the TAC of the standard harvest control rules. These are calculated as

$$TAC_{y+1,JMC} = \begin{cases} 139482.7 + 0.38TAC_{y+1HCR_0} & TAC_{y+1,JMC} < TAC_{y+1,HCR_0} \\ TAC_{y+1HCR_0} & TAC_{y+1,JMC} \geq TAC_{y+1,HCR_0} \end{cases} \quad (21)$$

And the realized catch

$$TAC_{y+1,realized} = \begin{cases} 177193.5 + 0.18TAC_{HCR_0} & TAC_{realized} < TAC_{HCR_0} \\ TAC_{HCR_0} & TAC_{realized} \geq TAC_{HCR_0} \end{cases} \quad (22)$$

The different scenarios create more realistic outcomes in terms of potential future catches.

Conditioning of operating model

The operating model is based on the equations described above, but is made flexible such that the parameter space can be changed, in order to test sensitivity and impact of specific parameters. An important part of the MSE is to condition the operating model, where the model is evaluated against available data. The data available for the conditioning is

- Catches
- Age composition in catches from Canada and the US (by fleet)
- Spatially explicit survey biomass estimate
- Spatially explicit survey age compositions

To initialize the model, we used a range of the estimated parameters from the maximum likelihood assessment model, described in detail in Edwards et al (2018), such as selectivity parameters, recruitment deviations, natural mortality and steepness. Due to the increased complexity in the operating model, we slightly adjusted the unfished recruitment to achieve similar spawning biomass distributions as in the assessment model.

Objectives

A goal of the MSE is to investigate how the current management system works in a future with uncertainty. To evaluate the effectiveness of the management strategy, we investigate a range of indicators to see how they meet a set of pre-specified objectives (table 2). The objectives have been set in collaboration with the Pacific Hake MSE working group, which consists of stakeholders, JMC and JTC members, and researchers from the Northwest Fisheries Science Center. The current objectives primarily aim at a sustainable coastwide fishery, and thus require summation of catches and abundances in the specified areas.

We test the objectives in six different scenarios, where scenario 1-3 utilize the default harvest control rule with no catch buffer, and with the two catch buffers described in equation 19 and 20.. All three scenarios have the same movement rates. Second, we test three scenarios with different movement, by changing the parameters κ and a_{50} (table 3), using the $HCR_{realized}$catch buffer. Each scenario is run 100 times with stochastic recruitment deviations, and observation error on the survey.

Results

The conditioning of the operating model leads to similar biomass distributions in the OM as in the maximum likelihood assessment model, both in terms of the survey (Figure 4) and the dynamics of the spawning stock biomass (Figure 5). The conditioning also led to similar age distributions between the OM and the historical data (Figure 6), though with some notable exceptions in year 2013, where the average age in the Canadian survey and catch were significantly higher than in the operating model. In the age composition in the survey, the preceding years (from year 2007) were also higher in the Canadian survey than predicted in the operating model. This result could be an artefact of movement being specified as constant among all models in the year.

In the scenario testing, the harvest control rule with the three catch buffers had some minor differences, with the HCR_0 buffer rule scoring lower on the indicators than HCR_{JMC} and $HCR_realized$ (figure 7). As the HCR_0 specifies a higher TAC than the other two rules, it also had an increased probability of going below 10% of the unfished population, and thus closing the fishery. The differences are generally small (about 1% higher probability of going below $0.1S_0$), but were more common in high movement scenarios (move2 and move3). The mean number of years with a closed fishery was generally less than 2 over the 30-year period, but we note that these numbers are a bit inflated by two runs that had a low recruitment over a long period of time, making it unable to rebuild (median number of closed fishery years were 0 for all runs except the two high movement runs which had 2 closed years).The scenario with low movement scored best in almost all categories (including highest catch), and lowest variability in catch, with the HCR_0 rule scoring lower than the two scenarios with catch buffers applied.

Generally, the catches were quite similar in all scenarios (Figure 8), with the main difference being the variability around the catches. The low movement scenario had the least variable catches, while the

realized strategy also shows much lower variability in catches than the HCR_0 and HCR_{JMC} scenario. Low movement also caused a high average age in the catch, likely owing to many large individuals staying in the south where 75% of the catch takes place. The average age in the catches and the surveys have high variability in all scenarios, owing to cohorts arising from strong or low recruitment years (Figure 9-10).

The average age in the catch and the survey in the two countries did not differ much between the three harvest control rules scenarios, as differences in catches were not sufficiently large. In the three movement scenarios the median average age is visibly different between the low movement scenario and the two high movement scenarios, but there is large variability among the different runs primarily owing to large variation in recruitment, which can drive strong or weak cohorts to influence the age compositions.

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Tables

Table 1: Parameters used in the operating and estimation model. Value denotes the value in the operating model. If the parameter is not estimated it is the same in the estimation model. n denotes the number of parameters estimated.

Parameter	Value	Estimated	Explanation
q	1	No	Catchability coefficient
σ_R^2	1.4	No	Standard deviation of recruitment deviations
θ_C		Yes	Dirichlet-Multinominal parameter in Catch
θ_{survey}		Yes	Dirichlet-Multinominal parameter in survey
h	0.8	Yes	Steepness
h_{min}	0.2	No	Shape parameter for steepness prior distribution
h_{max}	0.1	No	Shape parameter for steepness prior distribution
h_{prior}	0.777	No	Shape parameter for steepness prior distribution
σ_h^2	0.117	No	Standard deviation for steepness prior distribution
R_0	2108316	Yes	Unfished recruitment
M	0.214	Yes	Natural mortality
σ_s^2	0.26	Yes	Survey standard deviation
$p_{a,C}$ (n = 5)	[12,2.5,1.5,1.2,1.6]	Yes	Fisheries selectivity
$p_{a,survey}$(n = 4)	[1.77,0.80,1.36,1.45]	Yes	survey selectivity
$\tilde{R}$ (n = 72)	$N(0,\sigma_R^2)$	Yes	Recruitment deviations
$\epsilon_{a,y}$ (n = 135)	$N(0,\sigma_{sel}^2)$	Yes	Selectivity deviations
σ_{sel}^2	1.4	No	Standard deviation of selectivity
F_y (n = 52)		Yes	Fully selected fishing mortality
n_{space}	2	No	Number of spatial cells in the OM
κ	[0.1;0.75]	No	Maximum movement rate
γ	0.5	No	Slope of movement rate
a_{50}	[5;10]	No	Age at 50% maximum movement rate

Table 2: Management strategy evaluation scenarios. κ and a_{50} denote movement parameters in the operating model (see Table 1). SPR = Spawner Per Recruit, JMC = Joint Management Committee, HCR = Harvest control rule

Name	Harvest control rule	κ	a_{50}
HCR_0	$F_{40\%}$ SPR	0.5	5
HCR_{JMC}	$F_{40\%}$ SPR – adjusted to historical JMC recommendation	0.5	5
$HCR_{realized}$	$F_{40\%}$ SPR – adjusted to historical catch utilization	0.5	5
Move 1	$F_{40\%}$ SPR – adjusted to historical JMC recommendation	0.1	5
Move 2	$F_{40\%}$ SPR – adjusted to historical JMC recommendation	0.75	5
Move 3	$F_{40\%}$ SPR – adjusted to historical JMC recommendation	0.5	2

Table 3: Management objectives for the Pacific Hake management strategy evaluation. See figure 7 for visualization.

ID	Goal	Objective	Indicator	Probability	Time Period
A	Minimize risk of severe overfishing and closing the fishery	Spawning biomass is above 10 % of unfished biomass in 95 % of the years over a 30-year period.	$S > 0.1S_0$	0.95	*t*=1,…30
B	Minimize the risk of the stock dropping below the specified management target	Spawning biomass is above 40 % of unfished biomass in 75 % of the years over a 30-year period.	$S > 0.4S_0$	0.75	*t*=1,…30
C	Minimize the risk of the stock dropping below the specified management target	Spawning biomass is above 40 % of unfished biomass in 75 % of the years over a 30-year period.	$0.1S_0 < S < 0.4S0$	0.25	*t*=1,…30
D	Minimize the risk of the stock dropping below the specified management target for longer periods	If the stock drops below 40% of unfished biomass, the probability that it stays below the threshold for more than 3 consecutive years is less than 10%	$S > 0.4S_0$	0.90	*t*=1,…30
E	Avoid closing the fishery.	Fishery is open in both Canada and the US in 95% of the years over 30 years.	$S > 0.1S_0$	0.95	*t=1,…30*
F	Avoid high variability in total catches	No specified objective	$AAV_y = \frac{\lvert C_y - C_{y-1}) \rvert}{C_{y-1}}$		
G	Minimize risk of overfishing	See previous objectives	$mean(\frac{S}{S_0})$		
H	Maintain high average coast wide catch	Maximize long term catch	$mean\left(\sum_i C_{y,i}\right)$		

Figures

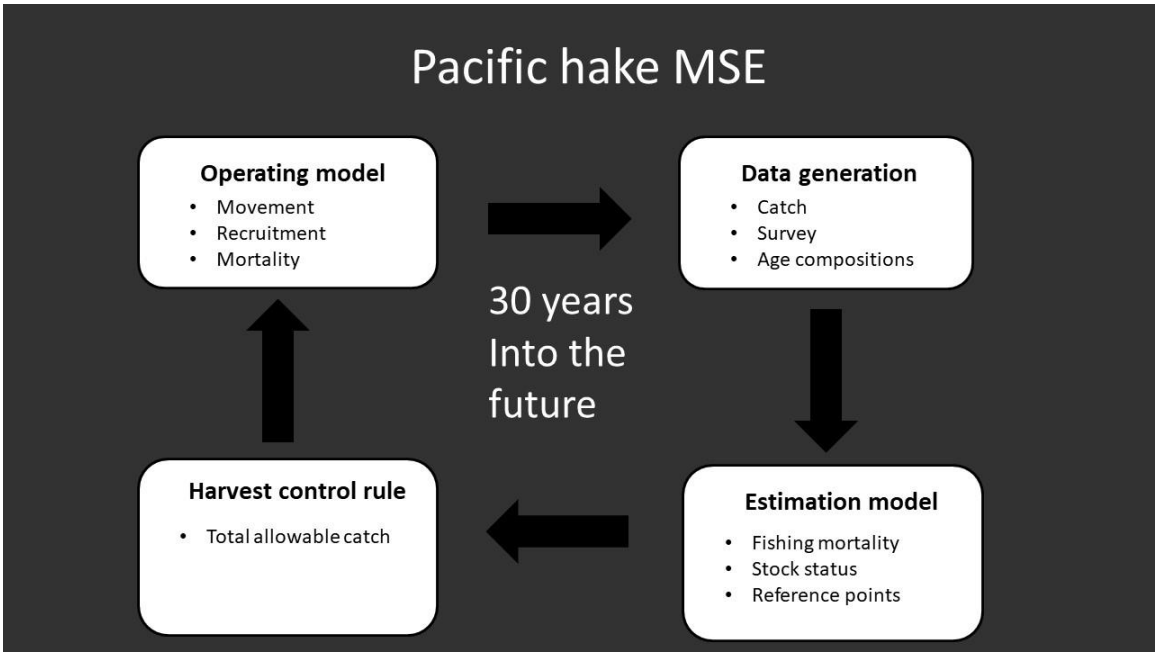

Figure 1: Conceptual description of the four components of the Pacific Hake management strategy evaluation (MSE). The operating model has process error on recruitment, and the data generation has observation error on the survey.

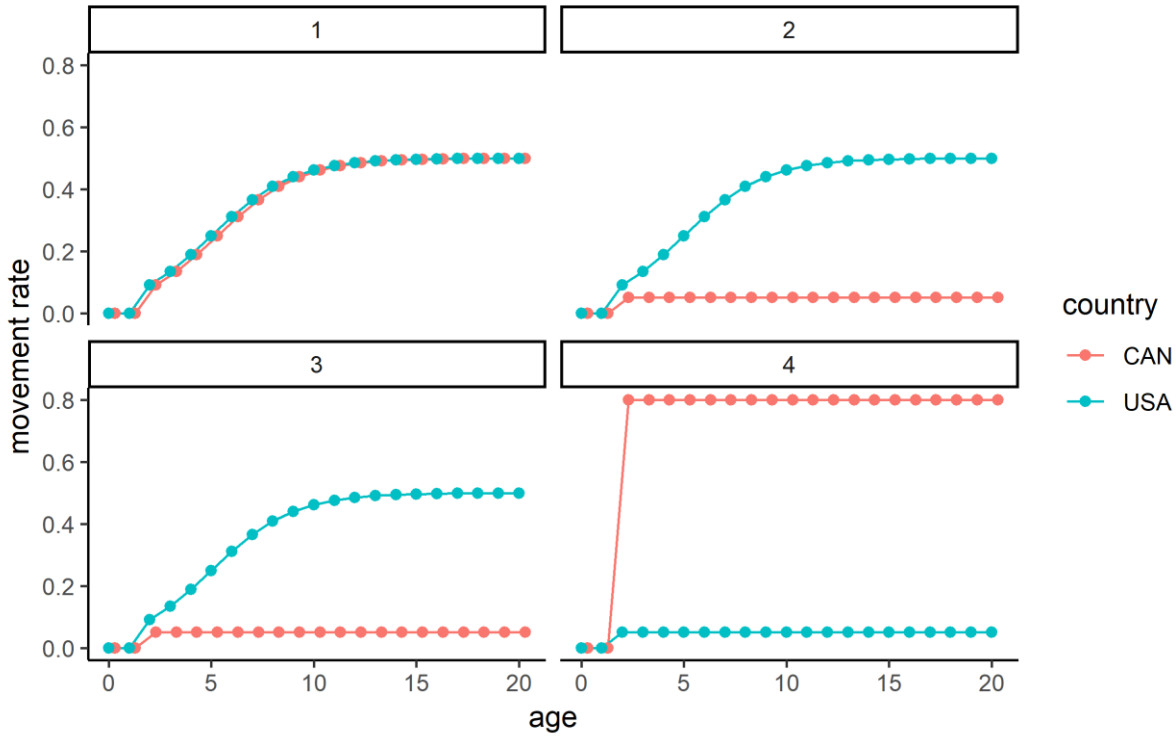

Figure 2: Movement rates as a function of age in the four seasons in the operating model. The number above each plot represents the season.

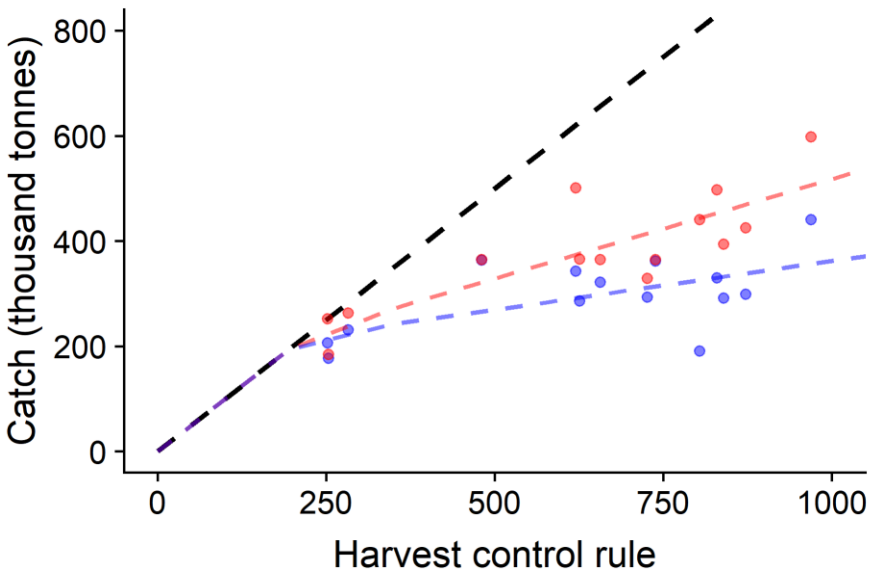

Figure 3: The TAC as a function different harvest control rules (HCR). The black line denotes the standard HCR recommendation, the red dots denote the historical JMC TAC, and the blue dots denote the historical realized catch. The red and the blue lines are linear regressions on the historical TAC/Catch. At the intercept with the standard HCR they are assumed to be equal to it.

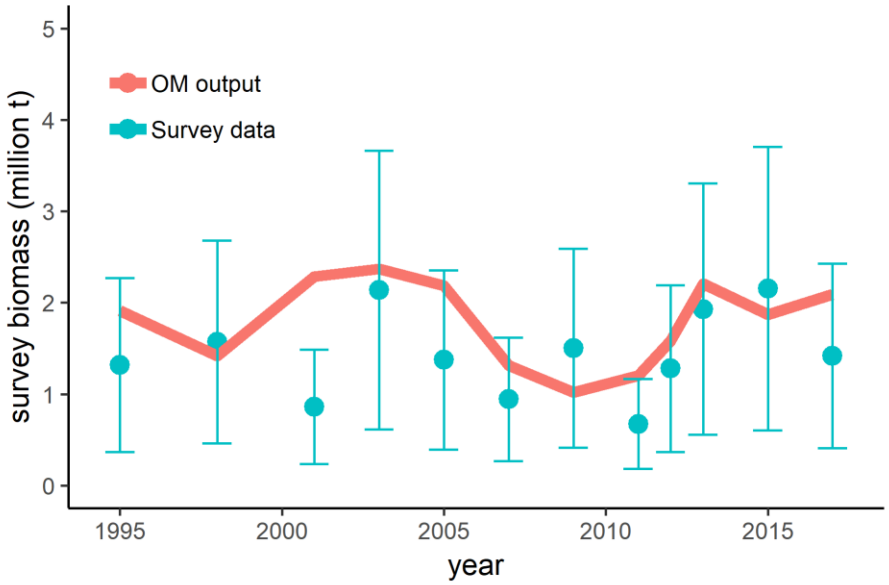

Figure 4: Historical observed survey biomass with its associated uncertainty (blue dots and error bars), and the survey output (without error) from the conditioned operating model (red).

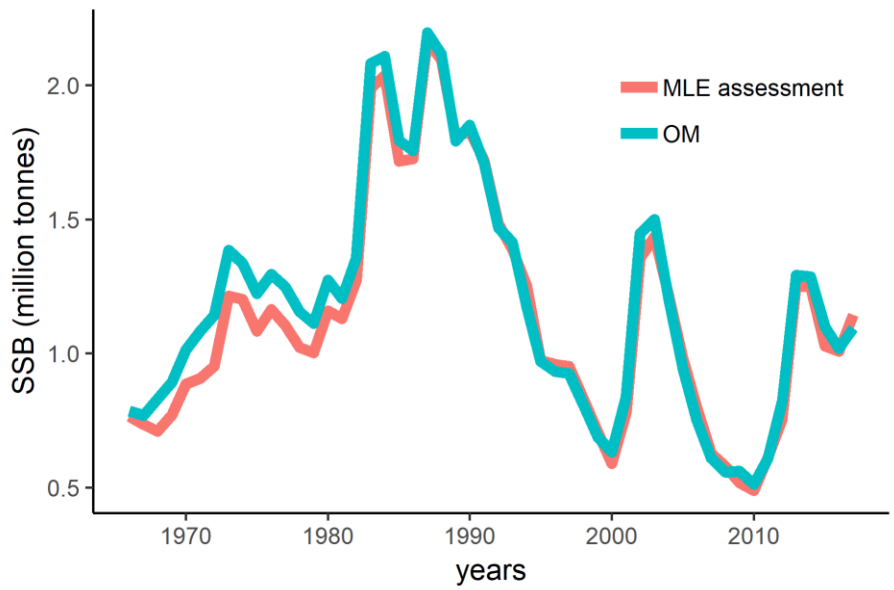

Figure 5: Historical biomass in the spatial operating model (seafoam green) and the maximum likelihood model (red).

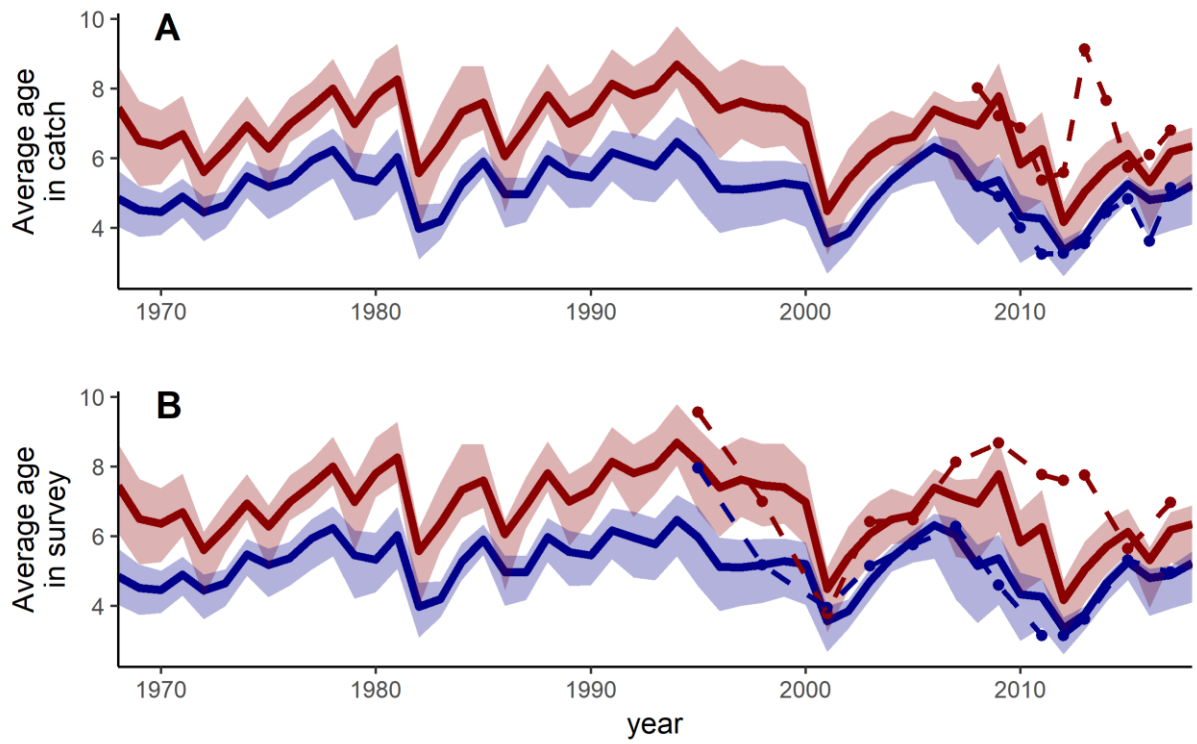

Figure 6: Average age in the catch (A) and the survey (B) in the operating model (red is Canada and blue is USA). Solid lines denote the median, and shaded area the range of possibilities with different values of κ and a_{50} (see table 1 for parameter ranges). The dashed lines with dots denote the observed average ages from the catch and the survey in the two countries.

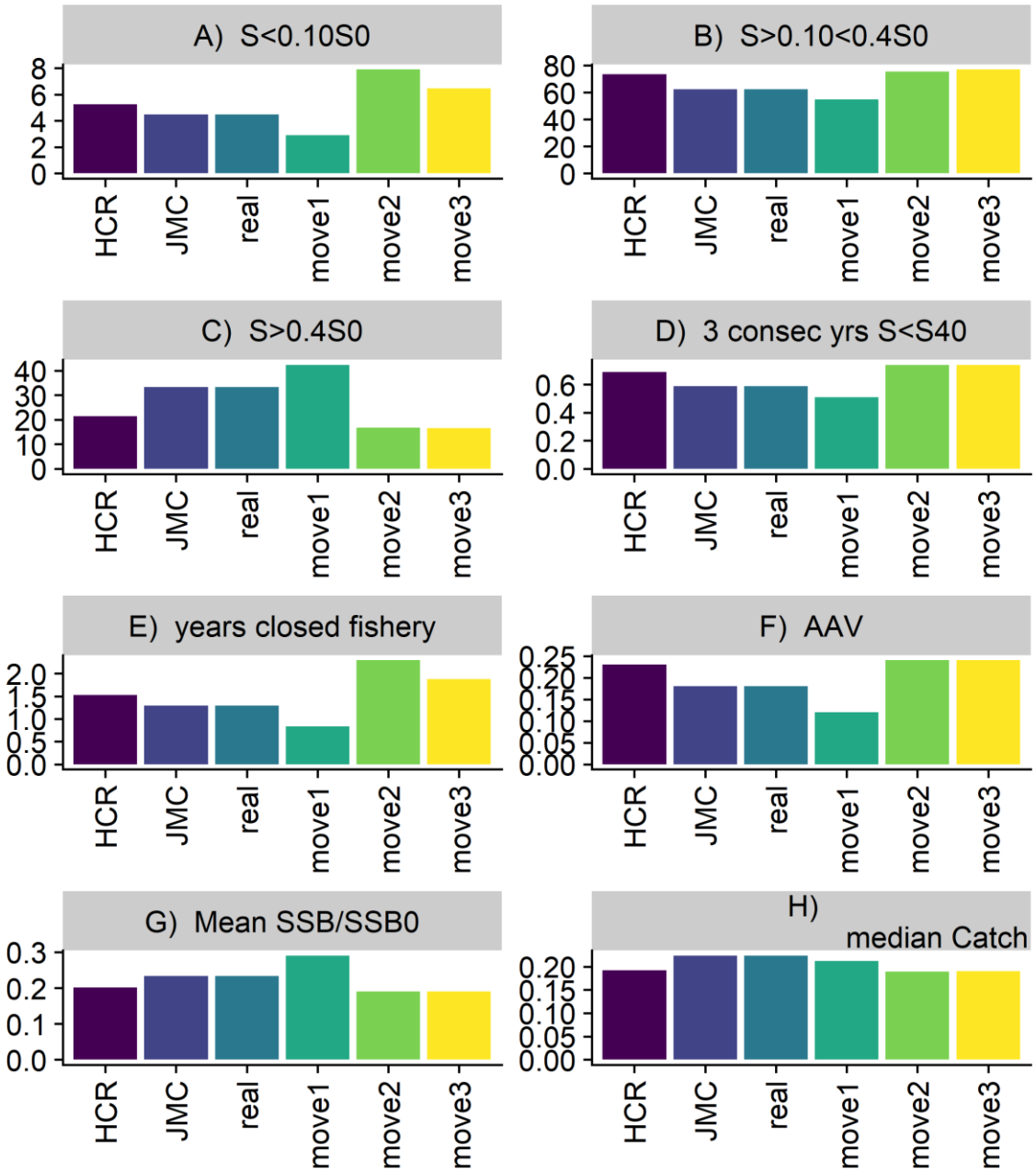

Figure 7: Barplots of the Pacific Hake management objectives in the MSE (30 year simulation). For description of management objectives see table 2. Units A) Percentage of years with spawning biomass less than 10% of unfished, B) percentage of years with spawning biomass between 10% and 40% of unfished, C) percentage of years with spawning biomass over 40% of unfished, D) percentage of years with spawning biomass under 40% of unfished in 3 consecutive years. E) median number of years with fisheries closed, F) Annual average variability in catches, G) average relative depletion of spawning biomass, H) median catch (in millions of tons).

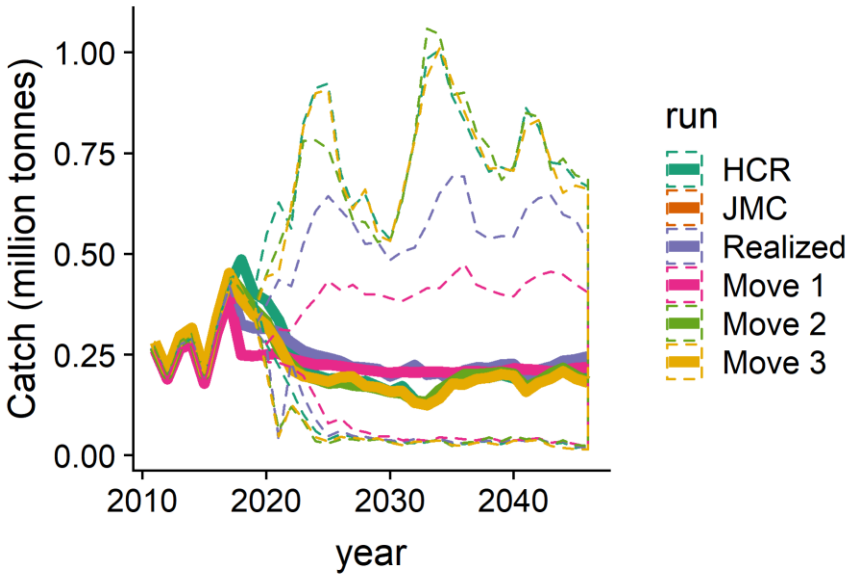

Figure 8: Average future catch in the six scenarios (table 2). Dashed lines indicate the 5th and 95th confidence intervals.

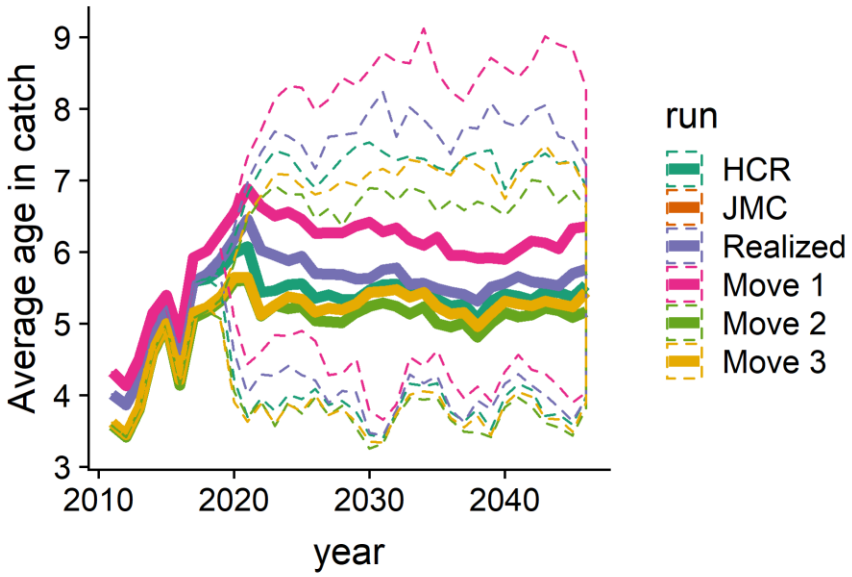

Figure 9: Average age composition in the survey. Dashed lines indicate the 5th and 95th confidence intervals.

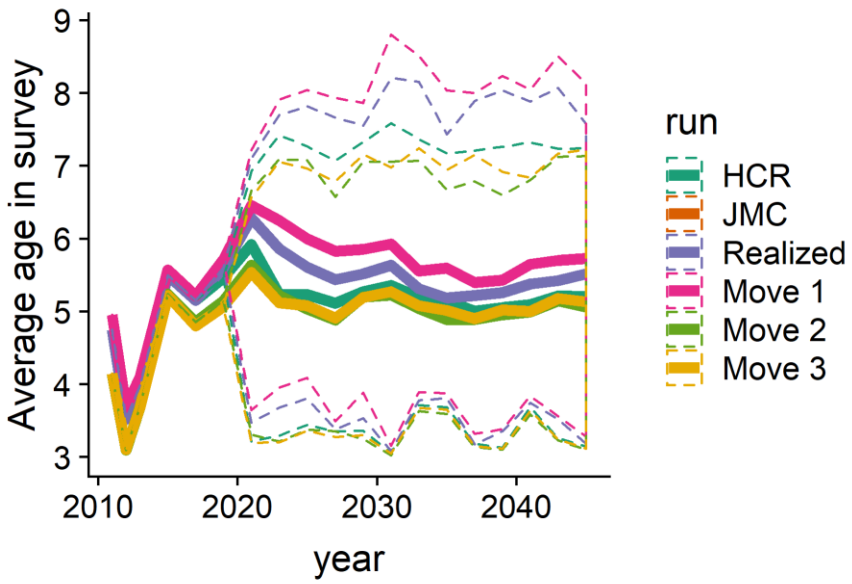

Figure 10: Average age composition in the survey. Dashed lines indicate the 5th and 95th confidence intervals.

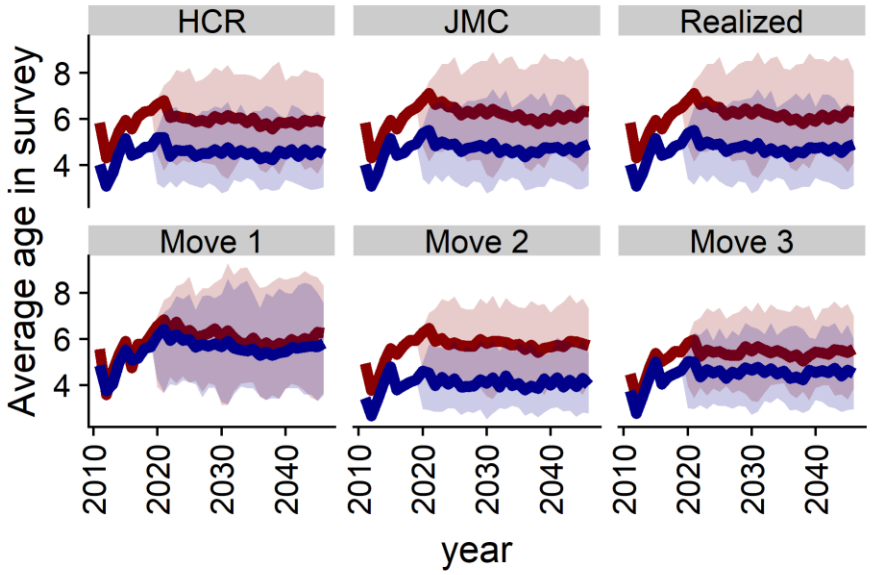

Figure 11: Average age composition in the survey in the two countries. Dashed lines indicate the 5th and 95th confidence intervals. Red denotes Canadian side, blue denotes US side.

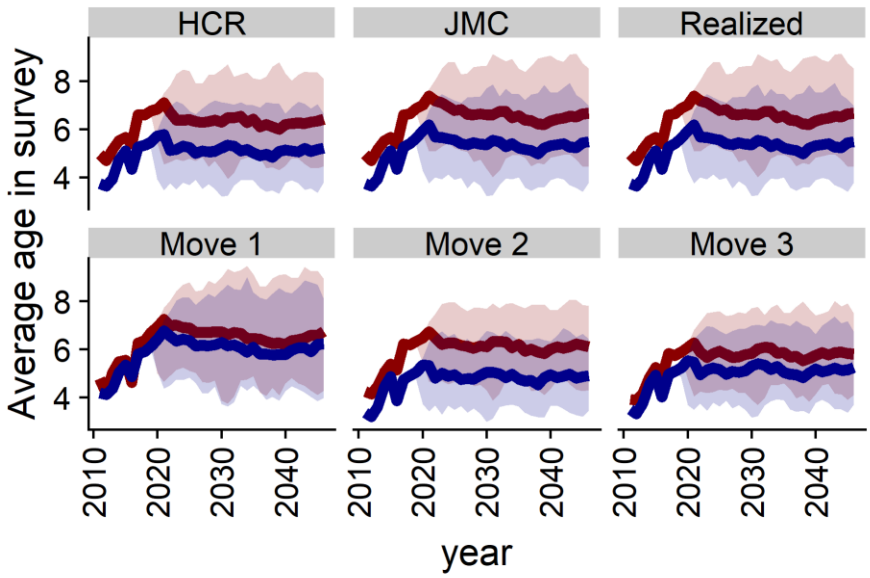

Figure 12: Average age composition in the catch in the two countries. Dashed lines indicate the 5th and 95th confidence intervals. Red denotes Canadian side, blue denotes US side.