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A Spatially Intregrated Statistica Catch-at-Age (SISCA) operating model for the Haida Gwaii major stock of Pacific Herring (*Clupea Pallassi*)

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Another Galaxy

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Pacific herring have been engaging in a management strategy evaluation since 2017, with a single cycle having been completed for all major stocks. For the next cycle, stakeholders have identified two major sources of uncertainty against which future candidate management procedures should be tested. First, the major stock areas may be concealing discrete or connected sub-stock structure that will make herring stocks more or less robust to fishing effort. Second, herring spawn-on-kelp fisheries have never been included as a source of fishing mortality or egg loss, which may be biasing biomass, productivity, and mortality estimates for those stocks that are subject to spawn-on-kelp fisheries.

This paper develops a new, flexible Pacific herring spatially integrated statistial catch-at-age operating model. The new model extends the previous model in the following ways: (i) spatial sub-stocks with optional age-dependent movement between sub-stock areas, (ii) closed-pond spawn-on-kelp fisheries, (iii) fisheries modeled as discrete events on a given day of the year, (iv) spatially correlated process error recruitment and natural mortality deviations, and (v) correlations in the likelihood function for age-composition residuals. Our new model is specified in Template Model Builder, and posterior distributions are estimated using Hamiltonian Monte-Carlo. As in most fisheries stock-assessment modeling, we required several fixed parameters and informative priors to fit our model, so we conducted sensitivity analyses to those assumptions. We also tested the retrospective behaviour of the operating model's maximum likelihood estimates

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Table 1. Notation used in the SISCA OM.

Symbol	Value	Description
T	69	Total number of time steps 1951 - 2019
A	10	Plus group age-class
t	$1, 2, \ldots, T$	Time step
a	$1, 2, \ldots, A$	Age-class index
P	3	Total number of sub-stocks
p	$1, 2, 3$	Indicator of sub-stock (C/S, JP/S, Lou)
g	$1, 2, \ldots, 6$	Gear index
$B_{0,p}$		Unfished spaning stock biomass for stock p
h_p		Stock-recruitment function steepness for stock p
$R_{0,p}$		Unfished equilibrium recruitment
$R_{init,p}$		Initial recruitment parameter
$S_{a,p}$		Unfished equilibrium survivorship-at-age
$\phi_{0,p}$		Unfished equilibrium spawning biomass per recruit
β_1, β_2	$10, 4.92$	Beta prior parameters for steepness
$\omega_{p,t}$		Annual recruitment processs error log-deviations
$\sigma_{R,p}$	.89	Standard error of $\omega_{p,t}$ recruitment deviations
$q_{p,g}$		Catchability coefficient for gear g in sub-stock p
$M_{p,0}$		Initial natural mortality rate for stock p
$\epsilon_{p,t}$		Annual log-deviations in natural mortality rate for stock p
$\sigma_{M,p}$	.1	Standard error in annual natural mortality log-devations for stock p
$M_{p,t}$		Annual natural mortality rate for stock p
$w_{a,p,t}$		Annual average weight-at-age observations for stock p
$s^{50}_{p,g}$		Age-at-50% selectivity for gear g in stock area p
$s^{Step}_{p,g}$		Difference between age-at-50% and age-at-95% selectivity for gear g in stock area p
$s_{a,p,g,t}$		Selectivity-at-age a for stock p and gear g in year t
t_g		Fractional time-step at which catch from gear type g is removed from the population
$N_{a,p,t+t_g}$		Total numbers-at-age a in stock p in year t at fractional time-step t_g
$N_{a,p,g,t+t_g}$		Total numbers-at-age a in stock p vulnerable to gear g in year t at fractional time-step t_g
$B_{p,t}$		Spawning biomass of stock p in year t
$C_{a,p,g,t}$		Expected catch-at-age a in numbers from stock p by gear g in year t
$C'_{a,p,g,t}$		Expected catch-at-age a in biomass units from stock p by gear g in year t
$U_{p,g,t}$		Harvest rate of gear g in stock p at time step t
$I_{p,g,t}$		Observed stock p spawn index for survey $g \in \{4, 5\}$ at time t
$\hat{I}_{p,g,t}$		Expected stock p spawn index for survey $g \in \{4, 5\}$ at time t
$\tau_{p,g}$		Standard deviation of spawn index observation log-residuals
μ_{M_0}		Complex mean initial natural mortality
$\delta_{M,p}$		log-deviation of $M_{0,p}$ from μ_{M_0}
$\mu_{s^{50},g}$		Complex mean age-at-50% selectivity for gear g
$\delta_{s^{50},p,g}$		log-deviation of s^{50}_p from $\mu_{s^{50},g}$
$\mu_{s^{Step},g}$		Complex mean step from age-at-50% to age-at-95% selectivity for gear g
$\delta_{s^{Step},p,g}$		log-deviation of s^{Step}_p from $\mu_{s^{Step},g}$
ϕ_g		Correlation-at-lag-1 coefficient for age composition residuals
$U_{p,g,t}$		Harvest rate of population p by gear g in year t
$K_{p,t}$		Total landed weight of Spawn-on-Kelp product from stock p at time t
$P_{p,t}$		Biomass of fish ponded for Spawn-on-Kelp fishery from stock p at time t
$\Psi_{p,t}$		Conversion factor from ponded fish to landed SOK
$\mathfrak{F}$	200	Average fecundity of mature, female herring (eggs per gram of spawning biomass)
$p_{m,p,t}$		Proportion of individuals that are mature in stock p at time t
$p_{f,p,t}$	.5	Proportion of individuals that are female in stock p at time t
$p_{eff,p,t}$		Proportion of individuals from stock p at time t that will spawn in the closed pond
γ	0.002	Conversion factor from eggs to SOK product

Table 2. Process Model equations for the SISCA OM.

No.	ModelEquation
Model Parameters	
(P.1)	$\Theta^{lead} = \left(B_{0,p}, R_{init,p}, \{\omega_{p,t}\}_{t\in 1:T}, M_{0,p}, \{\epsilon_{p,t}\}_{t\in 1:T}, s_p^{(50)}, s_p^{(step)}, \{\psi_g\}_{g\in 1:3}, \{\tau_{p,g}\}_{g\in\{4,5\}}\right)$
(P.2)	$\Theta^{cond} = \left(\{q_{p,g}\}_{g\in\{4,5\}}, \{\tau_{p,g}^{age}\}_{g\in 1:3}\right)$
(P.3)	$\Theta^{fixed} = \left(\{m_a\}_{a\in 1:10}, h_p, \sigma_{R,p}, \sigma_{M,p}\right)$
(P.4)	$\Theta^{priors} = \left(m_M, s_M, \{m_g^{s^{50}}, s_g^{s^{50}}, m_g^{s^{Step}}, s_g^{s^{Step}}, \sigma_g^{Sel}\}_{g\in 1:3}\right)$
(P.5)	$\Theta^{shrink} = \left(\mu_{M_0}, \delta_{M,p}, \mu_{s^{50},g}, \delta_{s^{50},p,g}, \mu_{s^{Step},g}, \delta_{s^{Step},p,g}\right)$
Unfished Equilibrium States	
(EQ.1)	$m_a = \left(1 + e^{-\log 19 \frac{a - a_{50}^{mat}}{a_{95}^{mat} - a_{50}^{mat}}}\right)^{-1}$
(EQ.2)	$S_{a,p} = \begin{cases} 1 & a = 1, \\ S_{a-1,p} e^{-\bar{M}_{a-1,p}} & 1 < a < A \\ S'_{a-1,g,p} e^{-\bar{M}_{a-1,p}} / (1 - e^{-\bar{M}_{A,p}}) & a = A. \end{cases}$
(EQ.3)	$\phi_p = e^{-\bar{M}_p} \cdot \sum_a S_{a,p} \cdot \bar{w}_{a,p} \cdot m_a$
(EQ.4)	$R_{0,p} = B_{0,p} / \phi_p$
(EQ.5)	$N_{a,p}^{eq} = R_0 \cdot S_{a,p}$
(NEQ.1)	$Z_{init,a,p} = \bar{M}_{a,p} + s_{a,g,p} * F_{init,p}$
Non-equilibrium Initial States	
(NEQ.2)	$S'_{a,p} = \begin{cases} 1 & a = 1, \\ S'_{a-1,p} e^{-Z_{a-1,p}} & 1 < a < A \\ S'_{A-1,g,p} e^{-Z_{A-1,p}} / (1 - e^{-Z_{A,p}}) & a = A. \end{cases}$ s
Catch from discrete fisheries	
(NEQ.3)	$N_{a,p,1} = R_{init,p} \cdot S'_{a,p} \cdot e^{\omega_{a,p}^{init}}$
(C.1)	$N_{a,p,t+t_{g^-}} = N_{a,p,t+t_{g-1}} \cdot e^{-1 \cdot (t_g - t_{g-1}) M_t}$
(C.2)	$s_{a,p,g} = \left(1 + e^{-\log 19 \frac{a - a_{p,50}^{sel}}{a_{p,95}^{sel} - a_{p,50}^{sel}}}\right)^{-1}$
(C.3)	$N_{a,p,g,t} = N_{a,p,t+t_{g^-}} \cdot s_{a,p,g}$
(C.4)	$B_{a,p,g,t} = N_{a,p,g,t} \cdot w_{a,p,t}$
(C.5)	$B_{p,g,t} = \sum_a B_{a,p,g,t}$
(C.6)	$C'_{a,p,g,t} = C_{p,g,t} \cdot \frac{B_{a,p,g,t}}{\sum_{a'} B_{a',p,g,t}}$
(C.7)	$C_{a,p,g,t} = C'_{a,p,g,t} / w_{a,p,g,t}$
(C.8)	$N_{a,p,t+t_g} = e^{-(t_g - t_{g-1}) \cdot M_{p,t}} \cdot N_{a,p,t+t_{g-1}} - C_{a,p,g,t}$
Mixed stock catch and catch-at-age	
(C.9)	$U_{p,g,t} = C_{p,g,t} / B_{p,g,t}$
(M.1)	$\hat{C}_{p,g,t} = \frac{\hat{B}_{p,g,t}}{\sum_p \hat{B}_{p,g,t}} C_{f,t}$
Closed Pond Spawn-on-Kelp	
(M.2)	$\hat{C}_{a,g,t} = \sum_p \hat{C}_{a,p,g,t}.$
(K.1)	$\Psi_{p,t} = \mathfrak{F} \cdot p_{m,p,t} \cdot p_{f,p,t} \cdot p_{eff,t} \cdot \gamma$
(K.2)	$P_{p,t} = \hat{K}_{p,t} / \Psi_{p,t}$
(K.3)	$P_{a,p,t} = P_{p,t} \cdot \frac{B_{a,p,g,t}}{\sum_{a'} B_{a',p,g,t}}$
(K.4)	$N_{a,p,t+t_{SOK}} = e^{-(t_{SOK} - t_{g-1}) \cdot M_{p,t}} \cdot N_{a,p,t+t_{g-1}} - P_{a,p,t}$
(K.5)	$P'_{a,p,t} = P_{a,p,t} \cdot e^{-M_{SOK}}$
Spawning Biomass, Recruitment, and Numbers-at-age	
(K.6)	$U_{p,t}^{SOK} = P_{a,p,t} \cdot (1 - e^{-M_{SOK}}) / B_{p,SOK,t}$
(A.1)	$B_{p,t} = e^{-(1-t_G) M_{p,t}} \cdot \sum_a N_{a,p,t+t_G} \cdot w_{a,p,t} \cdot m_a$
(A.2)	$R_{p,t+1} = \frac{a_p B_{p,t}}{1 + b_p B_{p,t}} \cdot e^{\omega_{R,p,t}}$
(A.3)	$N_{a,p,t+1} = \begin{cases} R_{p,t+1} & a = 1 \\ e^{-(1-t_G) M_{p,t}} \cdot N_{a-1,p,t+t_G} + P'_{a-1,p,t} & 2 \le a \le A - 1 \\ e^{-(1-t_G) M_{p,t}} \cdot (N_{a-1,p,t+t_G} + N_{a,p,t+t_G}) + (P'_{a-1,p,t} + P'_{a,p,t-1}) e^{-M_{SOK}} & a = A. \end{cases}$

Table 3. Observation model equations for the SISCA OM.

No.	ModelEquation
(O.1)	$\hat{I}_{p,g,t} = q_{p,g} \cdot B_{p,t}$
(O.2)	$\hat{u}_{a,p,g,t} = \frac{C_{a,p,g,t}}{\sum_{a'} C_{a',p,g,t}}$
(L.1)	$z_{p,g,t} = \log \frac{I_{p,g,t}}{\hat{I}_{p,g,t}}$
(L.2)	$\log \hat{q}_{p,g} = \frac{1}{n_{p,g}} \sum_{t=1}^{n_{p,g}} z_{p,g,t}$
(L.3)	$Z_{p,g} = \sum_{t=1}^{n_{p,g}} \left(z_{p,g,t} - \log \hat{q}_{p,g} \right)^2$
(L.4)	$l_1 = \frac{1}{2} \sum_{p \in 1:P, g \in 4:5} \left(n_{p,g} \cdot \log \tau^2_{p,g} + \frac{Z_{p,g}}{\tau^2_{p,g}} \right)$

Table 4. Differences in major model components between the current herring OM (ISCAM) and the SISCA OM.

ModelCpt	ISCAM	SISCA
Stock Structure	Aggregated	Three independent sub-stocks
Fishing Mortality	Continuous	Discrete fishing events
Age classes	$2, \ldots, 10$	$1, \ldots, 10$
Natural Mortality	Time-varying, cubic spline	Time-varying, random walk
Fished Initialisation	Recruitment deviations for all age classes, and initial recruitment R_{init}	Initial recruitment R_{init}
Stock-Recruitment	Average recruitment $\bar{R}$ model in early estimation phases, with post-fit Beverton-Holt S-R model in a later phase	Unfished biomass B_0 estimated freely as leading parameter; steepness fixed at .67
Survey Catchability	Vague prior on surface survey and informative prior on dive survey	Conditional MLE for surface survey and absolute survey ($q = 1$) assumption for dive survey
Survey Obs Error SD	Errors-in-Variables conditional MLE, with weighting to scale between two surveys	Freely estimated
Rec Proc Error SD	Errors-in-Variables conditional MLE	Fixed at .86
Age compositions	All age composition data included	Minimum 200 annual samples
Age-comp likelihoods	Logistic-normal with tail compression, equal annual weight; freely estimated standard deviation	Logistic-normal with tail compression and estimated AR1 correlation matrix weighted by sample size relative to average annual sample size; conditional MLE of standard deviation
Spawn-on-Kelp Fishery	Absent	Removals derived from landed SOK product, dependent vulnerable age-structure, proportion mature, and previous estimates of the ratio of ponded fish to landed SOK

2 FIGURES