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PERFORMANCE OF A $F_{0.1}$ MANAGEMENT PROCEDURE USING ALTERNATIVE OPERATING MODELS

A.E. Weston[1], L.A. Kerr[1], S.X. Cadrin[2], M.R. Morse[2,3]

SUMMARY

Management strategy evaluation (MSE) was used to determine if a $F_{0.1}$ management procedure was robust to life history uncertainties of Atlantic bluefin tuna. This work was supported by the NOAA Bluefin Tuna Research Program to compliment the ICCAT MSE. Here we build off a previous analysis that used this MSE framework to evaluate $F_{0.1}$ under stock mixing. Operating models were spatially explicit including two-populations and age structure. Models were initialized from ICCAT perceptions of recruitment, fishing mortality, and observation error independently modeled telemetry-based movement estimates. Alternative operating model scenarios incorporated key uncertainties in natural mortality-at-age, maturity-at-age, and projected recruitment for eastern and western bluefin tuna. We evaluated the status quo management procedure for bluefin tuna, including the current approach to stock assessment (virtual population analysis) and setting catch advice ($F_{0.1}$ management procedure) adopted by ICCAT. Preliminary results indicated that $F_{0.1}$ management produced some medium-term decreases in stock and yield but performed well for maintaining or increasing long-term stock and yield metrics across scenarios. This MSE approach is being used to facilitate workshops to gather input from US fishery stakeholders.

RÉSUMÉ

Une évaluation de la stratégie de gestion (MSE) a été appliquée pour déterminer si une procédure de gestion au niveau de F0,1 résistait aux incertitudes entourant le cycle vital du thon rouge de l'Atlantique. Ce travail a reçu le soutien du Programme de recherche sur le thon rouge de la NOAA afin de compléter la MSE de l'ICCAT. Nous nous sommes basés sur une analyse antérieure qui employait ce cadre de MSE pour évaluer F0,1 dans un cadre de mélange entre les stocks. Les modèles opérationnels étaient spatialement explicites à deux populations et structurés par âge. Les modèles ont été initialisés à partir de l'évaluation de l'ICCAT du recrutement et de la mortalité par pêche et de l'erreur d'observation avec le mouvement modélisé indépendamment utilisant des estimations des déplacements fondées sur la télémétrie. D'autres scénarios du modèle opérationnel incorporaient des incertitudes fondamentales en matière de mortalité naturelle par âge, maturité par âge et recrutement projeté du thon rouge de l'Ouest et de l'Est. Nous avons évalué la procédure de gestion du thon rouge de type statu quo, incluant l'approche actuelle d'évaluation des stocks (analyse de population virtuelle) et appliquant l'avis de capture (procédure de gestion à F0,1) adopté par l'ICCAT. Les résultats préliminaires indiquaient que la gestion à F0,1 entraînait des diminutions à moyen terme du stock et de la production, mais fournit de bons résultats pour maintenir ou augmenter le stock à long terme et les métriques de production des scénarios. Cette approche MSE est utilisée afin de faciliter le déroulement d'ateliers et de recueillir des informations de la part des parties prenantes du secteur de la pêche des États-Unis.

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RESUMEN

Se utilizó una evaluación de estrategias de ordenación (MSE) para determinar si un procedimiento de ordenación de $F_{0,1}$ era robusto ante las incertidumbres sobre el ciclo vital del atún rojo del Atlántico. Este trabajo fue respaldado por el Programa de investigación sobre atún rojo de la NOAA para complementar la MSE de ICCAT. Se basa en un análisis previo que usaba este marco de MSE para evaluar $F_{0,1}$ en el marco de la mezcla de stocks. Los modelos operativos eran espacialmente explícitos e incluían dos poblaciones y estructura por edad. Los modelos se inicializaron a partir de la evaluación de ICCAT de reclutamiento y mortalidad por pesca y el error de observación con el movimiento modelado de forma independiente utilizando estimaciones de movimiento basadas en la telemetría. Escenarios de modelos operativos alternativos incorporaban incertidumbres clave en la mortalidad natural por edad, la madurez por edad y el reclutamiento proyectado para el atún rojo del este y del oeste. Hemos evaluado el procedimiento de ordenación de statu quo para el atún rojo, lo que incluye el enfoque actual de la evaluación del stock (análisis de población virtual) y estableciendo el asesoramiento sobre captura (procedimiento de ordenación $F_{0,1}$) adoptado por ICCAT. Los resultados preliminares indicaron que la ordenación con $F_{0,1}$ producía algunos descensos a medio plazo en el stock y el rendimiento, pero funcionaba bien para mantener o aumentar a largo plazo las mediciones del stock y el rendimiento en los escenarios. Este enfoque de MSE se está utilizando para facilitar talleres que reúnan los comentarios de las partes interesadas de la pesquería de Estados Unidos.

KEYWORDS

Atlantic bluefin tuna, management strategy evaluation, simulation, management procedure

1. Introduction

In recent years, the International Commission for the Conservation of Atlantic Tunas (ICCAT) has embarked on a management strategy evaluation (MSE) process to evaluate the performance of alternative management procedures for Atlantic bluefin tuna in the context of key uncertainties (ICCAT 2019). MSE is a tool that can be used to test the performance of alternative candidate management procedures and allows for evaluation of the biological, economic, and social tradeoffs of different approaches. In an MSE framework, a fish and fishery operating model is simulated, subjected to a candidate management procedure, connected back to the operating model in a closed-loop simulation, and evaluated to determine if management objectives have been achieved. ICCAT is interested in developing a management procedure that achieves ICCAT's key management objectives (e.g., the explicit objective of maximum sustainable yield, the associated requirements of maintaining stocks near B_{MSY} and harvests near F_{MSY}, as well as other desired features, like stability in yield) and is robust to the main sources of uncertainty for Atlantic bluefin tuna. There is uncertainty about several aspects of Atlantic bluefin tuna life history, including recruitment, natural mortality, maturity, movement, and questions as to whether the current ICCAT management based on $F_{0.1}$ is robust to these uncertainties.

ICCAT supported development of a MSE tool for Atlantic bluefin tuna fisheries (Carruthers *et al.* 2015; Carruthers and Kell 2016; Carruthers and Butterworth 2018a, 2018b; ICCAT 2019), and the NOAA Bluefin Tuna Research Program (NOAA BTRP) supported a parallel and complementary effort to develop Atlantic bluefin tuna MSE (Kerr *et al.* 2013, 2015, 2016, 2018; Morse *et al.*, 2017a, 2017b, 2019). The ICCAT MSE is based on operating models that are conditioned on results from a two-stock statistical catch-at-age operating model that is spatially explicit and accounts for movement. Alternate model scenarios test assumptions about maturity, mortality, and future recruitment. Candidate management procedures are also being tested by ICCAT, but the MSE framework does not currently allow for evaluation of the $F_{0.1}$ management procedure used in the most recent stock assessment, because the MSE tool does not include age-based estimation models or management reference points. The NOAA BTRP supported MSE framework that was developed to compliment the ICCAT MSE and was previously applied to evaluate a $F_{0.1}$ management procedure under stock mixing (Morse *et al.* 2019). The major differences between this MSE framework and the ICCAT MSE framework was that this MSE was conditioned on ICCAT (2017) stock assessment results and telemetry-based movement estimates (Galuardi 2018), whereas the ICCAT MSE was conditioned on an integrated model that estimated movement. Here, we expand on previous work using this alternate MSE framework to test the performance of a $F_{0.1}$ management procedure under alternative operating models that differ in their assumptions about natural mortality, western stock maturity, and projected stock-recruitment relationships.

2. Methods

This MSE framework extended previous work developed by Morse *et al.* (2019). The MSE was written in R and applied age-structured operating models informed by the 2017 ICCAT stock assessment (R Core Team 2018, ICCAT 2018). We applied medium-term (20 year) projections in which an observation model generated simulated data and management procedures were applied on three-year management cycles. When testing the $F_{0.1}$ management procedure, simulated data were fit to a Virtual Population Analysis in VPA-2 Box (Porch 2003).

2.1 Operating models

Operating models were specified to have seven geographic zones with quarterly movement informed by fishery-independent satellite tags (Galuardi *et al.* 2018). Movement was constrained to produce natal homing of western population fish to the Gulf of Mexico and eastern population fish to the Mediterranean Sea. Models were initiated in 1974 and consisted of four seasonal quarters within each year. Historic recruitment, fishing mortality-at-age (partitioned into quarter and zone), and initial year abundance-at-age were conditioned on the latest ICCAT stock assessment (ICCAT 2018). Within each operating model, a stock view and a population view were preserved. The stock view was defined as fish being either west or east of the 45°W meridian, and the population view was defined fish as being western or eastern depending on their spawning grounds. Eastern fish followed the Richards model of growth while western fish followed a von Bertalannfy growth model (**Table 1,** Ailloud *et al.* 2017, Cort 1991). We configured eight operating model scenarios in which all combinations of natural mortality-at-age (high and low), western maturity-at-age (young and old), and projected stock-recruitment relationships (low or high) were explored (**Table 2**). High natural mortality-at-age was defined as reaching 0.10 at oldest ages whereas low natural mortality-at-age reached 0.07 at oldest ages (**Table 1**). Young western maturity-at-age was defined as fish all being mature by age 5 and old maturity-at-age consisted of fish being fully mature at age 15 (**Table 1**, Porch and Hanke 2017). Alternate projected stock-recruitment scenarios were fit externally to historic observed recruitment (ICCAT 2018) and effective spawning stock biomass produced from each operating model output. Effective spawning stock biomass was defined as spawning biomass in either the Gulf of Mexico for the West in the first quarter of the year, or the Mediterranean Sea for the Eastern stock in the first quarter of the year. Scenarios with hockey-stick (low) stock-recruitment were fit using the entire historic time period and scenarios with Beverton-Holt (high) stock-recruitment relationship were fit using data from 1988-2015. The hockey-stick stock-recruitment relationship was used to calculate abundance of age 1 fish as:

$$N_{y,a=1,q=1,z,u} = \begin{cases} \dfrac{R_{max,u} SSB_{y,q=1,z,u}}{SSB_u^*}\varepsilon & if\ SSB_{y,q=1,z,u} < SSB_u^* \\ R_{max,u} & if\ SSB_{y,q=1,z,u} > SSB_u^* \end{cases}$$

where $N_{y,a=1,q=1,z,u}$ was the abundance at age 1 in year *y*, quarter q 1, spawning zone *z*, and population unit *u*, $R_{max,u}$ was the asymptotic recruitment for the given population unit *u*; $SSB_{y,q=1,z,u}$ was the SSB for the given year *y*, quarter q 1, spawning zone *z*, and population unit u, SSB_u^* is the SSB hinge point for the given population unit u, and ε was the lognormal variation in recruitment.

Alternatively, when using the Beverton-Holt stock-recruitment relationship numbers of age 1 fish were quantified as:

$$N_{y,a=1,q=1,z,u} = \frac{\alpha SSB_{y,q=1,z,u}}{\beta + SSB_{y,q=1,z,u}}\varepsilon$$

where $N_{y,a=1,q=1,z,u}$ was the abundance at age 1 in year y, quarter q 1, spawning zone z, and population unit u, $SSB_{y,q=1,z,u}$ was the SSB for the given year y, quarter q 1, spawning zone z, and population unit u, α was the maximum number of recruits produced, β was the spawning stock biomass needed to produce recruitment equal to half of α, and ε was the lognormal variation in recruitment.

For each operating model scenario, we generated 100 stochastic simulated data sets that had random normal observation error. These data included catch-at-age, relative age composition with lognormal observation error, and indices of relative abundance. In the historic period there was a total of 27 indices of abundance, whereas in the projection period there was only 10 because they had observations in the terminal year of the historic period (2015) (**Table 3**).

2.2 Management Procedure

The management procedure applied simulated data to the VPA 2-Box stock assessment to derive catch advice based on $F_{0.1}$ for each three-year management cycle. The stock assessment and calculation of $F_{0.1}$ were consistent with Morse *et al.* (2019). These results represent correctly specified 'self-tests' (in which the operating model and estimation model have consistent assumptions) for natural mortality, maturity, and recruitment.

2.3 Performance metrics

We evaluated performance of the $F_{0.1}$ management procedure for eastern and western stocks under each of the eight operating model scenarios. These performance metrics are a subset of those being used in Carruthers (2019) for the ICCAT MSE. Time series of median spawning stock biomass and median yield were evaluated for eastern and western stocks and populations. We explored average stock yield in the first ten years of the projection and the second ten years of the projection. In addition, variability in stock yield was determined by calculating the average annual variation in yield (AAVY) in the projection period:

$$AAVY = \frac{1}{Y-y}\sum_{y}^{Y}\left|C_y - C_{y-1}\right|/C_{y-1}$$

where *Y* is the terminal projection year, *y* is the current year, C_y is yield in year *y*, and C_{y-1} is yield in year *y-1*.

Population depletion (DNC) at the end of the projection period relative to a zero-catch trajectory was evaluated as:

$$DNC_p = \frac{SSB_{p,ymax,F}}{SSB_{p,ymax,F=0}}$$

where $SSB_{p,ymax,F}$ was spawning stock biomass of population *p*, in the terminal projection year *ymax*, under *F* calculated by the management procedure, and $SSB_{p,ymax,F=0}$ was spawning stock biomass of population *p*, in the terminal projection year *ymax*, if zero catch occurred *F= 0.*

Lowest population depletion (LDNC) of the projection period relative to a zero-catch trajectory was calculated as:

$$LDNC_p = \frac{min\left(SSB_{p,F}\right)}{SSB_{p,ymax,F=0}}$$

where $min\left(SSB_{p,F}\right)$ was the minimum spawning stock biomass of population *p*, over the whole projection period, under *F* calculated by the management procedure, and $SSB_{p,ymax,F=0}$ was spawning stock biomass of population *p*, in the terminal projection year *ymax*, if zero catch occurred *F= 0.*

3. Results

Historic and Projected Eastern Population and Stock Trends

The spawning stock biomass (SSB) and yield trajectories of the eastern bluefin tuna resource were similar between the stock and population view over the historic and projection period within an operating model scenario, but the eastern population SSB and yield were consistently greater in magnitude than the eastern stock due to movement of eastern fish into the western stock area (**Figure 1, 2**). Across alternative scenarios of future recruitment, projections that assumed a lower natural mortality-at-age exhibited higher stock and population SSB compared to scenarios with higher natural mortality-at-age (**Figure 1).** Across alternative scenarios, the average SSB of the eastern population/stock was stable at a high level under scenarios of future low recruitment (**Figure 1, left panel**) and projected to increase under scenarios assuming future high recruitment (**Figure 1, right panel**).

Projected eastern stock yields while fishing at $F_{0.1}$ were initially high relative to the most recent years of the historical period (**Figure 2**). High yields in the initial years of the projection period resulted in the initial decline in SSB seen across alternative operating model scenarios (**Figure 1**). Average yields at the end of the projection period (years 10-20) subsequently leveled off to approximately 35,000 to 45,000 mT (across low and high recruitment scenarios) under scenarios of low natural mortality and approximately 25,000 to 30,000 mT (low and high recruitment scenarios) in scenarios of high natural mortality (**Figure 2, 3**). Inter-annual variation in yield was highest under scenarios of high natural mortality and high projected recruitment (**Figure 4**). Relative to the zero-catch trajectory, eastern bluefin tuna population SSB was depleted at the end of the projected management procedure application period with the lowest depletion levels under operating model scenarios that assumed high natural mortality-at-age and older western maturity-at-age (**Figure 5**).

Historic and Projected Western Population and Stock Trends

Across scenarios, the SSB and yield of the western bluefin tuna stock were considerably greater than the population over the historic and projected period, due to the influx eastern origin fish into the western stock area (**Figure 1 and 2**). Historic and projected trajectories also differed based on assumptions of maturity-at-age and natural mortality-at-age with higher SSB and yield under the assumption of younger maturity-at-age for western origin bluefin tuna and lower natural mortality-at-age (**Figure 1 and 2**). Projections of the western resource while fishing at $F_{0.1}$ resulted in stable SSB of the western population/stock under scenarios of future low recruitment (**Figure 1**) and projected increases in SSB under scenarios assuming future high recruitment (**Figure 1**). Projections that assumed a lower natural mortality-at-age, younger maturity-at-age and high recruitment exhibited the highest SSB values at the end of the projection period (**Figure 1**).

Similar to eastern population/stock yields, projected western population/stock yields were initially high in the most recent years of the historical period under the $F_{0.1}$ management strategy (**Figure 2**). High yields in the initial years of the projection period resulted in the slight initial decline in western bluefin tuna SSB (**Figure 1**). Average stock yields ranged from approximately 6,000 to 10,000 mT across scenarios of low/high natural mortality-at-age and young/old maturity-at-age across the projection period (**Figure 2, 3**). Average population yields in the projection period were approximately 2,500 mT across alternative scenarios (**Figure 2, 3**). Inter-annual variation in yield was highest under scenarios of high natural mortality-at-age and high projected recruitment (**Figure 4**). Relative to the zero-catch trajectory, western bluefin tuna population SSB was always depleted at the end of the projected management procedure application period with the lowest depletion levels under operating model scenarios that assumed high natural mortality and older maturity at age (**Figure 5**).

4. Discussion

MSE is a powerful tool that allows us to evaluate whether candidate management procedures are robust to life history uncertainty and to quantify whether management objectives are being met. As expressed by ICCAT MSE efforts and supported by US bluefin tuna stakeholder workshops, management objectives center around achieving maximum yield while reducing variability in yield and maintaining sustainable levels of biomass. Alternative operating model assumptions, including natural mortality-at-age, maturity-at-age, and future stock-recruitment relationships, had significant implications on the perceptions of spawning stock biomass and yield for the eastern and western bluefin tuna stocks and populations. Our results suggest that a management procedure based on a target F of $F_{0.1}$ produced some short-term and medium-term decreases in stock and yield but performs well for maintaining or increasing long-term stock and yield metrics with relatively low inter-annual variability. Fishing at $F_{0.1}$ for Atlantic bluefin tuna in the medium-term future resulted in high levels of depletion for eastern and western bluefin tuna populations relative to zero catch. Overall, performance metrics were relatively robust to the major uncertainties identified in recent stock assessments across scenarios.

Future work using this MSE framework will include evaluating additional alternate operating models, index-based management procedures, and incorporating feedback from stakeholder workshops. Additional operating model scenarios will evaluate reduced movement rates from the current movement transition matrix and time-varying movement. This MSE framework can evaluate model-based management procedures such as $F_{0.1}$, as well as index-based management procedures. We will test our alternative scenarios under index-based management procedures using indices such as the US larval index and Mediterranean larval index. Project collaborators have worked to present MSE concepts and this framework to US bluefin tuna stakeholders to elicit feedback on model scenarios, management procedures, and performance metrics. Future workshops will be focused on presenting results and tradeoffs of alternative candidate management procedures.

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Table 1. Operating models parameterizations.

<table>
<tr><td colspan="8">West</td><td colspan="9">East</td></tr>
<tr><td colspan="17">Length-weight relationship (Rodriguez-Marin et al. 2015)</td></tr>
<tr><td colspan="4">a</td><td colspan="4">0.0000177054</td><td colspan="4">a</td><td colspan="5">0.0000350801</td></tr>
<tr><td colspan="4">b</td><td colspan="4">3.001251847</td><td colspan="4">b</td><td colspan="5">2.878451</td></tr>
<tr><td colspan="17">Length-at-age (Ailloud et al. 2017, Cort 1991)</td></tr>
<tr><td colspan="8">Richards</td><td colspan="9">Von Bertalanffy</td></tr>
<tr><td colspan="4">L_1</td><td colspan="4">33</td><td colspan="4">K</td><td colspan="5">0.093</td></tr>
<tr><td colspan="4">L_2</td><td colspan="4">270.6</td><td colspan="4">L_∞</td><td colspan="5">319</td></tr>
<tr><td colspan="4">p</td><td colspan="4">-0.12</td><td colspan="4">t_0</td><td colspan="5">-0.97</td></tr>
<tr><td colspan="4">A_1</td><td colspan="4">0</td><td colspan="4"></td><td colspan="5"></td></tr>
<tr><td colspan="4">A_2</td><td colspan="4">34</td><td colspan="4"></td><td colspan="5"></td></tr>
<tr><td colspan="4">K</td><td colspan="4">0.22</td><td colspan="4"></td><td colspan="5"></td></tr>
<tr><td colspan="17">Mortality-at-age</td></tr>
<tr><td>Age</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16+</td></tr>
<tr><td>low</td><td>0.36</td><td>0.27</td><td>0.21</td><td>0.17</td><td>0.14</td><td>0.12</td><td>0.11</td><td>0.10</td><td>0.09</td><td>0.09</td><td>0.08</td><td>0.08</td><td>0.08</td><td>0.08</td><td>0.07</td><td>0.07</td></tr>
<tr><td>high</td><td>0.38</td><td>0.30</td><td>0.24</td><td>0.20</td><td>0.18</td><td>0.16</td><td>0.14</td><td>0.13</td><td>0.12</td><td>0.12</td><td>0.11</td><td>0.11</td><td>0.11</td><td>0.10</td><td>0.10</td><td>0.10</td></tr>
<tr><td colspan="17">Maturity-at-age (Porch and Hanke 2018)</td></tr>
<tr><td>Age</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16+</td></tr>
<tr><td>young</td><td>0</td><td>0</td><td>0.25</td><td>0.5</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>old</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0.0001</td><td>0.007</td><td>0.039</td><td>0.186</td><td>0.563</td><td>0.879</td><td>0.976</td><td>0.996</td><td>0.999</td><td>1</td><td>1</td></tr>
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Table 2. Alternative model scenarios evaluated using high or low natural mortality-at-age, old or young western maturity-at-age, and high or low projected stock-recruitment relationship.

			Operating Model		Estimation Model	
Population/Stock			**Historic**	**Projection**	**Historic**	**Projection**
WEST	**Scenario 1**	Maturity	young	young	young	young
		Mortality	low	low	low	low
		Recruitment	Deterministic	low	NA	NA
	Scenario 2	Maturity	old	old	old	old
		Mortality	low	low	low	low
		Recruitment	Deterministic	low	NA	NA
	Scenario 3	Maturity	young	young	young	young
		Mortality	high	high	high	high
		Recruitment	Deterministic	low	NA	NA
	Scenario 4	Maturity	old	old	old	old
		Mortality	high	high	high	high
		Recruitment	Deterministic	low	NA	NA
	Scenario 5	Maturity	young	young	young	young
		Mortality	low	low	low	low
		Recruitment	Deterministic	high	NA	NA
	Scenario 6	Maturity	old	old	old	old
		Mortality	low	low	low	low
		Recruitment	Deterministic	high	NA	NA
	Scenario 7	Maturity	young	young	young	young
		Mortality	high	high	high	high
		Recruitment	Deterministic	high	NA	NA
	Scenario 8	Maturity	old	old	old	old
		Mortality	high	high	high	high
		Recruitment	Deterministic	high	NA	NA
Population/Stock	**Scenario 1**	Maturity	young	young	young	young
EAST		Mortality	low	low	low	low
		Recruitment	Deterministic	low	NA	NA
	Scenario 2	Maturity	young	young	young	young
		Mortality	high	high	high	high
		Recruitment	Deterministic	low	NA	NA
	Scenario 3	Maturity	young	young	young	young
		Mortality	low	low	low	low
		Recruitment	Deterministic	high	NA	NA
	Scenario 4	Maturity	young	young	young	young
		Mortality	high	high	high	high
		Recruitment	Deterministic	high	NA	NA

Table 3. ICCAT 2017 stock assessment (ICCAT 2018) indices and whether they were used in the historic and projection periods of the operating models (OM) (from Morse *et al.* 2019).

Index	**Historic OM**	**Projected OM**
CAN_Combined_RR		
CAN_GSL_Acoustic	X	X
US_RR<145	X	
US_RR_66-144	X	X
US_RR_115-144	X	X
US_RR_145-177		
US_RR>195	X	
US_RR>195_COMB		
US_RR>177		
JLL_AREA_2_(WEST)	X	
LARVAL_ZERO_INFLATED	X	X
GOM_PLL_1-6	X	X
JLL_GOM	X	
TAGGING		
JLL_RECENT	X	X
MOR_SP_TP	X	
MOR_POR_TP	X	X
JPN_LL_EastMed	X	
JPN_LL1_NEA	X	
JPN_LL2_NEA	X	X
SP_BB1	X	
SP_BB2	X	X
FR_AER1	X	
FR_AER2	X	X
WMED_LARV	X	X

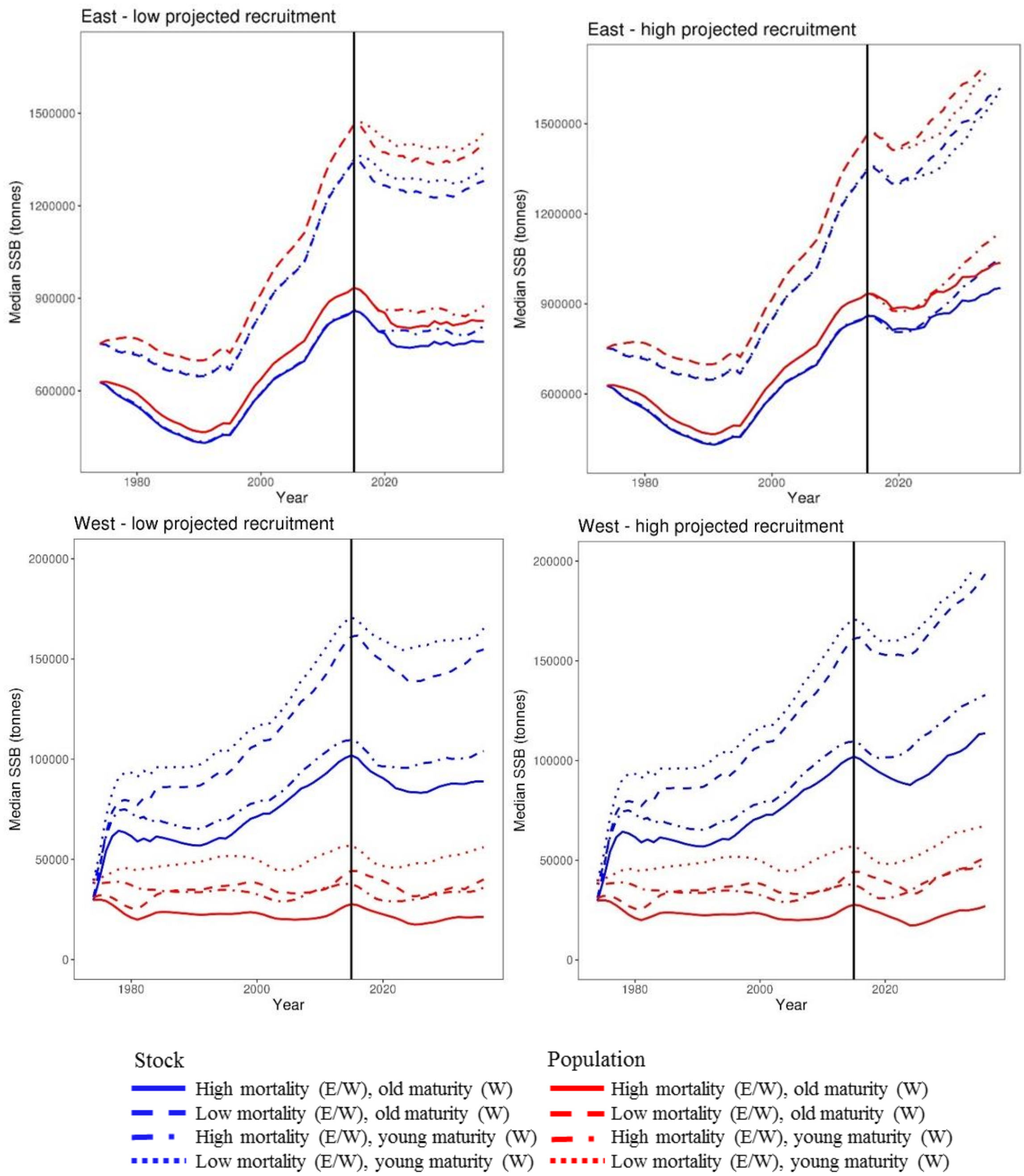

Figure 1. Median western (W) and eastern (E) stock and population spawning stock biomass for 100 realizations of each scenario. Low projected recruitment indicates models fit using a hockey-stick stock-recruitment relationship and high projected recruitment represents models fit using a Beverton-Holt stock-recruitment relationship. Blue lines indicate stock values, red lines indicate population values, and solid black line indicates start of the projection time period.

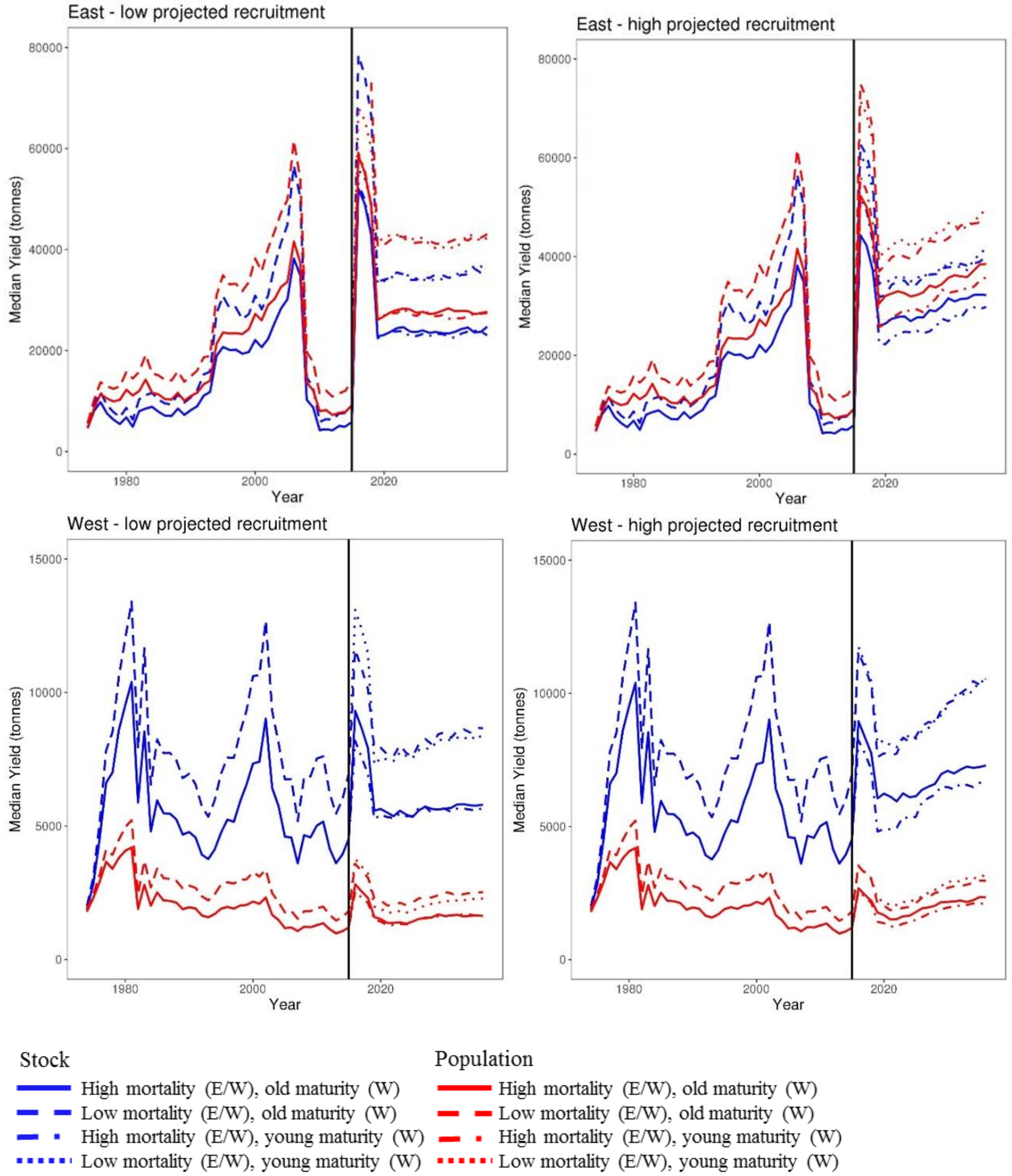

Figure 2. Median western (W) and eastern (E) stock and population yield for 100 realizations of each scenario. Low projected recruitment indicates models fit using a hockey-stick stock-recruitment relationship and high projected recruitment represents models fit using a Beverton-Holt stock-recruitment relationship. Blue lines indicate stock values, red lines indicate population values, and solid black line indicates start of the projection time period.

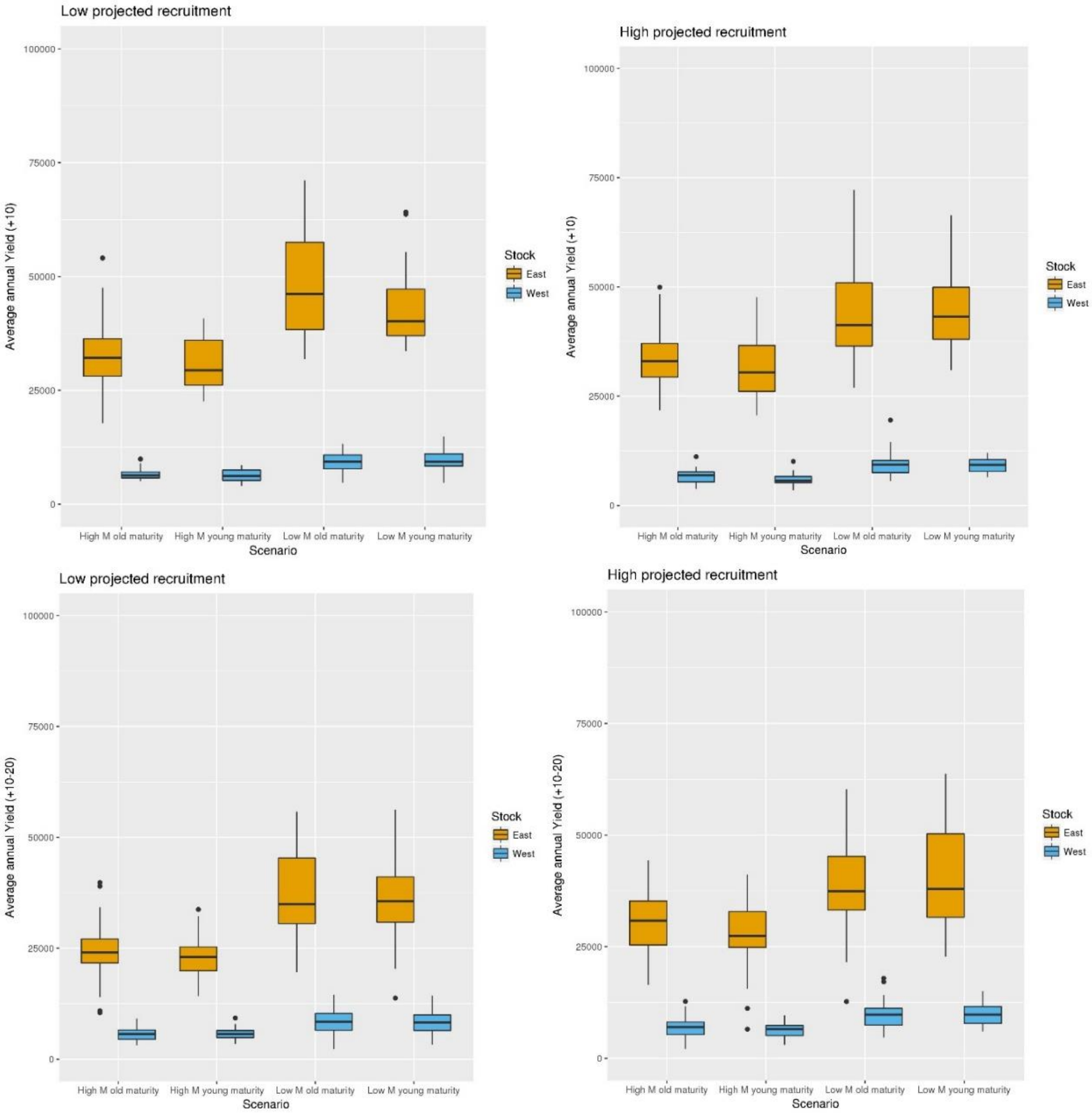

Figure 3. Average yield in the first ten projection years and average yield in the second ten projection years for all operating model scenarios.

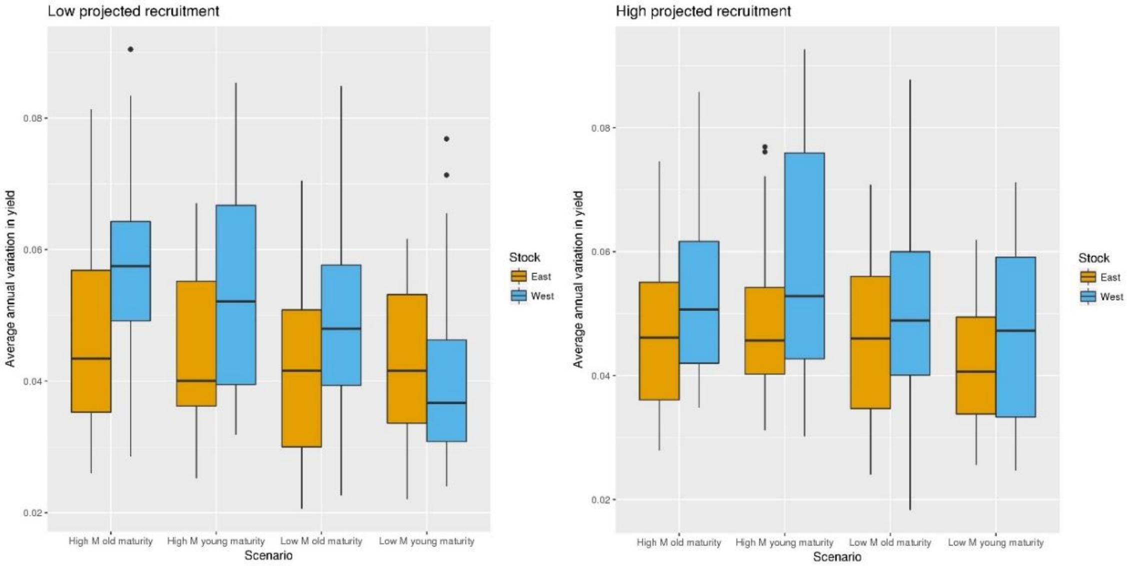

Figure 4. Average annual variation in yield for eastern and western stocks under alternate operating model scenarios.

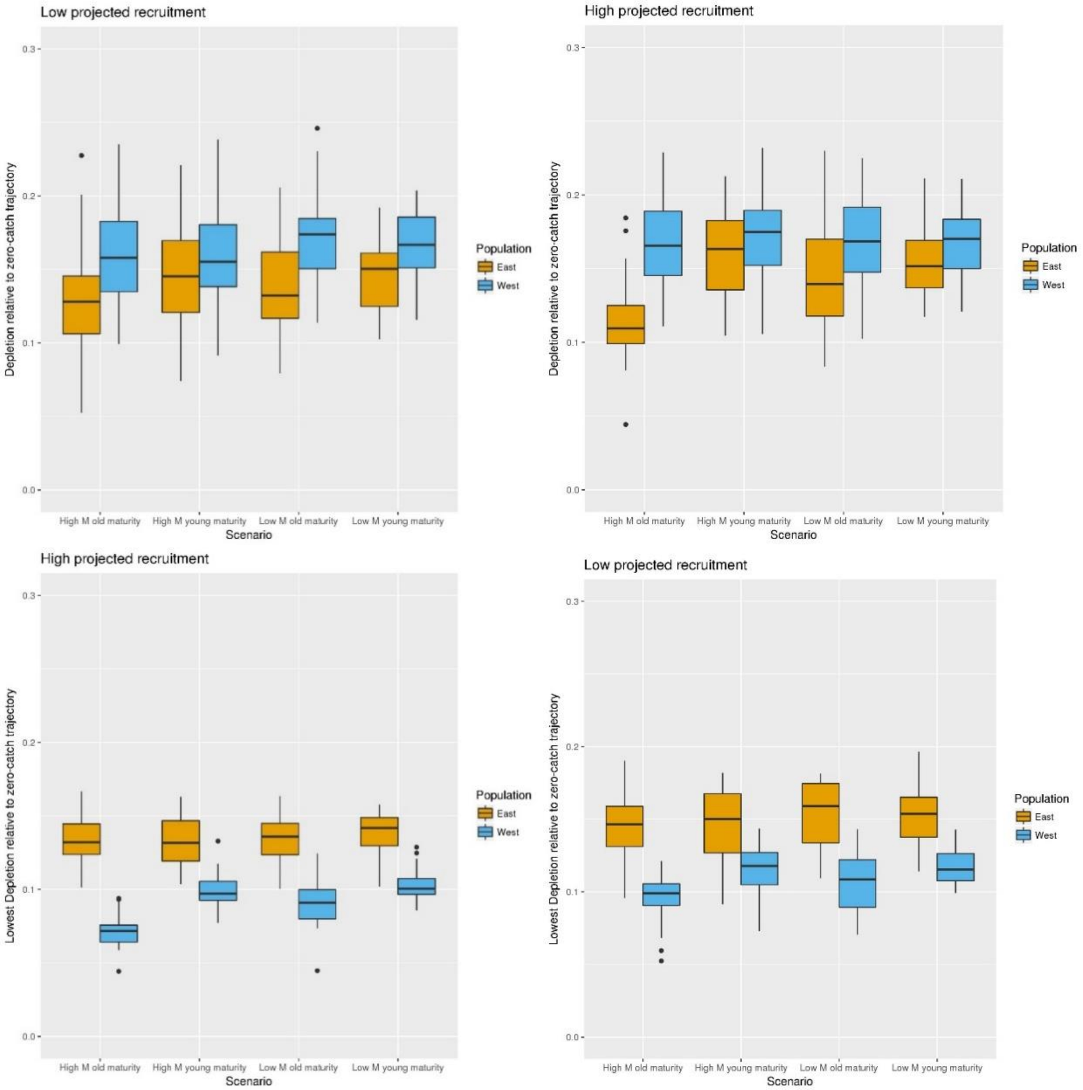

Figure 5. Depletion relative to zero-catch and lowest depletion over the projection period relative to zero-catch for eastern and western populations under all scenarios.