2022

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Recommended Citation

Peterson, Cassidy D.; Wiberg, Michael J.; Cortez, Eric; Courtney, Dean; and Latour, Robert J., Effects of Altered Stock Assessment Frequency on the Management of a Large Coastal Shark (2022). *Marine and Coastal Fisheries*, 14(5), e10221.
doi: 10.1002/mcf2.10221

Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 14:e10221, 2022

ISSN: 1942-5120 online
DOI: 10.1002/mcf2.10221

ARTICLE

Effects of Altered Stock Assessment Frequency on the Management of a Large Coastal Shark

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Abstract

Stock assessments are particularly resource-intensive processes. Demand for assessments typically exceeds capacity, stimulating interest in reducing stock assessment frequency for suitable species. Species with slow population growth rates, low economic importance, and low recruitment variability, like coastal sharks in the USA, have been identified as appropriate candidates for long-interim assessment periods. We conducted a Stock Synthesis–based management strategy evaluation with a threshold harvest rate control rule within the southeastern USA to assess the impact of stock assessment frequency for the slow-growing Sandbar Shark *Carcharhinus plumbeus*. Stock assessments for the Sandbar Shark in the southeastern USA have been conducted or updated every 4–6 years since 1998. The Sandbar Shark proved to be a particularly good candidate species for reduced assessment frequency, as noted by unaffected management procedure performance across interim periods of 1, 5, and 10 years. Management objectives, including probability of stock recovery, relative biomass level, cumulative U.S. commercial catch, and probability of overfishing, were minimally adversely impacted with interim periods equal to 15 years. Based on our findings, assessment frequency for large coastal shark species could reasonably be reduced in the future to once every 10 or more years without compromising management success.

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Received December 17, 2021; accepted July 20, 2022

In the USA, the reauthorization of the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006 includes a requirement for annual catch limits to be set for all federally managed fisheries (included in National Standard 1), heightening the demand for scientifically derived management advice, namely through stock assessments (Methot 2015). Stock assessments are costly and time consuming, requiring extensive scientific monitoring of abundance, fish biology, and catch and the expertise of limited and highly skilled analysts (NMFS 2001; Lynch et al. 2018). Within the federal U.S. management system, stock assessment processes are particularly costly endeavors, and the cost is estimated to be even higher in the Southeast region (R. Merrick and R. Methot, 2016 presentation to the North Pacific Fisheries Management Council, on the cost of stock assessments). High demand can potentially strain assessment scientists, who could alternatively be assessing underassessed and/or data-limited species or conducting research critical to the advancement of stock assessment methodology and fisheries management (Lynch et al. 2018).

Given that the demand for stock assessments currently outstrips capacity to conduct them, reducing stock assessment frequency is of interest as a mechanism to reduce costs and/or free up resources to assess additional species (e.g., ICES 2012; Methot 2015; Lynch et al. 2018). Historically, more commercially valuable species and species that comprise large proportions of landed catch have been preferentially assessed (Lynch et al. 2018; Neubauer et al. 2018). Larger-bodied and demersal species are also assessed more frequently, while certain taxonomic groups, including elasmobranchs (particularly order Carcharhiniformes), rockfishes *Sebastes* spp., and flatfishes (order Pleuronectiformes), are assessed more frequently than other groups of comparable commercial economic value (Neubauer et al. 2018).

Previous research on optimal assessment frequency is limited and conflicting. In certain circumstances, reduced assessment frequency has been shown to be viable, without resulting in substantial reductions to catch or biomass (Marchal 1997; Kell et al. 1999; Zimmermann and Enberg 2017; Huynh et al. 2020) or reducing catch variability, where catch remains constant between assessments (Sylvia 2015). Contrarily, others have cautioned against multiyear interim assessment periods since less frequent assessments may result in increased risk of an overfished stock and reduced yields (Marchal and Horwood 1995; Sylvia 2015; Li et al. 2016; Wiedenmann et al. 2017; Huynh et al. 2020), reduced economic value of the fishery (Marchal 1997; Hutniczak et al. 2019), and more variable yield (Marchal and Horwood 1995; Li et al. 2016). The negative impacts of less frequent stock assessments are reduced in stocks with a *K*-selected life history strategy (Sylvia 2015; Huynh et al. 2020), higher productivity (Li et al. 2016), higher target stock size (Marchal and Horwood 1995), and lower target fishing mortality (Li et al. 2016).

The potential benefits of reduced assessment frequency are heightened when considering that not all stocks need to be assessed annually to produce reliable management advice (Methot 2015; Lynch et al. 2018). While not all stocks are suitable for multiannual assessment interim periods, those that are have robust assessments, modest exploitation, and extended biological longevity (ICES 2012). Additionally, stocks for which management is weakly influenced by assessments, subject to particularly noisy data, or for which limited new information is generated each year would be acceptable candidates for nonannual assessments (ICES 2012). Within the USA, species that are not commercially or recreationally valuable and that do not exhibit strong annual fluctuations in abundance should be considered lower priority with respect to stock assessment frequency (Lynch et al. 2018). Following guidance from Methot (2015) on target assessment frequency, longer-lived species with relatively low recruitment variability and low economic and ecosystem importance should be assessed less frequently, with interim periods of up to 10 years. These stock characteristics, combined with others including stock status, relative biomass and relative fishing mortality (including target and incidental), unexpected changes in stock indicators, newly available information, and the number of years the assessment is overdue, should be used to prioritize assessment activities (Methot 2015). Ultimately, application of an appropriately parameterized harvest control rule (HCR) with a sufficient buffer and reducing delays in management action may have a greater impact in maintaining appropriate biomass and fishing mortality targets than increasing the frequency of stock assessments (Marchal and Horwood 1995; Sylvia 2015; Wiedenmann et al. 2017).

Even if a stock is considered a suitable candidate for reduced assessment frequency, the effects of assessment frequency on a fishery should be evaluated using management strategy evaluation (MSE; ICES 2012; Methot 2015; Li et al. 2016). Management strategy evaluation is a framework in which candidate management procedures are tested using closed loop simulation (Punt et al. 2016). Accordingly, application of MSEs to measure the effect of assessment frequency on several reference stocks should be prioritized (Methot 2015). Yet to date, relatively few studies have assessed the effects of altered assessment frequency (Sylvia 2015; Hutniczak et al. 2019), and additional research has been requested (ICES 2012; Methot 2015; Li et al. 2016; Zimmermann and Enberg 2017; Lynch et al. 2018). In this study, we evaluate the effect of stock assessment frequency for a representative, slow-growing, coastal shark using MSE.

METHODS

Study species.— Sandbar Shark *Carcharhinus plumbeus* is a large coastal shark with a low intrinsic population growth rate (Au et al. 2015) that comprises a single stock within the U.S. Atlantic Ocean and Gulf of Mexico (Heist et al. 1995). Median age at maturity is 13 years, longevity is estimated to be 31 years, and the reproductive cycle is considered to be 2.5 years for stock assessment purposes (Baremore and Hale 2012; SEDAR 2017). The U.S. stock of Sandbar Shark was overfished in the 1980s due to a lack of regulations and has shown early signs of recovery following federal management regulations implemented in the early 1990s (Peterson et al. 2017; SEDAR 2017).

Exploitation of this stock is assumed to have started at very low levels in the early 1960s and progressively increased from the early 1980s to the early 1990s, after which catches decreased. The main fisheries involved were commercial bottom longline and recreational hook and line, with additional contributions of Mexican artisanal fisheries and a very low level of bycatch in the Gulf of Mexico fishery for Menhaden *Brevoortia patronus* Combined U.S. recreational and Mexican fisheries dominated catches from the late 1970s to the late 1980s, after which the contribution of the commercial longline fisheries in both the Atlantic Ocean and Gulf of Mexico were also important from the early 1990s to 2000. After 2000, the contribution of the recreational and Mexican components to the overall catches declined, whereas commercial catches remained relatively more important until 2008, when additional management measures were introduced and the commercial fishery became a research-only fishery, while the recreational and Mexican fisheries became proportionally more important (SEDAR 2017).

The stock's current fishing mortality rate is less than the maximum threshold (i.e., is not experiencing overfishing), but the stock is below its biomass threshold (i.e., overfished). The stock is consequently under a rebuilding plan, where commercial and recreational harvest is prohibited outside a designated research fishery (SEDAR 2017). The rebuilding plan was based on a 2006 stock assessment (SEDAR 2006) wherein stock projections with zero fishing mortality led to a 70% probability of the stock not being overfished by 2041. One generation time was added to 2041, following federal guidelines when rebuilding time is necessarily greater than 10 years (MSA 2007), to establish a rebuilding timeline for the Sandbar Shark of 2070. The Sandbar Shark was first assessed both as part of the large coastal shark complex and individually in 1998 (NMFS 1998) and later in 2002 (Cortés et al. 2002). It was subsequently assessed through the SouthEast Data, Assessment, and Review (SEDAR) process in 2006, 2011 (SEDAR 2011), and 2017 (SEDAR 2017).

Management strategy evaluation.— An MSE is an approach to simulate the performance of various management procedures to identify those management procedures that are robust to uncertainty and that best maximize the management objectives of the fishery (Punt et al. 2016). The MSEs are comprised of (1) a series of operating models that simulate the true dynamics of the stock and that reflect the important uncertainties in the stock and fishery; (2) the data-generating or observation model, which simulates the process of collecting data; (3) an estimating model to assess the status of the stock; (4) an HCR that actively scales catch advice based on the status or trajectory of the stock; and (5) an implementation model, which simulates the process of scientifically proposed catch advice being translated into management advice and the inherent implementation error (Figure 1; De Oliveira et al. 2008; Holland 2010). Management procedures are defined by the data-generation, estimating model, HCR, and implementation model processes (Sainsbury et al. 2000).

We applied an MSE using Stock Synthesis (version 3.30.15; Methot and Wetzel 2013; Methot et al. 2020) to the Sandbar Shark to explore the long-term impacts of varied stock assessment frequency on the status of the stock. The approach employed (modified from Peterson et al. 2022) is based on the Maunder (2014) MSE applied to Pacific Bluefin Tuna *Thunnus orientalis*. The simulation

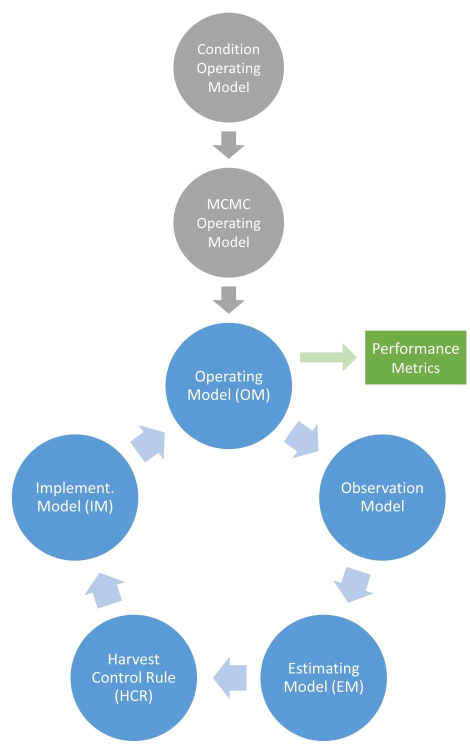

FIGURE 1. Diagram of the management strategy evaluation process, starting with conditioning of the operating models to observed data, Markov chain–Monte Carlo (MCMC) resampling of conditioned operating models to generate multiple iterations with uniquely applied process error, the cycle of applying a management procedure (comprised of the observation model, estimating model, harvest control rule, and implementation model) to the operating model repeatedly throughout the simulation period and noting that performance metrics are obtained from the operating model.

was built in R (version 3.6.3; R Core Team 2020) and Stock Synthesis. Wrapper R code is available via https://github.com/cassidydpeterson/SS_MSE_AssessmentFrequency. The simulated time horizon was 100 years, and each sensitivity scenario was run for 100 iterations. Interim assessment frequency varied among 1, 5, 10, or 15 years.

Operating and data-generating models.— A Stock Synthesis assessment model based on SEDAR (2017) served as the foundation of our operating models, which included two sexes, four fishing fleets, and two surveys (Figures S1–S5 in the Supplement available separately online). Multiple operating models were developed to fully encapsulate the impacts of uncertainty on assessment frequency. Our base operating model reflected current estimates of natural mortality (M), steepness (h), and virgin recruitment (R_0) and included a low-fecundity stock–recruitment (LFSR) relationship (Taylor et al. 2013). The LFSR relationship makes a different assumption regarding the density-dependent compensatory mechanism, inherently assuming that offspring survival would decrease at high biomass levels, which is a more appropriate assumption for internally fertilizing species, like sharks (Taylor et al. 2013). The effect of assuming an LFSR instead of a Beverton–Holt (BH) stock–recruitment relationship was found to be reduced stock productivity and higher biomass that supports removal of maximum sustainable yield (B_{MSY}; Peterson et al. 2022). In addition to (1) the base operating model (OM_Base), alternative operating model configurations included (2) a BH stock–recruitment relationship (OM_BH), (3) high h (OM_Hih), (4) low h (OM_Loh), (5) high R_0 (OM_lnR0), and (6) reduced M with BH stock–recruitment relationship (OM_M_BH; Table 1). The altered assumptions of each operating model were conditioned on available data to ensure projections would be consistent with historical data (see Supplementary Materials for more information on model formulation).

Additional complexity was added to each operating model by inducing time-varying catchability and selectivity (implemented through zero-reverting random walks) and time-invariant error in growth and stock–recruitment parameters (excluding scenarios where steepness was fixed). The modeling time frame was extended to be the length of the simulation time horizon, which was 100 years beyond observed dynamics in this study. We placed informative priors, selected based on operating model conditioning, on all estimated quantities (see Supplementary Materials for more information on model formulation) and used ADMB's Markov chain–Monte Carlo resampling algorithm to generate realistic parameterizations of the operating model with process uncertainty (Monnahan et al. 2014).

Stock Synthesis's parametric bootstrapping protocol (Methot et al. 2020) was used as the data-generating process by adding uncertainty to expected values of survey index observations, length-frequency compositions, and commercial catches in future years. Catch and survey standard errors and effective sample sizes of length frequency observations needed to be manually specified along with commercial catch as determined from the HCR. The observed data produced from the data-generating process were added to the estimating model in each time step.

Estimating model.— The estimating model was a simpler model than the operating model because assessment models are simplifications of the true stock dynamics. The estimating model reflected the configuration of the most recent assessment model used in practice, which assumed a BH stock–recruitment relationship and followed the OM_BH conditioning operating model formulation (SEDAR 2017). The estimating model also assumed selectivity and catchability were time invariant and life history parameters were fixed, including recruitment parameters. Catchability coefficients were numerically calculated, while virgin recruitment along with 19 of 38 selectivity parameters were estimated (see Supplementary Materials for more information on model formulation). The frequency of the estimating model varied from every year to every 15 years

TABLE 1. List of six operating models with associated levels of relevant parameters. Abbreviations are as follows: M is natural mortality, h is steepness, $\ln(R_0)$ is the natural logarithm of virgin recruitment, and S-R is the form of the stock–recruitment relationship. Note that the operating model with ½ M produced a nonsensical yield–biomass curve when low-fecundity stock–recruitment (LFSR) was specified; consequently, we chose to apply the Beverton–Holt (BH) stock–recruitment function to this operating model scenario. "Current" denotes that the model assumed the estimated value from the most recent stock assessment (SEDAR 2017).

	Operating models					
Parameters	OM_Base	OM_BH	OM_Hih	OM_Loh	OM_lnR0	OM_M
M	Current	Current	Current	Current	Current	½ current
h	$h = 0.3$	$h = 0.3$	$\uparrow h = 0.4$	$\downarrow h = 0.25$	$h = 0.3$	$h = 0.3$
R_0	Current	Current	Current	Current	2 × Current	Current
S-R	LFSR	BH	LFSR	LFSR	LFSR	BH

(interim frequency of 1, 5, 10, or 15 years). The forecast module was turned off, and all HCR and implementation model steps were coded in R.

Harvest control rule.— Biomass-based HCRs are variations of threshold HCRs, wherein one or more biomass-defined breakpoints are identified at which the control rule changes. Typical shifts in the control rule include ramps in allowable F or setting catch equal to zero (Deroba and Bence 2008; Punt 2010). We built a biomass-based HCR, which was used to identify target harvest rate at a given biomass level (Figure 2):

$$F = \begin{cases} 0 & B < a \\ F_{\mathrm{lim}}\left(\frac{B-a}{b-a}\right) & a \le B \le b \\ F_{\mathrm{lim}} & b < B \end{cases}, \quad (1)$$

where F is the HCR-defined fishing mortality rate, B is current stock biomass, F_{lim} is the maximum-limit fishing mortality rate, and b and a are parameters dictating the biomass below which F declines or is set to zero, respectively. In this application, the HCR was parameterized to have threshold biomass parameters $a=0$ and $b=\mathrm{SSB}_{\mathrm{MSY}}$ (spawning stock biomass at which the stock would produce maximum sustainable yield [MSY]), and $F_{\mathrm{lim}}=F_{\mathrm{MSY}}$ (fishing mortality rate that would lead to the stock reaching a biomass that would produce MSY).

Implementation model.— The Sandbar Shark fishery is assessed assuming four fleets: (1) Gulf of Mexico U.S. commercial fishery, (2) South Atlantic Ocean U.S. commercial fishery, (3) combined removals from the U.S. recreational fishery and the Mexican fishery (MexRec fishery), and (4) dead discards from the Gulf of Mexico menhaden fishery (SEDAR 2017). Because Mexican catches are not directly managed through U.S. quota designation, a portion of the catches within the U.S. Sandbar Shark fishery are not controlled by the management procedure (Mexican removals from the MexRec fleet). Consequently, the future MexRec removals were considered as an additional source of uncertainty. Three implementation models (Figure 3) were generated to reflect this uncertainty: (1) a HiMexRec scenario, where MexRec removals increased with increasing biomass consistent with the historical observations between 1995 and 2013, (2) a LoMexRec scenario, where catches were assumed to remain constant (with annual variability) around the constant low level observed between 2008 and 2013, and (3) a conceptual scenario, where MexRec catches were subjected to the annual catch limits designated by the HCR.

In each implementation model, the allowable catch was set equal to the catch that would be obtained by fishing at the HCR-defined F. In the HiMexRec and LoMexRec implementation scenarios, following current practice, 58 metric tons was subtracted from the allowable catch to obtain the annual catch limit, accounting for anticipated removals from the recreational fishery and commercial dead discards (SEDAR 2017). In the conceptual

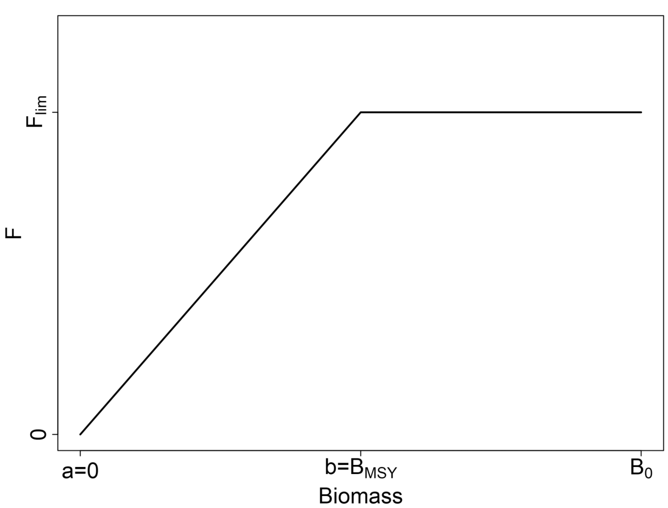

FIGURE 2. Form of the threshold harvest control rule, where F_{lim} is the maximum prescribed fishing mortality rate (F), a is the threshold biomass below which prescribed $F=0$, and b is the threshold biomass below which prescribed F is reduced. The parameterization in the current study followed $F_{\mathrm{lim}}=F_{\mathrm{MSY}}$, $a=0$, and $b=\mathrm{SSB}_{\mathrm{MSY}}$, or the spawning stock biomass that would produce maximum sustainable yield.

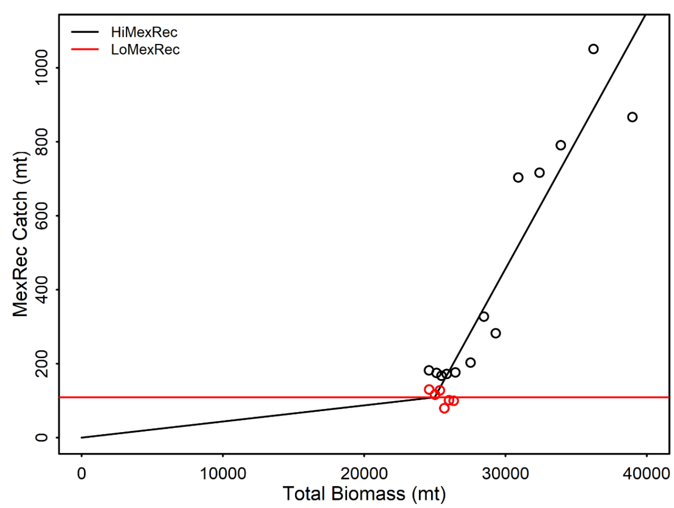

FIGURE 3. Historical relationship (1995–2013) of observed Mexican and U.S. recreational (MexRec) catches and total Sandbar Shark stock biomass. Points plotted in black represent observations from the years 1995 to 2007, and red points are observations between the years 2008 and 2013. The superimposed lines demonstrate the alternate simulated relationships between MexRec catches with biomass (black line represents the "HiMexRec" implementation scenario, while the red line represents the "LoMexRec" implementation scenario). Catches below the average catch between years 2008 and 2013 were linearly ramped to zero in the HiMexRec case to ensure that removals were still taken at low biomass levels (e.g., to account for the negative intercept).

implementation scenario, the allowable catch was set equal to the annual catch limit and half of the annual catch limit was partitioned to the MexRec fishery and half to the U.S. commercial fishery, where the designation of half for each fishery was arbitrary. U.S. commercial allocations were simulated following a beta distribution defined by fitting to the historical data. Future simulated menhaden fishery catches were determined by assuming that dead discards increased with biomass following a fitted linear regression to the historical time series.

The operating model was updated every year to ensure that the nonmanaged catch (e.g., MexRec catches within the HiMexRec and LoMexRec implementation model scenarios) was consistent across management procedures; otherwise, altered assessment frequency scenarios would not be directly comparable. In all implementation scenarios, the annual catch limit was constant between assessment years. Lognormal implementation uncertainty was added following historical mismatch between total allowable catch and observed catch from the years 2008–2019 (Figure S6). Empirically calculated relationships between fishery catch and/or biomass and effective sample size of length composition data were propagated into the future.

Management objectives and assessment frequency analysis.— For the purposes of this desk MSE (i.e., MSE with no stakeholder input), the management objectives of interest were obtained from the most recent stock assessment report (SEDAR 2017), the Atlantic Highly Migratory Species Fishery Management Plan (NMFS 2006), and MSE best practices (Punt et al. 2016). Highlighted management objectives included the probability of stock recovery to the minimum stock size threshold by 2,115 (defined as $SSB_{2115} \geq 87\%\ SSB_{MSY}$, where 87% SSB_{MSY} represents the minimum stock size threshold (MSST) for Sandbar Sharks following the definition $MSST = (1 - M) \times B_{MSY}$, where $M = 0.13$), the relative stock biomass in the terminal year of the simulation (SSB_{2115}/SSB_{MSY}), total U.S. commercial catch, and the probability of overfishing across the simulation period (calculated by summing the number of years in which $F > F_{MSY}$ divided by the 100 years in the simulation horizon). Because the operating model used for the simulation projections was not fitted or estimating any parameters, operating-model-based fishery reference points (e.g., SSB_{MSY} and F_{MSY}) were obtained based on conditioning operating model models for the year 2015.

To assess the impact of altered stock assessment frequency on the management objectives of the Sandbar Shark fishery, we applied a series of generalized linear models to the MSE results, where the response variables were resulting performance statistics, including probability of recovery, terminal relative spawning stock ratio, total U.S. commercial catch, and probability of overfishing. Covariates included assessment frequency as a categorical covariate, implementation model, operating model, and interactions between covariates. Optimal models were selected following the information theoretic approach (Akaike information criterion [AIC]; Akaike 1973).

RESULTS

We define management procedure performance according to resulting management objectives as observed from the operating models. Recall that management advice is generated from the estimating model, which does not necessarily match the simulated stock dynamics generated by the operating model. Further, note that results are presented relative to static reference points calculated for the year 2015 during the operating model conditioning step. We further emphasize that the purpose of an MSE is not an in-depth analysis of the predictions of each operating model, but rather to test the comparative performance of each management procedure across the operating model grid. As such, management procedure performance was measured across operating models, inherently assuming that all operating models were equally plausible.

The effect of lower assessment frequency was fairly small for most management objectives considered (see Supplementary Materials for additional performance statistics and model diagnostics, including average annual variability in catches and relative error and variability of spawning stock biomass estimated from the estimating model). Trajectories of median relative spawning stock biomass appeared to be very similar regardless of assessment frequency (Figure 4). Management procedure performance was certainly more affected by operating model and implementation model (Figures 4 and 5). Since stock collapse is defined as a stock biomass that is less than 5% of B_{MSY}, we found that the stock collapsed only in the OM_Loh operating model in the conceptual implementation scenario. Stock collapse occurred in 0, 12, 14, and 7% of projections where interim periods were 1, 5, 10, and 15 years, respectively.

Statistical interpretation illustrated that the effects of assessment frequency on management objectives were conflated with the implementation and operating models (Table 2; Figure 5), resulting in some nonintuitive (i.e., sometimes nonmonotonic) patterns when analyzed across operating models (Figure 6). In each of the four management objectives assessed, the effect of assessment frequency was not linear for each operating model–implementation model scenario, indicating that each additional interim year may not have the same impact on management goals. Considering this nonlinear impact of interim years, average annual percent changes in management objective results with interim periods are presented for comparative purposes only. Nevertheless, the effect of assessment frequency on management objectives was

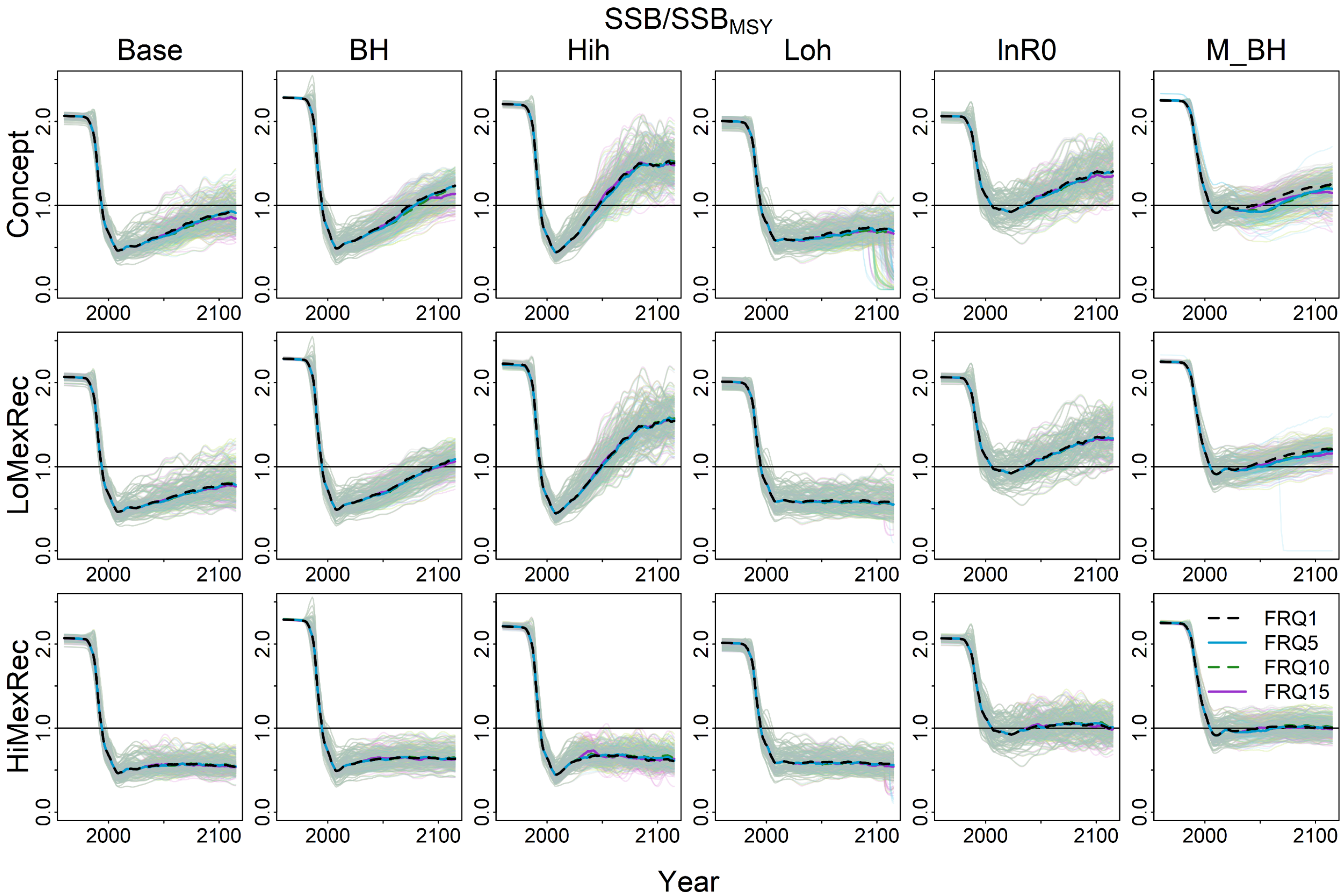

FIGURE 4. Worm plots depicting trajectories of SSB/SSB$_{MSY}$ for each operating model (in each column) across implementation models (in each row) for four assessment frequencies labeled by their interim assessment period length (FRQ1, FRQ5, FRQ10, FRQ15 for interim periods of 1, 5, 10, and 15 years, respectively). Each simulated trajectory for each iteration is graphed transparently following the color scheme noted in the legend, and the median SSB/SSB$_{MSY}$ is superimposed and in bold for each model–frequency scenario. Note that the transparent trajectories for each iteration are overlapping.

generally small, typically showing little impact of increased interim years through the 15-year interim scenario (Figure 6).

Probability of Recovery to Minimum Stock Size Threshold

There was an interaction between operating model and implementation model on the probability of stock recovery to minimum stock size threshold (Table 2). The probability of stock recovery remained relatively constant when the interim assessment period ranged between 1 and 10 years (Figure 6). When the interim duration increased to 15 years, the predicted probability of recovery was the same or declined in all scenarios (Figure 5). Across operating models in the conceptual implementation scenario, the probability of recovery under the 15-year interim period was reduced by 3.2% relative to the 1–10 interim period average, indicating that the probability of recovery declined less than 1% per year on average after the interim period exceeded 10 years (Figure 6).

In the conceptual OM_Base scenario, the scenario in which this decline was by far the greatest, the probability of recovery was reduced by 13.0% between the 1–10-year and 15-year interim periods (2.6% reduction per year for years >10; Figure 5). This decline was also observed in the OM_Base LoMexRec scenario (11% decline between the 1–10-year and 15-year interim periods; 2.2% reduction per year after 10 years; Figure 5). In all other operating model–implementation model scenarios, the relative reduction in probability of recovery was ≲1% per year between 15-year and less than 10-year interim periods. The relatively small impact on probability of stock recovery between interim periods of 1–10 years was also observed in the LoMexRec and HiMexRec scenarios, to a lesser extent. Probability of recovery was reduced by 2.5% and 2% between interim periods of less than 10 years

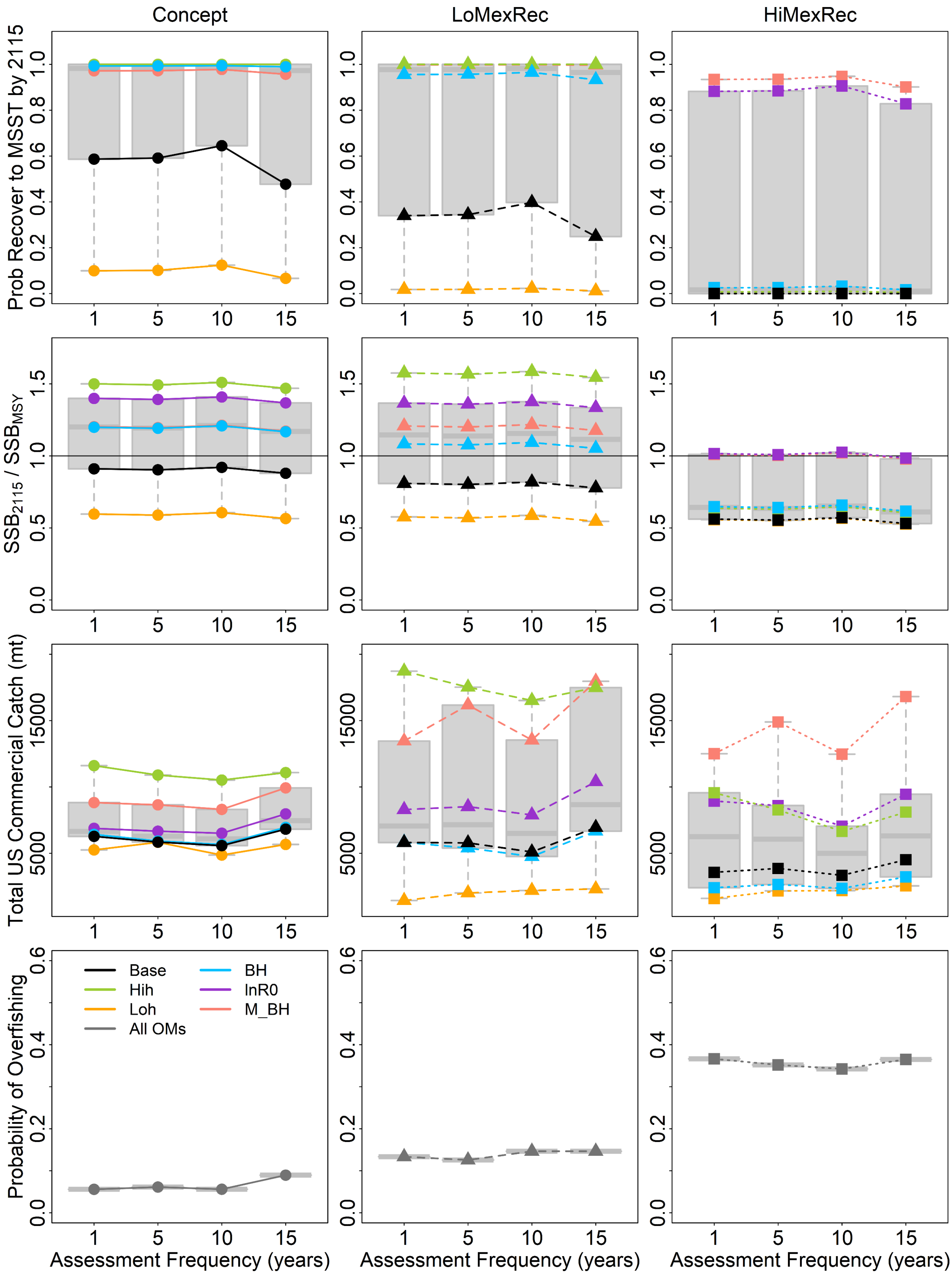
Concept
LoMexRec
HiMexRec
Prob Recover to MSST by 2115
SSB2115 / SSBMSY
Total US Commercial Catch (mt)
Probability of Overfishing
Base
Hih
Loh
All OMs
BH
lnR0
M_BH
Assessment Frequency (years)
Assessment Frequency (years)
Assessment Frequency (years)

FIGURE 5. Resulting management objectives predicted from generalized linear models as dependent on assessment frequency. Management objectives are presented by row and include probability of stock recovery to 87% SSB_{MSY} by 2,115, terminal SSB_{2115} relative to SSB_{MSY}, total U.S. commercial catch across the simulated time horizon, and the probability of overfishing in the simulated time horizon. Box plots are mean model predictions across operating model for each implementation model. Responses for each operating model and implementation model are superimposed, where operating models are differentiated by color and implementation models are differentiated by column. Due to interaction effects within the generalized linear models, the response of altered frequency on each management objective varies across operating model and implementation model. Operating model was not a significant predictor of the probability of overfishing, so operating-model-specific results are not shown. Note that in the HiMexRec implementation model scenario, the terminal relative SSB is overlapping across operating models as plotted (Base overlapping Loh, BH overlapping Hih, lnR0 overlapping M_BH).

compared to 15 years for the LoMexRec and HiMexRec scenarios, respectively (resulting in average annual probabilities of less than 1%; Figure 6).

Terminal Spawning Stock Biomass

There was an interaction between operating model and implementation model on terminal SSB ratio (SSB_{2115}/SSB_{MSY}). Spawning biomass ratio in the terminal year of the simulation was particularly dependent on operating model, where SSB_{2115}/SSB_{MSY} was regularly greater than 1.2 or less than 0.8 when the operating model dynamics were mismatched to those of the estimating model (e.g., Base, Hih, Loh, lnR0, M_BH; Figure 4). These impacts were further dependent on implementation model as catch allocation varied in each implementation scenario and the presence of unaccounted removals from the MexRec fishery resulted in SSB_{2115}/SSB_{MSY} of most operating models falling well below 1.0 in the HiMexRec implementation scenario (Figure 5).

The pattern in terminal SSB ratio naturally followed the probability of recovery. Accordingly, relative terminal SSB appeared generally constant when assessment interim periods varied between 1 and 10 years and declined slightly when the interim period was equal to 15 years (Figure 6). However, these declines were relatively small (3% reduction in terminal SSB ratio between the 1–10-year interim period average and the 15-year interim period across all operating model–implementation model combinations). This reduction in terminal SSB in the management procedure with a 15-year interim period did not necessarily reflect a reduction in management procedure performance. When the mismatch between operating model and estimating model resulted in a terminal SSB ratio much larger than 1.0, a reduction in terminal SSB ratio actually brought the SSB ratio closer to the ideal level of 1.0. Across all operating model–implementation model scenarios, the median terminal SSB ratio was very close to 1.0 for all assessment frequency scenarios explored (Figure 7).

Cumulative U.S. Commercial Catch

There was an interaction between assessment frequency, operating model, and implementation model on cumulative U.S. commercial catch (Table 2). The impact of altered assessment frequency on cumulative U.S. commercial catch was less intuitive, sometimes increasing and sometimes decreasing with additional years between assessments depending on the operating model–implementation model scenario (Figure 5). Overall, cumulative U.S. commercial catch was generally similar in most operating model–implementation model scenarios, then increased when the interim period reached 15 years. The patterns in cumulative U.S. commercial catch generally mirrored the results of terminal SSB ratio and probability of recovery, clarifying the trade-offs associated with managing fisheries (i.e., increase in cumulative catch corresponds to a reduction in terminal SSB ratio and decreased probability of recovery; Figure 6). However, it is important to consider the impact of all removals (including MexRec catches; Figure S11), which explains how U.S. commercial catches of similar magnitude can lead to drastically reduced probability of recovery and terminal SSB ratio and a higher probability of overfishing.

TABLE 2. Optimal generalized linear model formulations as identified by AIC. A times sign indicates an interaction effect, FRQ indicates assessment frequency, IM indicates implementation scenario, and OM indicates operating model. Note that the probability of overfishing management objective contained 0, which cannot be transformed via a logit link function, so the probability of overfishing was first transformed using the equation $x_c = \frac{x(N-1)+0.5}{N}$, where N is the sample size, following Smithson and Verkuilen (2006). Consequently, this distinction is denoted by a dagger (†).

Management objective	Response distribution	Link function	Model formulation
Probability of recovery	Binomial	Logit	FRQ + IM + OM + IM × OM
SSB_{2115}/SSB_{MSY}	Normal	Identity	FRQ + IM + OM + IM × OM
Total U.S. commercial catch	Lognormal	Identity	FRQ + IM + OM + FRQ × IM × OM
Probability of overfishing†	Normal	Logit	FRQ + IM + FRQ × IM

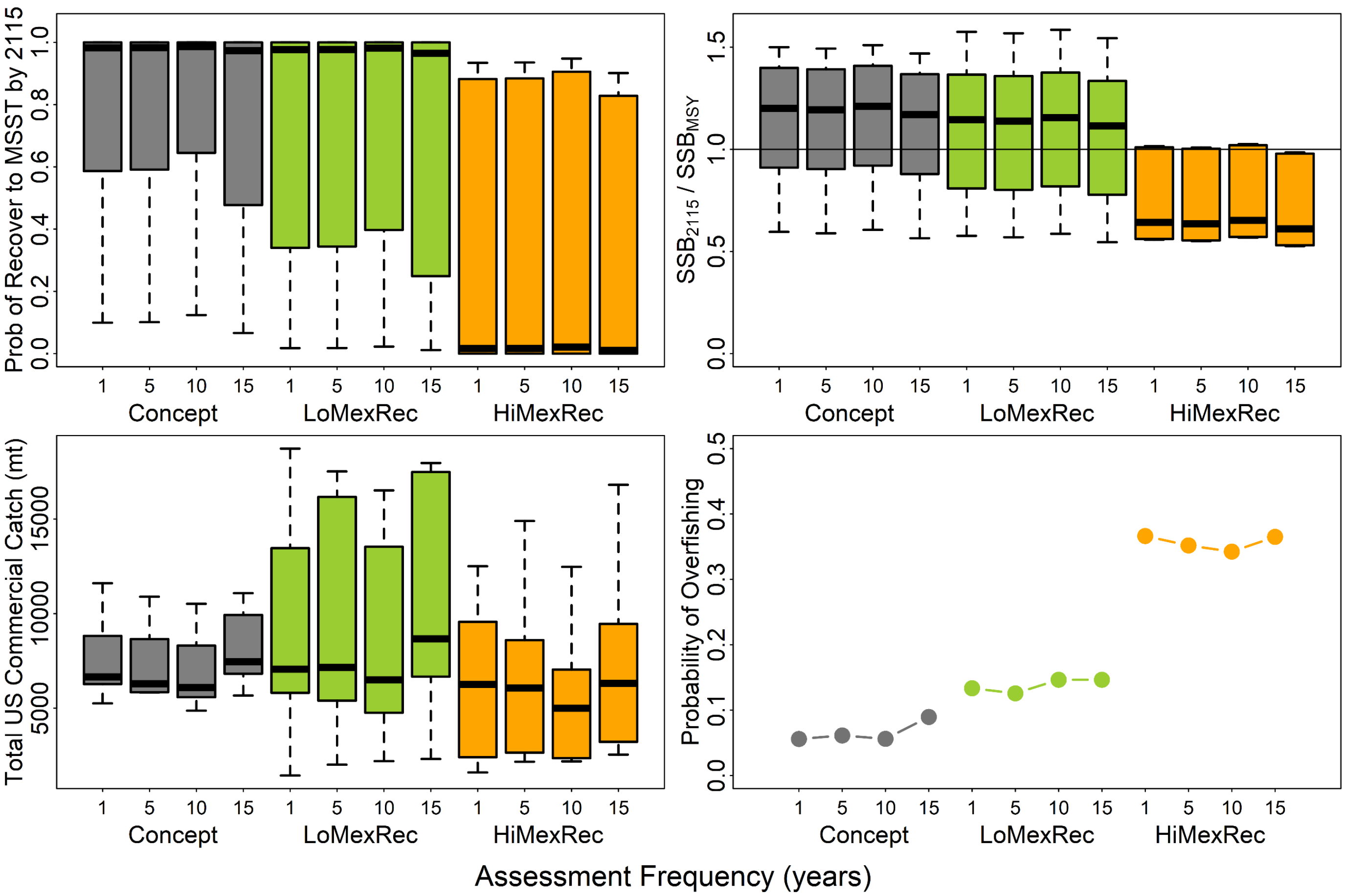

FIGURE 6. Performance of altered stock assessment frequency (with interim periods of 1, 5, 10, 15 years) on four management objectives: probability of stock recovery by 2,115 ($SSB_{2115} \geq 87\%$ SSB_{MSY}; top left), relative terminal stock biomass (SSB_{2115}/SSB_{MSY}; top right), cumulative U.S. commercial catch from 2016 to 2,115 (bottom left), and probability of overfishing from 2016 to 2,115 (bottom right). Note results are presented by each implementation model (conceptual scenario in gray, LoMexRec in green, and HiMexRec in orange) across all operating models. For the box plots, the horizontal line in each box indicates the median, the box dimensions show the 25th–75th percentile ranges, and the whiskers represent the range of the results.

Probability of Overfishing

Operating model was not included in the optimal generalized linear model configuration as identified by AIC for the probability of overfishing. There was, however, an interaction between implementation model and assessment frequency (Table 2). In the conceptual implementation scenario, the probability of overfishing remained relatively stable when assessment frequency varied between every year to every 10 years (~5.7% probability of overfishing), then increased when there were 15 years between assessments (9% probability of overfishing). This pattern was generally complementary with the patterns in probability of recovery and terminal SSB ratio (Figures 5, 6). In the LoMexRec scenario, this division in probability of overfishing occurred in contrasting assessment interim periods of 1 to 5 years (~13% probability of overfishing) compared to 10 to 15 years (14.6% probability of overfishing). The probability of overfishing was relatively constant in the HiMexRec scenario, regardless of assessment frequency, and was overall much higher due to larger MexRec removals (35.6% probability of overfishing).

DISCUSSION

Given the relatively small impact of assessment frequency on management procedure performance, we found that the Sandbar Shark is a good candidate for lower assessment frequency. Management procedure performance varied only slightly based on 1-, 5-, 10-, or 15-year assessment cycles and generally only appeared to show adverse responses when interim periods reached 15 years. This marginal decline in performance between 10- and 15-year interim periods may be linked to the life history of the Sandbar Shark, wherein median age at female maturity is estimated to be 13 years (Baremore and Hale 2012). The large variability inherent in the data and uncertainty

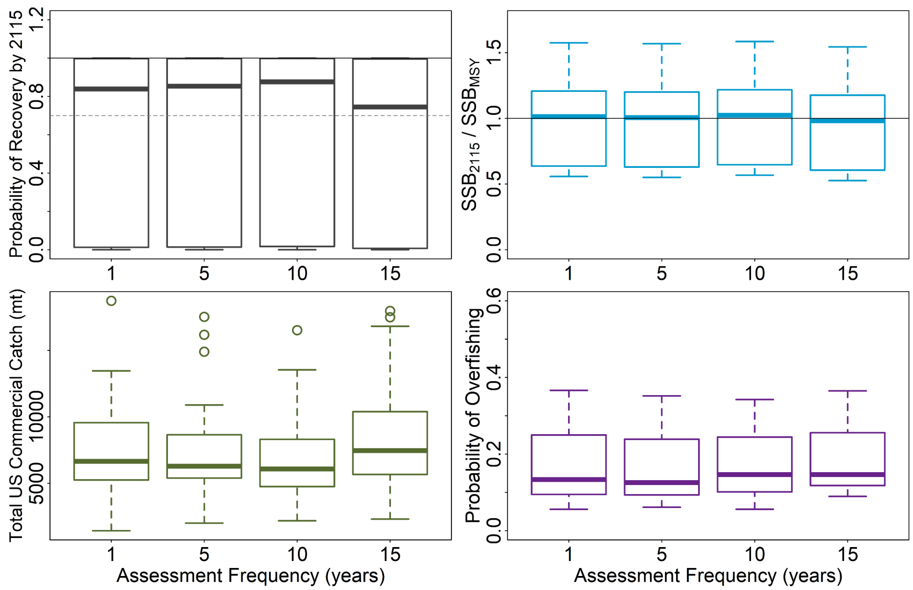

FIGURE 7. Performance of altered stock assessment frequency (with interim periods of 1, 5, 10, 15 years) combined across all operating model and implementation model scenarios on four management objectives: probability of stock recovery by 2,115 ($SSB_{2115} \geq 87\%\ SSB_{MSY}$; top left), relative terminal stock biomass (SSB_{2115}/SSB_{MSY}; top right), cumulative U.S. commercial catch from 2016 to 2,115 (bottom left), and probability of overfishing from 2016 to 2,115 (bottom right). For the box plots, the horizontal line in each box indicates the median, the box dimensions show the 25th–75th percentile ranges, the whiskers show the range of the data, and circles are outliers outside of 1.5× the interquartile range.

in the implementation process (as simulated following real-world error) likely overwhelmed any improved management performance that would be expected from increased assessment frequency. Similarly, Sylvia (2015) found that slow life history fish were less likely to be adversely affected by increased assessment interval.

Given the small effect that assessment frequency had on management objectives for the Sandbar Shark, longer interim periods may be the most effective way to assess slow-growing coastal shark species. Since the first assessment of the Sandbar Shark, the stock has been assessed every 4.75 years on average. We show that assessment frequency can be reduced up to at least 10 years without adversely affecting management goals. After assessment interim periods reached 15 years, the probability of stock recovery to minimum stock size threshold and terminal SSB ratio declined slightly in the conceptual and LoMexRec implementation scenarios, accompanied by a slight increase in cumulative U.S. commercial catch and probability of overfishing throughout the simulation period. The effect of assessment frequency was complicated by the nonlinear impact of interim period such that additional years between assessments did not all have an equal impact on overall management performance.

The impact of assessment interim periods varied considerably based on operating model and implementation model, following findings from a similarly structured Sandbar Shark MSE (Peterson et al. 2022). That MSE application focused on the management performance of various configurations of a threshold harvest rate control rule, and we refer to that study for additional information on the effect of the structure of the HCR, more detailed analyses on the impact of each implementation modeling scenario, and factors that impact recovery potential for the stock. Accordingly, Peterson et al. (2022) demonstrated that the MexRec catches will have perhaps the largest impact on the future of the Sandbar Shark stock in the Southeast, wherein unregulated increases in Mexican harvest with biomass (HiMexRec) adversely impacted the ability of the stock to recover.

Not all stocks would be good candidates for decreased stock assessment frequency. For instance, stock assessment frequency should be higher for stocks that are particularly economically valuable (Methot 2015; Lynch et al. 2018; Hutniczak et al. 2019). Fisheries where stocks are faster growing, with higher target *F*, that have a less well-defined stock–recruitment relationship, and which are frequently dependent on strong age- and size-classes should be assessed more frequently (ICES 2012). Faster-growing species were found to have greater annual impacts on catch, biomass, and probability of overfishing with increased time between assessments as compared with slow-growing species (Sylvia 2015). Stocks for which assessments show retrospective patterns should also be updated more frequently (Hutniczak et al. 2019).

Overfished stocks or stocks in rebuilding plans, like the Sandbar Shark, should be assessed more frequently to ensure recovery to optimal levels (Methot 2015). Despite perceived low economic value, prior to stock reduction the Sandbar Shark was a relatively economically valuable resource for the legal shark fin trade. Sandbar Sharks were particularly prioritized within the shark fishery due to their large sizes and proportionally large fins (Dulvy et al. 2014). Further, consideration should be taken of ecosystem importance, noncatch value, and constituent demand when determining stock assessment frequency (Methot 2015). As higher trophic level predators (Cortés 1999), large coastal sharks may have an ecosystem role as top-down predators and maintainers of ecosystem stability (Ferretti et al. 2010; Britten et al. 2014). Further, large coastal sharks have proven particularly challenging to manage among conflicting stakeholder interests (Carlson et al. 2019). These aspects of the large coastal shark fishery should also be considered when identifying optimal stock assessment frequency.

Limitations and Future Directions

We emphasize that the purpose of this study was not to develop the most appropriate and robust estimating model for this stock. Rather, we measured the impact that assessment frequency would have if implemented using the current stock assessment model configuration. This inherently assumes that the estimating model structure remains relatively static throughout the simulation period and is minimally adjusted in the future. In practice, a great deal of analyst adjustment is involved in each updated assessment, which may result in changes in assessment model structure over time. Management strategy evaluations typically cannot automate this structural variability of the estimating model in the projection period. Further, if the estimating models allow too much freedom in parameter estimation or other such flexibilities, they run the risk of failing to converge during the MSE projection period. Some structural rigidity in the estimating models is often necessary to allow for a successful simulation. In the current study, the similarity of median relative spawning stock biomass trajectories (Figure 4) may indicate that the structure of the estimating model used in practice may not be flexible or adaptable enough to identify and manage across model misspecification, even when applied annually. Our findings are likely reflective of the limitations of our modeling process, wherein a management procedure with a less restrictive estimating model may have resulted in a greater impact of longer interim assessment periods.

It is important to consider that the risk to the resource is asymmetric with respect to assessment frequency. For example, if a catch level is set too high where interim assessment periods are longer, the stock will undergo additional years of overexploitation which could result in a detrimental impact to the stock of greater magnitude than would be experienced if assessments were conducted more frequently. Further, an MSE is only as valuable as its ability to fully capture the range of uncertainties of the system (Butterworth and Punt 1999). Given the complex and subjective nature of fisheries assessment and management, the management process in the year 2115 will likely not be the same as it is today, thereby diverging from the way it was modeled in the current approach. However, assumptions, like that of subtracting a fixed constant to account for recreational catches and dead discards from the catch limit into the future, are necessary within an MSE framework. Consequently, any management procedures implemented in practice should be regularly revisited to ensure that the management procedures are not operating under conditions that were not simulation tested (Carruthers and Hordyk 2019). We emphasize that the current simulation assumed stationarity, and as such, a number of untested uncertainties, including climate change impacts, changes in the management framework, episodic events, and others, could influence how these management procedures perform in practice. It is therefore important to revisit any changes to current management practices regularly to ensure that they are still valid and performing appropriately (Punt et al. 2016).

These concerns could be partially alleviated by strategic management. Managing by implementing interim assessment analyses (Huynh et al. 2020), wherein reliable indicators of stock abundance (i.e., indices of abundance) are routinely analyzed between stock assessments to adjust allowable catch advice, could be employed to ensure that management advice is continually responsive to the stock dynamics. Regular monitoring of these stock indicators between assessments, even if not utilized to adjust catch advice, could serve as early indicators that stock dynamics have strayed into untested territory, triggering analysts to revisit the management procedure under "exceptional circumstances" (Kolody et al. 2008; Holland 2010; Carruthers and Hordyk 2019). Long interim periods should be overridden and updated full stock assessments should be prioritized if significant advancements are made or new information becomes available that would significantly impact the management of that stock (Methot 2015). Further, simply managing conservatively, an idea that has been largely supported for coastal sharks (Cortés 1998; Musick et al. 2000; Dulvy et al. 2014), would reduce the likelihood of setting harvest rates that are too high and accordingly reduce the likelihood of overfishing for many years between assessments.

Though the Sandbar Shark has relatively low recruitment variability, like other stocks bearing live young, future explorations of the impact on stock assessment frequency could explicitly consider alternate levels of recruitment variability. The effect of recruitment variability and assessment frequency will also interact with the form of the selectivity curve. For instance, if fish are not selected to the fishery prior to age 10 and the assessment interval is less than 10 years, then the projected variability should have a minimal impact (M. J. Wilberg, unpublished data). We would accordingly expect recruitment variability to have a smaller impact on the LoMexRec scenarios, in which selectivity of younger ages is smaller compared with implementation scenarios where MexRec catches are proportionally larger.

Notably, we did not consider the impact of delays in management implementation and lags in data availability (e.g., Shertzer and Prager 2007; Sylvia 2015). Like many U.S. stocks, management implementation generally takes well over 1 year for coastal sharks. Delays in management implementation were found to reduce fishery yield and increase recovery time on depleted stocks (Shertzer and Prager 2007). Sylvia (2015) found that the adverse impacts of management lag were generally greater than those from increased assessment frequency. However, like assessment frequency, these impacts were found to be smaller for a *K*-selected species (Brown et al. 2012; Sylvia 2015).

Conclusion

Results herein ultimately demonstrate that Sandbar Sharks represent a suitable species for reduced assessment frequency, supporting U.S. federal guidance with respect to future assessment activities (Methot 2015; Lynch et al. 2018). The Sandbar Shark is slow growing, with a largely environmentally independent stock–recruitment relationship and currently low economic value (Stevens 2000), suggesting that coastal shark stocks may be more robust to environmental and fishery perturbations that would have a greater impact on other fishes. Accordingly, Methot (2015) suggested that longer interim periods of up to 10 years are appropriate for long-lived species with low recruitment variability and low economic importance. Ultimately, reducing stock assessment frequency, where appropriate, will reduce resource expenditure and free up assessment scientists to advance stock assessment methodologies and/or assess other underassessed stocks, thereby increasing assessment throughput as recommended by the next generation of stock assessment enterprise in the USA (Lynch et al. 2018). We show that *K*-selected coastal shark species, like the Sandbar Shark, could reasonably undergo longer interim periods between stock assessments without compromising management objectives.

ACKNOWLEDGMENTS

We acknowledge College of William & Mary Research Computing (https://www.wm.edu/it/rc) for providing computational resources and technical support. We thank Nathan Vaughan and two anonymous reviewers for comments on the manuscript. This paper is contribution 4109 of the Virginia Institute of Marine Science, College of William & Mary. There is no conflict of interest declared in this article.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.