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EVALUATION OF REFERENCE MANAGEMENT PROCEDURES IN HYPOTHETICAL UNCERTAINTY SCENARIOS FOR NORTH ATLANTIC SWORDFISH

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SUMMARY

A broad range of hypothetical scenarios are developed for four key uncertainties related to the conditions of the swordfish fishery in the future: 1) spatial structure and movement patterns, 2) environmentally-driven cyclic patterns in recruitment deviations, 3) persistent increases in catchability, and 4) implementation error in the catch advice. Operating models (OMs) are constructed by modifying the North Atlantic swordfish base case OM with assumptions spanning a broad range of uncertainties for each scenario. A management strategy evaluation (MSE) framework is used to evaluate the performance of a set of reference management procedures (MPs) spanning the typical range of MP types against a set of performance criteria. The results are compared to those from the base case OM. The study found that spatial structure and movement patterns were least consequential compared to the base case. Cyclic recruitment patterns and increasing catchability had the biggest impact on the performance of simple index-targeting MPs. The results can be used to identify the key uncertainties for this fishery and prioritize future research on areas that are most consequential for MP performance and selection.

RÉSUMÉ

Un large éventail de scénarios hypothétiques a été mis au point pour quatre incertitudes clés liées aux conditions de la pêche ciblant l'espadon dans le futur : 1) la structure spatiale et les schémas de mouvement, 2) les schémas cycliques liés à l'environnement dans les écarts de recrutement, 3) les augmentations persistantes de la capturabilité, et 4) l'erreur de mise en œuvre dans l'avis de capture. Les modèles opérationnels (OM) sont construits en modifiant le cas de base de l'OM de l'espadon de l'Atlantique Nord avec des hypothèses couvrant un large éventail d'incertitudes pour chaque scénario. Un cadre d'évaluation de la stratégie de gestion (MSE) est utilisé pour évaluer la performance d'un ensemble de procédures de gestion de référence (MP) couvrant la gamme typique des types de MP par rapport à un ensemble de critères de performance. Les résultats sont comparés à ceux du cas de base de l'OM. L'étude a montré que la structure spatiale et les modèles de mouvement étaient moins conséquents que dans le cas de base. Les schémas de recrutement cycliques et l'augmentation de la capturabilité ont eu le plus grand impact sur la performance des MP à ciblage indiciel simple. Les résultats peuvent être utilisés pour identifier les principales incertitudes pour cette pêcherie et donner la priorité dans les recherches futures aux domaines qui sont les plus importants pour la performance et la sélection des MP.

RESUMEN

Se ha desarrollado una amplia gama de escenarios hipotéticos para cuatro incertidumbres clave relacionadas con las condiciones de la pesquería de pez espada en el futuro: 1) la estructura espacial y los patrones de movimiento, 2) los patrones cíclicos impulsados por el medio ambiente en las desviaciones del reclutamiento, 3) los aumentos persistentes de la capturabilidad y 4) el error de implementación en el asesoramiento de captura. Los modelos operativos (OM) se construyeron modificando el caso base del OM del pez espada del Atlántico norte con supuestos que abarcan una amplia gama de incertidumbres para cada escenario. Se ha utilizado un marco de evaluación de estrategias de ordenación (MSE) para evaluar el desempeño de un conjunto de procedimientos de ordenación (MP) de referencia que abarcan la gama típica de tipos de MP con respecto a un conjunto de criterios de desempeño. Los resultados se compararon con los del caso base del OM. El estudio determinó que la estructura espacial y los patrones de movimiento tenían menos consecuencias en comparación con el caso base. Los patrones de reclutamiento cíclico y el aumento de la capturabilidad fueron los que más influyeron en el desempeño de los MP de índices simples. Los resultados pueden utilizarse para identificar las principales incertidumbres de esta pesquería y priorizar la investigación futura en las áreas más importantes para el desempeño y la selección de los MP.

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KEYWORDS

Management Strategy Evaluation, operating model, closed-loop simulation, performance metrics, candidate management procedures

1. Introduction

Management strategy evaluation (MSE) is widely regarded as the most transparent and objective method for identifying modes of management that are robust to uncertainty and likely to meet the management objectives for a fishery (Butterworth 2007; Punt *et al*. 2016). The first step in the MSE approach is to develop a range of plausible alternative hypotheses of the fishery dynamics, generally called reference operating models (OMs), that span the key uncertainties in the fishery. A set of candidate management procedures (cMPs) are then proposed, and closed-loop simulation modeling used to evaluate the expected performance of the cMPs across the reference OMs against a predefined set of performance criteria. The cMP that has the best performance and is most robust to uncertainty is selected as the appropriate management method for the fishery (Punt *et al*. 2016).

Although often described as a linear approach, the MSE approach is often iterative, with preliminarily analyses conducted initially to identify the sources of uncertainty that are most consequential in terms of performance and selection of the cMPs, and then further refinement of the reference OMs to ensure that they adequately span the most important uncertainties.

An MSE approach is being used to evaluate candidate management procedures for the North Atlantic swordfish fishery. A set of reference OMs has been developed, with a base case OM based on the 2017 stock assessment, and an uncertainty grid of 288 OMs spanning alternative assumptions in 7 factors (Hordyk 2020).

The uncertainty grid largely deals with alternative assumed values of biological parameters (i.e., natural mortality (M) and steepness of the stock-recruit relationship (h)) and alternative assumptions of the data used to condition the OMs (e.g., effective sample size of length composition data and the coefficient of variation for the indices of abundance) (Hordyk 2020). Several other uncertainty scenarios have been proposed by the Swordfish Working Group for investigation, particularly regarding assumptions of the stock dynamics in the future projection period.

This paper examines the impact of 4 uncertainties related to the stock dynamics in the projection period on the performance of a set of reference management procedures for the North Atlantic swordfish fishery, specifically the impact of:

1. Alternative assumptions of the spatial structure of the stock;
2. Cyclic patterns in recruitment deviations;
3. Increases in catchability;
4. Implementation error in the total allowable catch (TAC) advice

A set of hypothetical scenarios were developed for each of these 4 conditions, with the aim of bracketing the plausible range of uncertainty related to each. The objective of this study is a preliminary analysis to evaluate the relative impact of each of these uncertainty scenarios on the performance of a set of reference management procedures. The results from this study can be used by the Swordfish Working Group to prioritise the focus on future the uncertainty scenarios that are most consequential in terms of selection of a cMP.

2. Methods

2.1 Structure of the Analysis

Five reference management procedures were used to evaluate the impact of each of the uncertainty scenarios on the performance and selection of the cMPs. These reference management procedures were:

1. Current Catch (curC) – the TAC is fixed at the level of the most recent catch;
2. Perfect FMSY (FMSYref) – the TAC is calculated each year so that $F = F_{\text{MSY}}$;
3. Index Target 1 (Ind_1) – the TAC is calculated each year based on the ratio of the index to a target level with a maximum annual change in TAC of 5%;
4. Index Target 2 (Ind_2) – Same as Ind_1 but with a maximum annual change in TAC of 10%;

5. Surplus Production Model (SP_MSY) – A surplus production model is used to set the annual TAC to the level corresponding with fishing at the estimated F_{MSY}.

These reference management procedures were selected as they cover a range of typical candidate management procedures that may be proposed for the swordfish fishery (Ind_1, Ind_2, and SP_MSY) and hypothetical management options that are expected to have widely different performance (curC and FMSYref). More details on the reference management procedures are found in Hordyk (2020).
Performance of the reference management procedures was evaluated against 3 criteria:

1. The probability that spawning biomass (SB) is greater than SB_{MSY} throughout the projection period;
2. The average short-term catch (first 10-years of the projection period) relative to the highest catch obtainable with a fixed-F policy;
3. The average long-term catch (last 10-years of the projection period) relative to the highest catch obtainable with a fixed-F policy.

These performance metrics were selected to evaluate the type of metrics that are generally used for evaluating performance: biological sustainability and short- and long-term catches. They do not represent the metrics that will be used to select candidate management procedures in the full MSE process for the swordfish fishery.

The five reference management procedures were evaluated for each OM of the uncertainty scenarios (described below), with 20 simulations per OM and a 50-year projection period. Within each OM, the simulated stock dynamics were identical across the 20 simulations during the historical period, with stochastic recruitment deviations and index observation error in the projection years. In each case, the uncertainty scenario OMs were developed by modifying the North Atlantic base case OM (Hordyk 2020).

The results are summarised by calculating the performance of each reference management procedure in each scenario with respect to the three performance metrics, and dividing the resulting statistics by the performance of the base case OM. This allows the impact of the uncertainty scenarios to be examined in terms of deviation in expected performance relative to the base case OM.

2.2 Hypothesized Spatial Structure

A two-area model was used to conduct the preliminary evaluation of the impact of spatial structure on the performance and selection of the cMPs. Twelve hypothetical scenarios were developed, spanning a wide range of uncertainties related to spatial structure of the stock (**Table 1**).

Two levels of mean probability of remaining in an area were evaluated: 1) a completely mixed stock (50%) and 2) a stock with high viscosity (90%). Three levels were assumed for the size of Area 1: 5%, 25% and 50% of the total area (**Table 1**). The first 6 scenarios assumed that the unfished stock biomass is distributed proportional to the relative size of each area; that is, the density of the unfished stock is equivalent in each area (**Table 1**). Scenarios 7 – 12 assumed age-based movement, with recruitment occurring primarily in Area 2 and ontogenetic movement to Area 1 (**Figure 1**). Scenario 5 is a fully mixed (50% probability of moving between areas each year) stock with two areas of equal size, and has the same properties as a single area OM (i.e., the assumption of the swordfish base case OM).

Fishing mortality was distributed in each year across the areas in proportion to the density of vulnerable biomass in each area. The index of abundance in the projection period was generated assuming that all sampling occurred in Area 2.

2.3 Cyclic Recruitment Patterns

Four scenarios were developed to examine the impacts of a cyclic pattern in recruitment deviations. This was done by modifying the recruitment deviations in the projection period of the swordfish base case OM. In the base case OM, the recruitment deviations for the projection period were generated by stochastic sampling from a distribution characterised by the variability and auto-correlation of the recruitment deviations estimated in the OM conditioning. The cyclic patterns were generated by superimposing a sinusoidal curve over the recruitment deviations from the base case OM.

The four scenarios were developed by a factorial design of two alternative time periods and two levels of amplitude in the sinusoidal curve (**Table 2**). The Short time period was defined as 5 – 10 years, and the Long time period as 20 – 25 years. The amplitude of the sine wave was determined by the two levels of the assumed amplitude: 1) Low – the amplitude ranged from 20 – 40% and 2) High - the amplitude ranged from 60 – 80% (**Table 2**).

For each scenario, 20 values for the amplitude and period of the sine curve were sampled from a uniform distribution with minimum and maximum values corresponding to the relevant scenario. **Figure 2** gives an example of one simulation for each scenario, and shows the recruitment deviations from the base case OM (red) and the corresponding recruitment deviations from the cyclic recruitment scenario (blue).

2.4 Increases in Catchability

The impact of a persistent increase in catchability in the projection period was evaluated with two scenarios: 1) a 1% average annual increase in catchability, and 2) a 2.5% average annual increase in catchability. The increasing catchability was modelled via a directional increase in the observation error for the index of abundance (**Figure** 3). For example, for the first scenario with an average 1% annual increase in catchability, the index observation error of the base case OM was modified to assume an 1% increase each year over the 50-year projection period (**Figure** 3).

The two scenarios were compared with the base case OM, where the index of abundance was assumed to be, on average, proportional to the total stock biomass.

2.5 Implementation Error in TAC

The final uncertainty scenario evaluated the impact of implementation error in the TAC advice from each reference management procedure. The base case OM assumed that the catch taken each year was equivalent to the recommended TAC (if sufficient biomass was available). Three alternative scenarios were considered for implementation error: 1) Low – catch was 10% higher than the TAC, 2) Medium – catch was 20% higher than the TAC, and 3) High – catch was 40% higher than the TAC. The performance of the reference management procedures was evaluated for these three scenarios and compared to the performance under the conditions of the base case OM.

3. Results

3.1 Hypothesized Spatial Structure

The analysis of assumed spatial structure scenarios revealed that, in the case where all age-classes had the same movement pattern, there was no impact on the relative performance of the reference management procedures (**Figure 4**). This result demonstrates that these assumptions of spatial structure do not impact the expected performance of the candidate management procedures, and the results are essentially identical to the base case OM that assumed a fully mixed stock in two areas of equal size.

The scenarios with an age-dependant movement pattern revealed some minor differences in performance. Fishing exactly at F_{MSY} resulted in a lower probability of $SB > SB_{MSY}$ compared to the base case OM and slightly higher average short-term yield for the scenarios where Area 1 was 5% and 50% of the total area (**Figure 5**). The long-term yield of the Ind_2 method was the most sensitive to the assumed spatial structure and movement pattern, with lower average yield compared to the base case OM when mixing rate was 50% (top row **Figure 5**) and slightly higher when probability of staying in Area 1 was 90% and the size of Area 1 was 25% and 50% of the total area (bottom row **Figure 5**).

Overall the 12 spatial structure scenarios had only a marginal impact on the expected performance compared to the base case OM. This result suggests that, at least for the range of spatial structure and movement patterns examined in this analysis, these assumptions are inconsequential in terms of performance and selection of the cMPs.

3.2 Cyclic Recruitment Patterns

With the exception of long-term yield for Ind_2, the performance the 5 reference management procedures were essentially equivalent to the base case OM in the scenario with short cycles of low amplitude in recruitment deviations (**Figure 6**). The average long-term yield of the Ind_2 method was ~75% lower than in the base case OM; a consistent pattern in all four scenarios (**Figure 6**).

The scenario with high amplitude in short recruitment cycles resulted in similar performance to the base case OM for probability SB > SB_{MSY} and average short-term yield (**Figure 6**). Average long-term yield was more varied, with higher average yield compared to the base case OM for the Ind_1 method and lower for the Ind_2 method (**Figure 6**).

Results were more varied for the scenarios with longer cycles in the pattern of recruitment deviations (bottom row **Figure 6**). The low amplitude scenarios resulted in lower probability SB > SB_{MSY} and average long-term yield for two index target methods (Ind_1 and Ind_2), and slightly higher average short-term yield for these methods (**Figure 6**).

A similar pattern was observed for the high amplitude scenarios, with a greater difference in performance for all 5 reference management procedures (**Figure 6**). The three adaptive management methods (SP_MSY, Ind_1, and Ind_2) were sensitive to the long cycles of high amplitude, particularly the index target methods which has considerably lower probability SB > SB_{MSY} and average long-term yield compared to the base case OM (**Figure 6)**.

These results suggest that the performance and selection of candidate management procedures is most sensitive to conditions where there are long cycles in recruitment deviations, particularly if those cycles have high amplitude.

3.3 Increases in Catchability

The scenarios with increasing catchability in the projection period revealed that the index target methods (Ind_1 and Ind_2) were most sensitive, with lower probability SB > SB_{MSY} and lower average long-term yield compared to the base case OM (**Figure 7**). The surplus production model (SP_MSY) was also affected by the increasing catchability, with a decrease in probability SB > SB_{MSY} compared to the base case. However, this method appeared to compensate for the biased index of abundance, and resulted in slightly higher average long-term yield compared to the base case OM (**Figure 7**).

These results reveal that index targeting methods are most sensitive to increases in catchability and biased indices of abundance, while stock assessment methods such as the surplus production model may have some ability to compensate and still achieve acceptable performance.

3.4 Implementation Error in TAC

In the scenario with Low implementation error, the FMSYref and curC methods were most sensitive in terms of probability SB > SB_{MSY} (**Figure 8**). The performance of the other reference management procedures was similar to that in the base case OM with respect to all 3 performance metrics.

The results were more varied in the scenarios with Medium and High implementation error. The two static methods, curC and FMSYref, were most affected by the increased implementation error, with considerably lower probability SB > SB_{MSY}, and in the case of curC, lower average long-term yield (**Figure 8**). The SP_MSY method was also affected by the increased implementation error, with a reduction in the probability SB > SB_{MSY} but slightly higher average short- and long-term yield compared to the base case OM (**Figure 8**). The index target methods were least affected by the increased implementation error, with only a marginal decrease in probability SB > SB_{MSY} and moderately higher and lower average long-term yield for Ind_1 and Ind_2 respectively.

These results suggest that all methods are sensitive to implementation error, particularly the static methods that do not adjust the management recommendation based on signals in the data (curC and FMSYref). The index target methods appear least sensitive to implementation error.

4. Discussion

This paper examined the performance of reference candidate management procedures that span the broad types of typical cMPs (constant catch, fishing at FMSY, stock assessment methods, and simple index target MPs) for a range of hypothetical uncertainty scenarios related to the fishery dynamics in the projection period.

These scenarios are not intended as the most plausible or comprehensive scenarios for the swordfish fishery. Rather, the scenarios are designed to bracket the broad range of uncertainty within each category of uncertainty, and are used to provide an initial evaluation of the likely impact of these uncertainties on the performance and selection of the candidate management procedures. Future research can focus on developing more realistic or comprehensive scenarios for the uncertainties that appear most consequential in terms of the performance and selection of the candidate management procedures.

Spatial structure of the swordfish fishery has been hypothesized to be important (Schirripa *et al*. 2017). However, the current approach for conditioning the operating models does not account for spatial structure, primarily because of a lack of spatially explicit data and information on movement pattern. The results of this analysis suggest that the various assumptions of spatial structure and movement pattern are relatively inconsequential for the performance of cMPs compared to the base case OM which assumes a fully mixed stock. Further analysis could be conducted with more specific hypothesis of spatial structure and movement pattern. However, the results suggest that other uncertainties are more consequential in terms of performance and selection of the cMPs.

Long-term cycles in recruitment deviations appear to be the most important for determining the performance of simple index targeting management procedures. The OM uncertainty grid includes cases where the CPUE indices were evaluated as a function of the Atlantic Multidecadal Oscillation (AMO) in the OM conditioning (Hordyk 2020). The results of this analysis suggest that accounting for environmental impacts on the trends in recruitment and indices of abundance is important, especially if the proposed candidate management procedures include methods that simply adjust management advice based on a signal in an index of abundance.

Unless accounted for in the preparation of the CPUE data, increasing catchability in the projection years results in biases in the index of abundance, which the cMPs use to evaluate the condition of the fish stock and determine management advice. The index target methods are most sensitive to this situation. The OM uncertainty grid includes an axis that assumes a 1% average increase in catchability in the historical fishery. If this trend is likely to continue, it is important that it is accounted for when standardizing the CPUE indices for use by simple index-target type management procedures.

Finally, implementation error in the management advice generated by the candidate management procedures has important consequences for their performance. This is particularly the case for cMPs that do not update the management advice regularly based on signals in the data. The index target and stock assessment methods are more resilient to the implementation error, as they adjust the management recommendations to account for declines in the stock. This analysis only considered persistent overages in the catches compared to the TAC recommendations. Other studies have shown that consistent implementation error is often inconsequential in terms of performance of adaptive cMPs (Rudd and Branch 2017). However, directional changes in implementation error (e.g., implementation error increases over time) have a greater impact (Rudd and Branch 2017). If scenarios with directional or stepped changes in implementation error are considered plausible for the swordfish fishery, further research would be required to develop the operating models reflecting this situation and to evaluate the sensitivity to these conditions.

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Table 1. The 12 scenarios for alternative assumptions of spatial structure for the North Atlantic swordfish, with two levels of mean probability of remaining in each area, and three levels of the relative size of Area 1. In scenarios 1-6, the density of unfished biomass in equivalent in each area. In scenarios 7-12 the distribution of the unfished stock involves ontogenetic movement from Area 2 to Area 1.

Scenario	Mean Probability of Staying in Area	Relative Size of Area 1	Fraction of Unfished Stock in Area 1
1	0.50	0.05	0.05
2	0.90	0.05	0.05
3	0.50	0.25	0.25
4	0.90	0.25	0.25
5	0.50	0.50	0.50
6	0.90	0.50	0.50
7	0.50	0.05	Age-Dependant
8	0.90	0.05	Age-Dependant
9	0.50	0.25	Age-Dependant
10	0.90	0.25	Age-Dependant
11	0.50	0.50	Age-Dependant
12	0.90	0.50	Age-Dependant

Table 2. The four scenarios used to evaluate the impact of cyclic pattern in recruitment deviations in the projection years. Short and Long period had ranges 5 – 10 and 20 – 25 years respectively across the simulations. Low and High amplitude had ranges 20 – 40% and 60 – 80% respectively across the simulations.

Scenario	Period	Amplitude
1	Short	Low
2	Long	Low
3	Short	High
4	Long	High

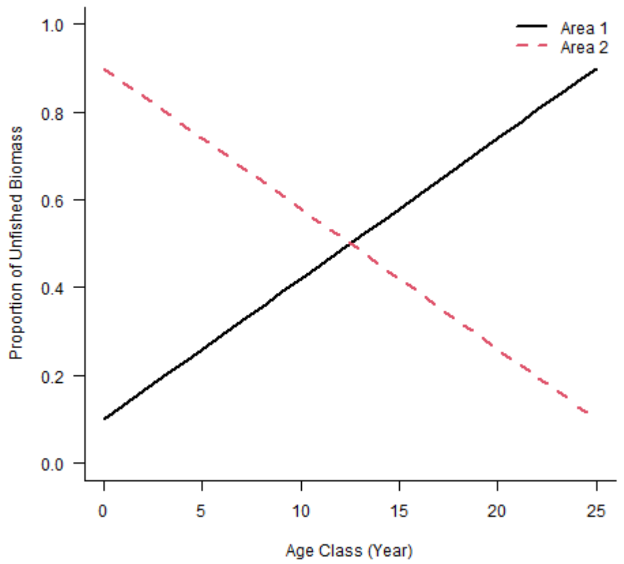

Figure 1. The ontogenetic movement pattern assumed for scenarios 7 – 12 in the evaluation of impact of spatial structure for the North Atlantic swordfish. Spawning in unfished conditions occurs primarily in Area 2 and the stock moves with age towards Area 1.

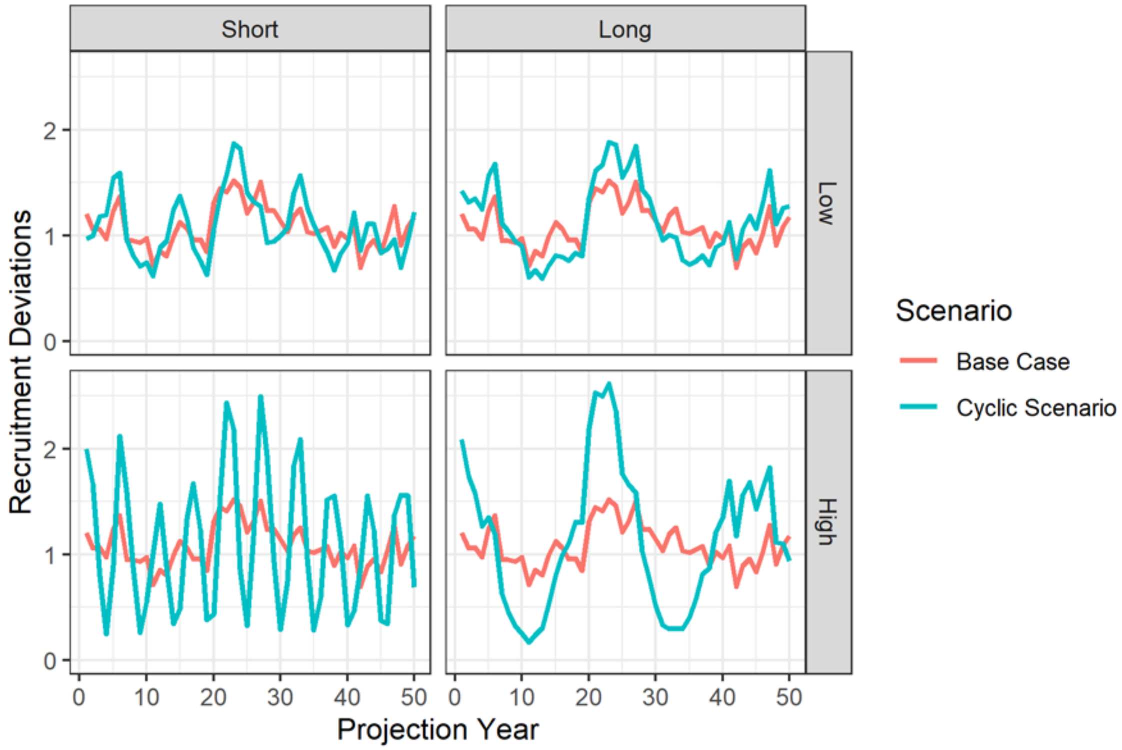

Figure 2. An example of one simulation for each cyclic recruitment scenario, and shows the recruitment deviations from the base case OM (red) and the corresponding recruitment deviations from the cyclic recruitment scenario (blue). The two scenarios with Short period (5-10 years) are shown in column 1 and the two with Long period (20 – 25 years) are shown in column 2. The Low amplitude scenarios (20 – 40%) are shown on row 1, and the High amplitude (60 – 80%) are shown on row 2.

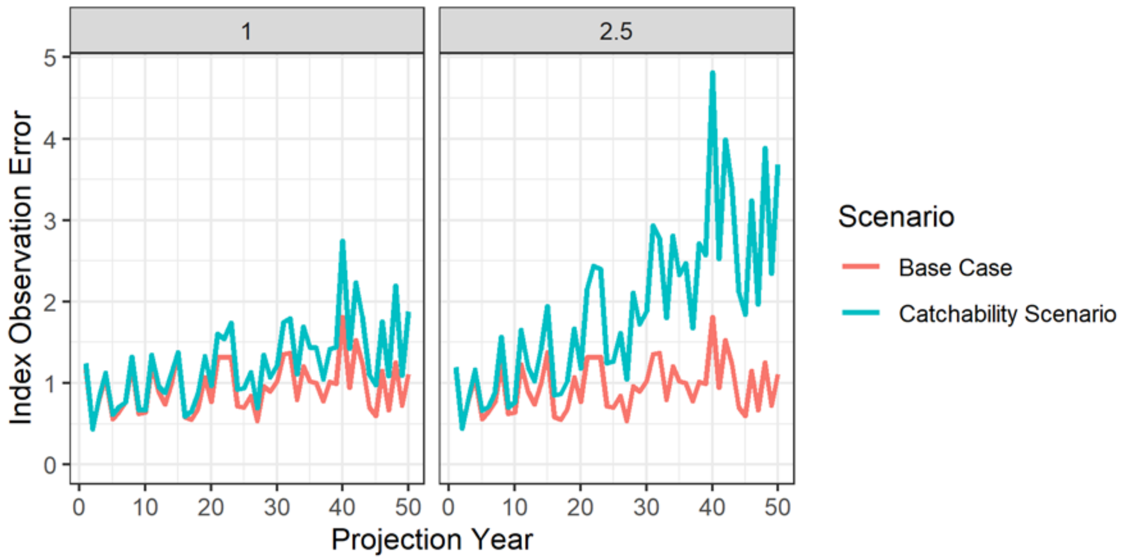

Figure 3. Example of observation error for the index for one simulation from each of the two scenarios examining the impact of a persistent increase in catchability in the projection years. The observation error for the base case is shown in red. The blue line indicates the index observation error for the scenario where catchability is assumed to an average annual increase of 1% (left column) and 2.5% (right column).

Figure 4. The performance of the five reference management procedures for the 6 spatial structure scenarios with age-independent movement. The mean probability of staying within an error was 50% (top row) and 90% (bottom row). The relative size of Area 1 was 5% (first column), 25% (second column), and 50% (third column). Results for the 3 performance metrics are shown relative to the performance of the swordfish base case OM.

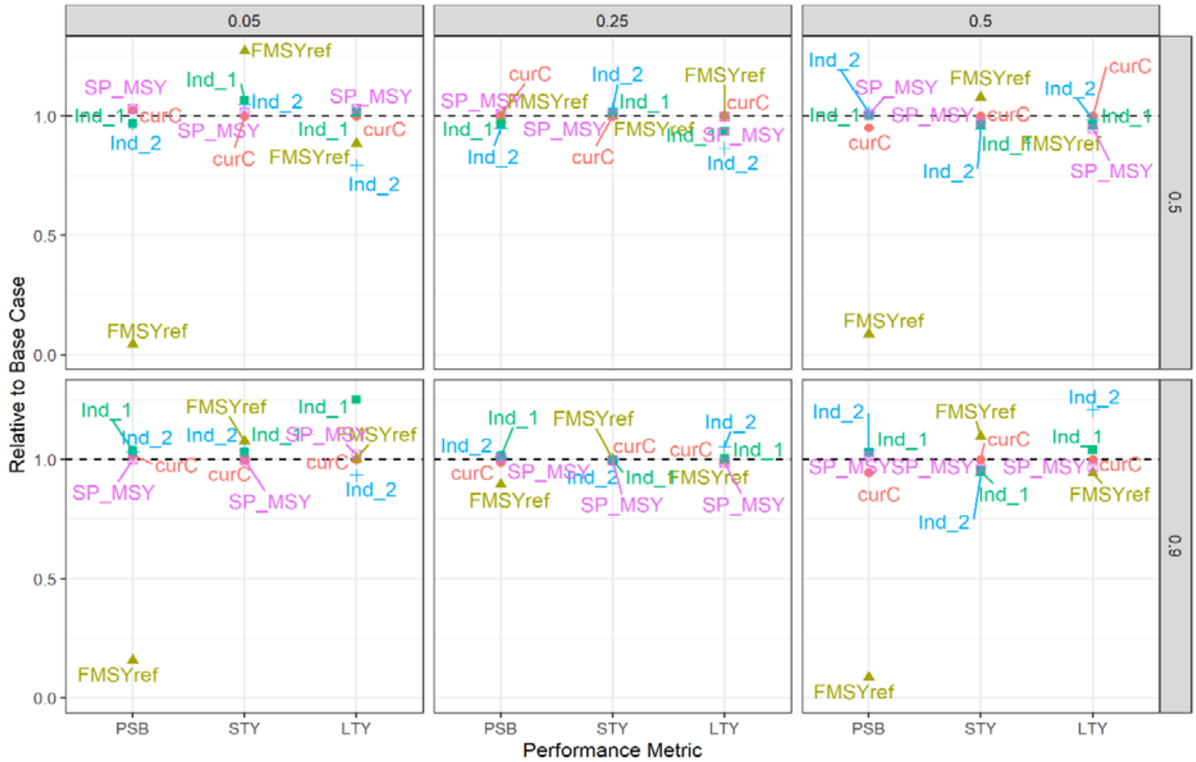

Figure 5. The performance of the five reference management procedures for the 6 spatial structure scenarios with age-dependent movement. The mean probability of staying within an error was 50% (top row) and 90% (bottom row). The relative size of Area 1 was 5% (first column), 25% (second column), and 50% (third column). Results for the 3 performance metrics are shown relative to the performance of the swordfish base case OM.

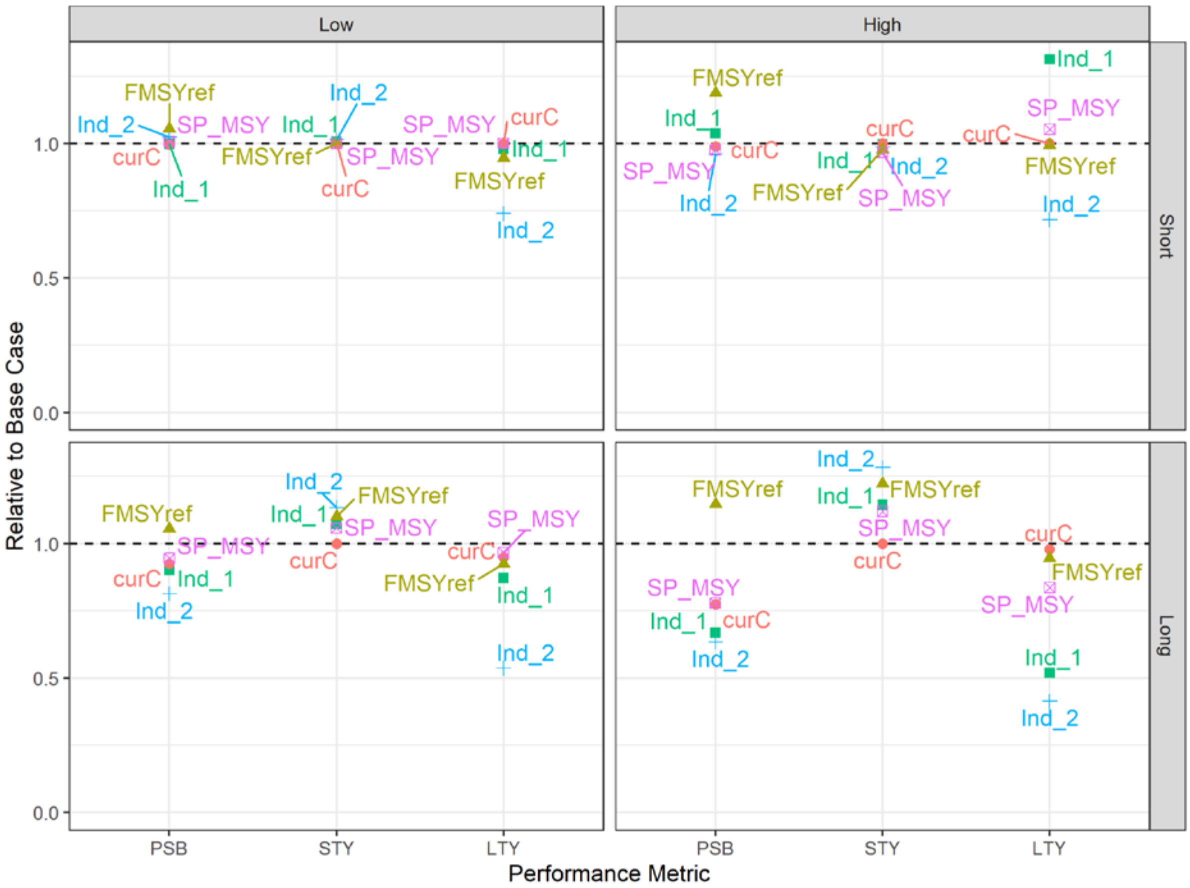

Figure 6. The performance of the five reference management procedures for the 4 scenarios examining the impact of cyclic recruitment pattern. The period of the sinusoidal wave in the recruitment deviations was 5 – 10 years (Short; top row) and 20 – 25 years (Long; bottom row). The amplitude of the superimposed cycle was 20 – 40% (Low; left column) and 60 – 80% (High; right column). Results for the 3 performance metrics are shown relative to the performance of the swordfish base case OM.

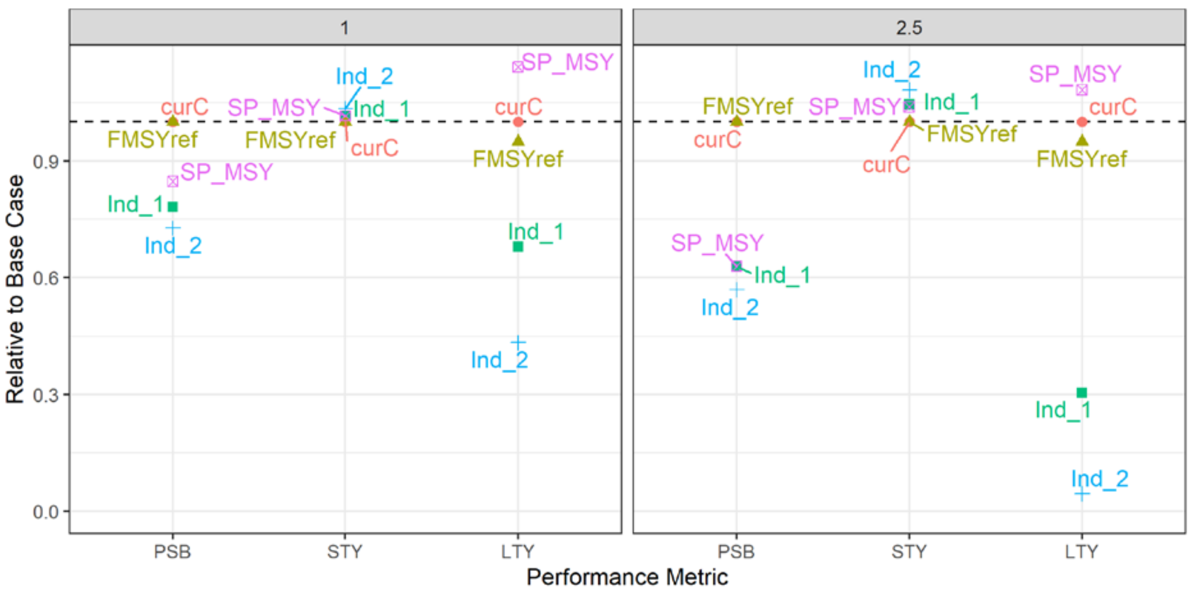

Figure 7. The performance of the five reference management procedures for the 2 scenarios examining the impact of increased catchability in the projection period. The scenarios assumed an average annual increase in catchability of 1% (left) and 2.5% (right). Results for the 3 performance metrics are shown relative to the performance of the swordfish base case OM.

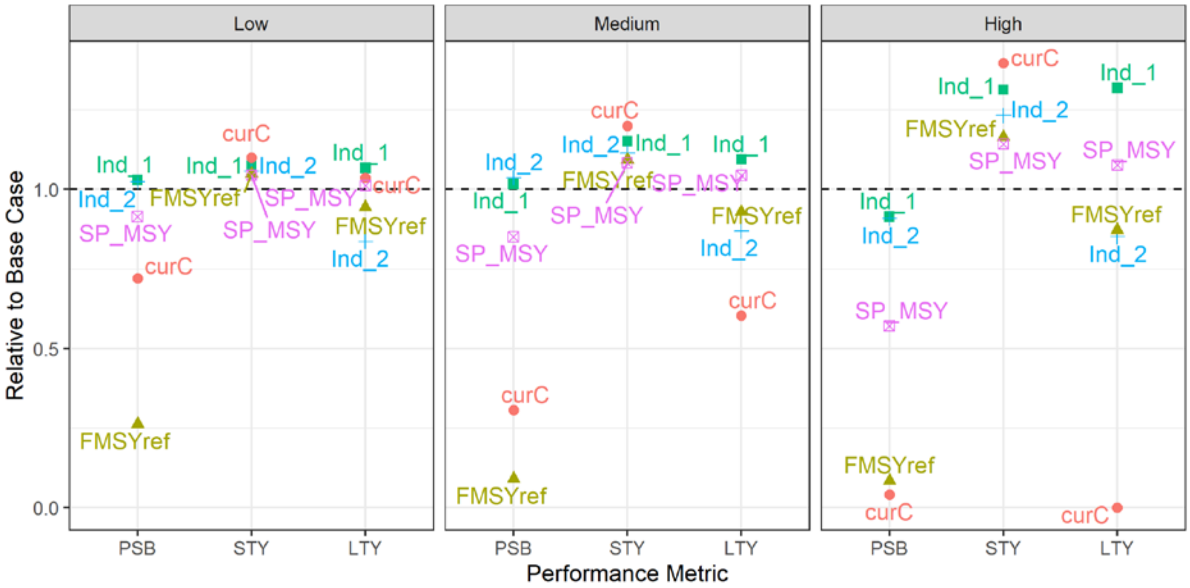

Figure 8. The performance of the five reference management procedures for the 3 scenarios examining the impact of implementation error in the management advice. The scenarios assumed the annual catches were 10% (Low; left), 20% (Medium; center), and 40% (High; right) higher than the TAC prescribed by the cMP. Results for the 3 performance metrics are shown relative to the performance of the swordfish base case OM.