

## MANAGEMENT STRATEGY EVALUATION FRAMEWORK FOR NORTH ATLANTIC SWORDFISH

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### SUMMARY

*The framework for conducting management strategy evaluation for North Atlantic swordfish is described including setting up an operating model, developing management procedures to evaluate, and establishing performance metrics to evaluate the performance of the candidate management procedures. To illustrate the features of the framework in the context of North Atlantic swordfish, an example management strategy evaluation was conducted on a swordfish operating model using 5 example management procedures. The management procedures were evaluated against 4 example performance metrics and the results were presented as a table of summary statistics and graphically via trade-off and projection plots.*

### RÉSUMÉ

*Le cadre d'évaluation de la stratégie de gestion de l'espadon de l'Atlantique Nord est décrit, y compris l'établissement d'un modèle opérationnel, l'élaboration de procédures de gestion à évaluer et l'établissement de mesures des performances pour évaluer les performances de possibles procédures de gestion. Pour illustrer les caractéristiques du cadre dans le contexte de l'espadon de l'Atlantique Nord, un exemple d'évaluation de stratégie de gestion a été réalisé sur un modèle opérationnel de l'espadon en utilisant 5 procédures de gestion à titre d'exemple. Les procédures de gestion ont été évaluées en fonction de quatre exemples de mesures des performances et les résultats ont été présentés sous forme de tableau de statistiques récapitulatives et de graphiques sous forme de diagrammes de compromis et de projections.*

### RESUMEN

*Se describe el marco para llevar a cabo la evaluación de la estrategia de ordenación para el pez espada del Atlántico norte, incluyendo el establecimiento de un modelo operativo, el desarrollo de procedimientos de ordenación para evaluar, y el establecimiento de mediciones de desempeño para evaluar el desempeño de los procedimientos de ordenación candidatos. Para ilustrar las características del marco en el contexto del pez espada del Atlántico norte, se realizó una evaluación de un ejemplo de estrategia de ordenación sobre un modelo operativo de pez espada utilizando cinco ejemplos de procedimientos de ordenación. Los procedimientos de ordenación fueron evaluados considerando cuatro ejemplos de mediciones de desempeño, y los resultados fueron presentados como una tabla de estadísticas resumidas y gráficamente a través de gráficos de compromiso y proyección.*

### KEYWORDS

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

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## 1. Introduction

The management strategy evaluation (MSE) framework for the North Atlantic swordfish (*Xiphias gladius*) has been developed as an R package: *SWOMSE*. Distributing code as part of an R package has several advantages including: straightforward installation that does not require extensive setup, transparent open-source code that is easy to copy and modify, a free, open-source software environment, built-in help documentation for all functions, and the ability to link to and build on other existing R packages.

The *SWOMSE* package is built upon a foundation of two existing R packages, *DLMtool* (Carruthers and Hordyk, 2018; Carruthers and Hordyk, 2019) and *MSEtool* (Huynh, Carruthers, and Hordyk, 2019). Technically, *DLMtool* is an R package that contains the code for a single-sex, multiple-area, age-structured operating model (OM), a collection of 100+ data-limited (i.e., do not use a quantitative stock assessment) management procedures, and code for summarizing and presenting performance of alternative management procedures (MPs), while the *MSEtool* package is an extension that includes a range of computationally efficient quantitative stock assessment models, including statistical catch-at-age, surplus production, and delay-difference assessment models, and a range of other extensions. As *MSEtool* uses the *DLMtool* package as a dependency (i.e., all *DLMtool* code is available in the *MSEtool* package), hereafter we only refer to the *MSEtool* package.

Conducting an MSE is typically an iterative process, requiring numerous rounds of examining and refining the operating model, proposing additional candidate management procedures, and agreeing upon a set of performance metrics that will be used to evaluate the MPs. For this reason, it is important that an MSE framework is extensible, and easily allows for the addition or modification of management procedures, performance metrics, and other components of the MSE process. The *MSEtool* package was considered a suitable foundation for the swordfish MSE primarily because it is extensible and easily allows custom management procedures and custom performance metrics to be developed and included in the analysis.

There are several other reasons why *MSEtool* was used as the primary dependency for the *SWOMSE* R package. Firstly, the proposed operating models for North Atlantic swordfish are a set of alternative stock assessment models (a base case model, and various alternative models from an uncertainty grid using different assumptions) conducted with the Stock Synthesis 3 (SS3) platform (Methot and Wetzel, 2013). *MSEtool* includes functions to import the results of the fitted SS3 models to be used operating models in the MSE framework. Secondly, using *MSEtool* allows access to the computationally efficient stock assessment models. The assessment models have been constructed with Template Model Builder (TMB; Kristensen et al., 2018), which is required to make the models run fast enough to be evaluated by closed-loop simulation testing. Finally, *MSEtool* is available on the Comprehensive R Archive Network (CRAN) online repository, which means that the package is freely available, easy to install, and meets the strict programming (all code is tested on various platforms) and documentation (all functions are documented with help files and examples) requirements specified in the CRAN policy.

This paper describes the North Atlantic swordfish MSE framework, and provides examples of the primary features and functions of the package to evaluate the performance of alternative management procedures.

## 2. Methods

MSE requires several components: 1) the construction of one or several operating models describing historical fishery dynamics, 2) specification of models for observation and implementation error processes for future projections, 3) development of management procedures to be evaluated, and 4) mathematical description of performance metrics used to evaluate performance.

The following sub-sections describe how these components are developed in the swordfish MSE framework, and provides brief examples of the basic functions in setting up the MSE, running the analysis, and interpreting the results.

### 2.1. Operating Models

Operating models are imported from SS3 assessments into the *MSEtool* framework with a single line of code:

```
OM <- SS2OM(SSdir)
```

where `SSdir` is the file path to the output files from an SS3 assessment, an OM is an R object containing the operating model. `MSEtool` follows the object-oriented programming paradigm, which means that all objects are defined in a particular object class and have properties associated with that class.

In the example code above, OM is an object of class 'OM'. Help documentation for all objects of class 'OM' can be found following the usual R manner, by typing the following in the R console:

```
?'OM-class'
```

The contents of class 'OM', i.e., the dynamics of the operating model, can be examined by the `plot` command (e.g., `plot(OM)`), which produces a report that contains figures of the population dynamics that are generated from the operating model.

The reference case swordfish SS3 model and the 173 reference set SS3 models from the uncertainty grid that converged, can be evaluated individually (i.e., 174 separate OMs), or combined into a single OM (i.e., one OM with 174 separate simulations) to identify a management procedure that is robust to the uncertainty in all the SS3 models. A model validation process is required to identify the most plausible SS3 models and exclude those that are not considered to be a plausible representative of the fishery.

For strictly demonstration purposes, this paper uses a single OM containing the 174 SS3 assessments. It is straightforward to modify this OM to only include SS3 models that meet the validation criteria developed elsewhere.

## 2.2. Observation and Implementation Models

Evaluating the impacts of observation error is an important part of MSE. `MSEtool` contains 6 example observation models, with parameters that define the bias and precision of all simulated fishery data, including catches, indices, life-history parameters, and other data such as annual catch-at-age and catch-at-length compositions.

For example, an OM with no observation error, i.e., perfect information, can be constructed by simply replacing the observation model in the OM with a perfect information observation model:

```
OM_perfect <- Replace(OM, Perfect_Info)
```

where `Perfect_Info` is an object from `MSEtool` of class 'Obs' and `OM_perfect` is a new object of class 'OM' with no observation error.

Custom 'Obs' objects can also be constructed to specify the observation errors for a particular fishery. For example, an observation object such as `SWO_Obs` can be developed containing the parameters for the swordfish observation error model and added to the OM following the manner demonstrated above.

Implementation error relates to how well a total allowable catch (TAC) recommended by an MP is implemented in the fishery. High implementation error means that actual catches are not strongly determined by the MP, whereas low implementation error means that the annual catches closely match the TACs recommended by the MPs.

`MSEtool` also includes the ability to characterize the statistical properties of model fits to data. For example, by including the real data as an argument to the MSE, error, autocorrelation and hyperstability / hyperdepletion can be maintained in MSE projections.

## 2.3. Management Procedures

Management procedures are functions of class 'MP' that take fishery data (an object of class 'Data') and return a management recommendation of a TAC, a total allowable effort (TAE), size regulation, spatial closure, or some combination of all four management types. `MSEtool` includes over 100 MPs, ranging from simple approaches such as a setting at TAC at the historical average catch, to more complex approaches such as a statistical catch-at-age assessment model with a harvest control rule.

It is straightforward to develop custom MPs and added them to the MSE analysis. The `SWOMSE` R package includes 2 example MPs that adjust TAC recommendations based on trends in the index of abundance relative to a target index level, and one example MP that fixes the TAC at the current level for all projection years. The

SWOMSE user manual describes how these MPs are constructed and imported into the MSE framework. As they were intended for demonstration purposes, these MPs are very simple in their design. However, more complex MPs, for example, including multiple indices or nested decision rules, can be developed following these same principles.

## 2.4. Performance Metrics

Performance metrics are functions of class ‘PM’ that take the output of an MSE (an object of class ‘MSE’) and returns a quantitative summary of the performance of the MPs included in the MSE. MSEtool includes 9 built-in PM functions covering various metrics related to sustainability and economic performance, such as the probability of biomass falling below some fraction of  $B_{MSY}$ , and average short- or long-term yield. The SWOMSE package includes two example PM functions, and includes all PM functions from MSEtool. Following the same approach described for MPs above, it is straightforward to develop custom PM functions specific to the swordfish fishery and include these in the MSE analysis. Examples of the construction of custom MPs are provided in the SWOMSE and MSEtool user manuals and help documentation.

## 2.5. Running and evaluating the MSE

The MSE is run on an operating model using the runMSE function in single line of code:

```
MSE <- runMSE(OM, MPs)
```

where MSE is an object of class ‘MSE’ containing the MSE results, OM is the operating model described above, and MPs is a list of names of MPs to be evaluated. For example, to run the MSE using the 3 demonstration MPs from the SWOMSE package and some reference MPs from MSEtool the following command is used:

```
MPs <- c("ConstC", "Itarg1", "Itarg2", "FMSYref", "NFref")
```

where ConstC, Itarg1, and Itarg2, are the constant catch MP, and the two index-targeting MPs in SWOMSE respectively, and FMSYref and NFref are reference MPs from MSEtool that specify at fishing at FMSY and no fishing respectively.

The results of the MSE can be examined as a table of performance statistics for the MPs using:

```
summary(MSE, PMs)
```

where PMs is a list of names of performance metrics used to evaluate the MPs. The results can also be presented graphically using a series of plots such as trade-off plots (TradePlot(MSE, PMs)), projection plots (Pplot(MSE)), or wormplots (wormplot(MSE)). Custom plotting functions can also be developed for presenting the results of the MSE.

## 3. Results

The results of an MSE for the North Atlantic swordfish OM, evaluating the 5 management procedures described above, are presented here for demonstration purposes only. It is important to note that these results are based on the 174 SS3 models without any consideration of model validation, and the MSE was conducted without any observation or implementation error.

The quantitative performance of the 5 MPs is calculated for the four example performance metrics (**Table 1**). These results indicate that unsurprisingly the FMSYref reference MP results in both the highest short-term and long-term yield, and has one of the highest probabilities of the spawning biomass remaining above half of  $B_{MSY}$  (**Table 1**). The ConstC (constant catch) and Itarg1 (index-targeting) MPs perform similarly in terms of average short-term yield, but the Itarg1 MP performs worse in terms of long-term yield, probability of spawning biomass remaining above the reference point, and stability of future catches (**Table 1**). In contrast, the Itarg2 MP has lower average short-term catches, but catches remain relatively stable throughout the projection period and there is a high probability that the spawning biomass remains above the critical level (**Table 1**).

These results suggest that there are trade-offs in the performance of the three TAC management procedures. These trade-offs are more clearly seen when examining the results graphically. **Figure 1** shows a trade-off plot for the 5

MPs and the 4 performance metrics, and clearly indicates that, apart from FSMYref and NFref which are reference MPs and intended to be applied in reality, trade-offs exist between all the MPs such that no single MP outperforms all of the others.

Projection plots are useful for examining the performance of the alternative MPs over time, with respect to fishing mortality, biomass, catch, or other metrics of interest. **Figure 2** shows projection plots of  $F/F_{MSY}$  and  $B/B_{MSY}$  for the 5 MPs over the 50-year projection period. Examination of the projection plots reveals why the Itarg1 MP performed worse than Itarg2 for all performance metrics except average short-term catch; simulations where the initial biomass was close to  $B_{MSY}$  tended to result in the stock declining to very low levels, whereas simulations with a higher initial biomass tended to result in the stock remaining above  $B_{MSY}$ .

#### **4. Discussion**

This paper described the MSE framework for the North Atlantic swordfish fishery, and provided examples of the main functions used to set up the MSE, select the management procedures, set the performance metrics, run the analysis, and interpret the results.

The framework for the swordfish MSE has been developed as an R package, and built upon the existing MSEtool framework. This allows users the flexibility of accessing all functions and documentation in MSEtool and extending the package with custom built OMs, MPs, performance metrics, and others functions specifically for the North Atlantic swordfish fishery.

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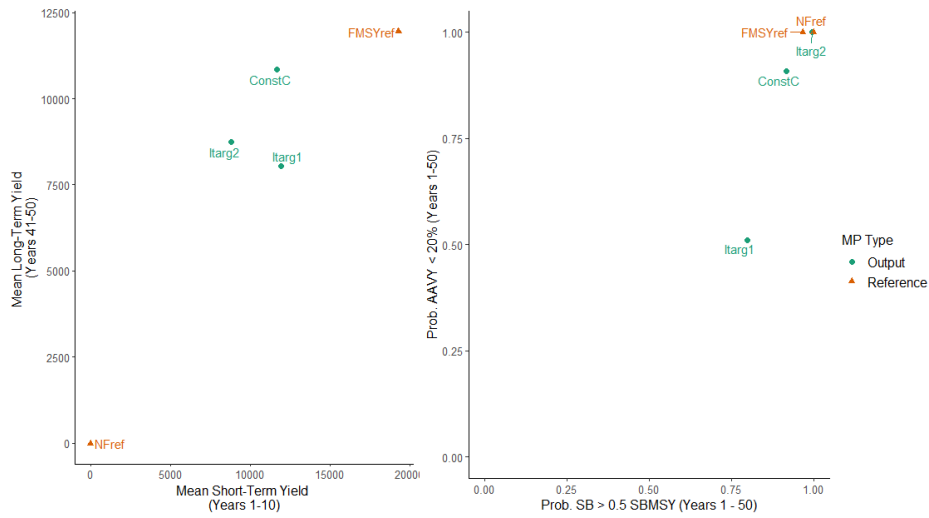
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## References

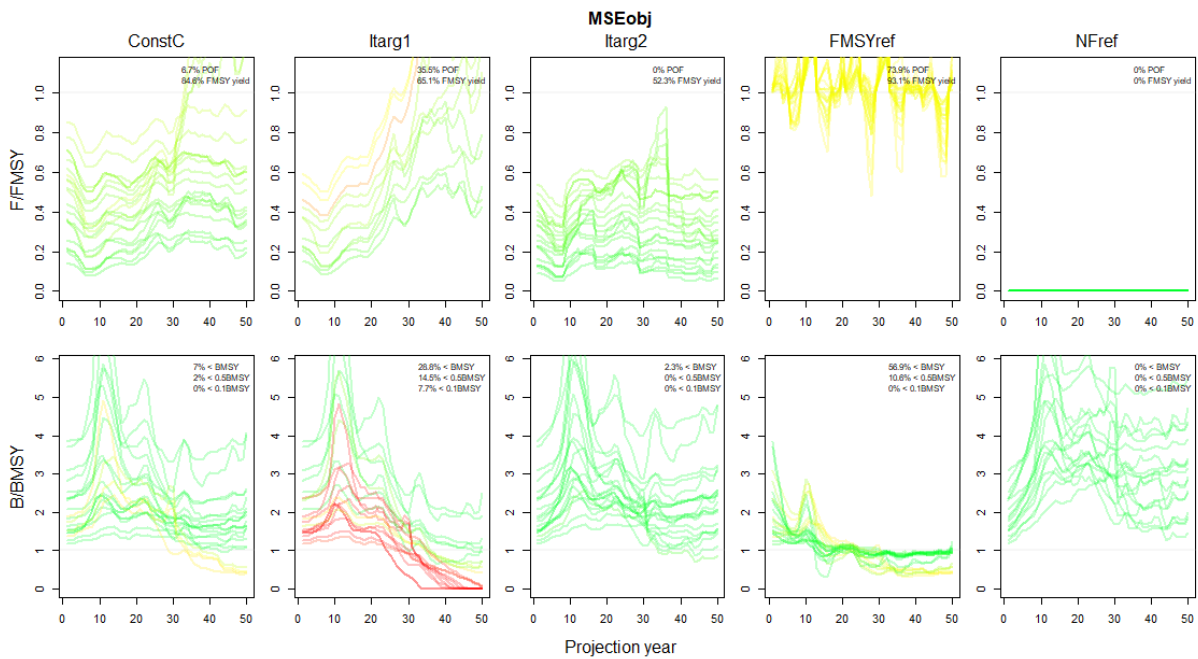
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**Table 1.** Summary statistics of the five example management procedures (ConstC: constant catch at current TAC; Itarg1: iteratively adjusts TAC based on trend in recent index compared to a target; Itarg2: similar to Itarg1 but uses a different target; FMSYref: reference MP fishing at  $F_{MSY}$ ; and NFref: a no-fishing reference MP) calculated for four example performance metrics: STC, average catch in the first 10-years of the projection period; LTC, average catch in the last 10-years of the projection period, the probability spawning biomass ( $SB$ ) is greater than  $SB_{MSY}$ , and the probability the average annual variability in yield (AAVY) is less than 20%.

<b>Management Procedure</b>	<b>STC (ton)</b>	<b>LTC (ton)</b>	<b>Prob. <math>SB &gt; 0.5SB_{MSY}</math></b>	<b>Prob. AAVY &lt; 20%</b>
ConstC	1.2e+04	1.1e+04	0.92	0.91
Itarg1	1.2e+04	8.1e+03	0.80	0.51
Itarg2	8.8e+03	8.7e+03	1.00	1.00
FMSYref	1.9e+04	1.2e+04	0.97	1.00
NFref	0.00	0.00	1.00	1.00



**Figure 1.** Example trade-off plot showing the performance of 5 management procedures (ConstC: constant catch at current TAC; Itarg1: iteratively adjusts TAC based on trend in recent index compared to a target; Itarg2: similar to Itarg1 but uses a different target; FMSYref: reference MP fishing at  $F_{MSY}$ ; and NFref: a no-fishing reference MP) for 4 example performance metrics (STC, average catch in the first 10-years of the projection period; LTC, average catch in the last 10-years of the projection period, the probability spawning biomass ( $SB$ ) is greater than  $SB_{MSY}$ , and the probability the average annual variability in yield (AAVY) is less than 20%).



**Figure 2.** Example projection plots of  $F/F_{MSY}$  and  $B/B_{MSY}$  for the 5 management procedures (ConstC: constant catch at current TAC; Itarg1: iteratively adjusts TAC based on trend in recent index compared to a target; Itarg2: similar to Itarg1 but uses a different target; FMSYref: reference MP fishing at  $F_{MSY}$ ; and NFref: a no-fishing reference MP).