Report of the 1st Meeting of ICCAT GBYP Core Modelling Group
1-4 December 2014,

ICCAT Secretariat, Calle Corazón de Maria 8, 28002 Madrid, Spain

1. **Opening of the meeting (CD)**

Dr Davies, Chair and MSE Coordinator, opened the meeting and welcomed participants to the first meeting of the BFT Modelling and MSE Group.

Apologies were received from:

- Dr. Clay Porch, Rapporteur W-BFT,
- Dr. Sylvain Bonhommeau, Rapporteur E-BFT,
- Dr. Polina Levontin, independent expert in risk assessment, Imperial College,
- Dr. Rich Hillary, independent expert in stock assessment and MSE, CSIRO,
- Prof. Doug Butterworth, University of Capetown

who were not able to attend the meeting.

The list of participants is attached in Annex 1

2. **Confirmation of agenda (CD)**

The agenda was accepted as circulated (Annex 2).

3. **Nomination of Rapporteur(s) (CD)**

Rapporteurs were appointed as follows

Rapporteurs	Item
Antonio Di Natale	Update on progress and funding decisions for GBYP
Campbell Davies	Relevant outcomes of SCRS and Commission meeting; Overview of draft modelling and MSE work program; Revision of modelling and MSE work program.
Tom Carruthers	Review of deliverables from current MSE modelling contract
Laurie Kell	Review or previous and current GBYP and ICCAT activities on modelling and MSE; Engagement strategy for BFT-SpG, SCRS & Commission
David Die, Haritz Arrizabalaga, Yukio Takeuchi	Review of stock assessment requirements and work plan 2015-2016
Paul De Bruyn	Data collation requirements

4. **Relevant outcomes from 2014 Annual meeting of Commission**

The report from the 2014 Commission meeting was not available at the time of the meeting. However, Dr. Pallarés provided an overview of the items of relevance to the Modelling Group.

These included:

- The agreed recommendations for eastern (14-04) and western (14-05) BFT, which included TAC increases for both stocks.
- The high priority the Commission placed on the completion of the MSE work program and development of new and/or improved assessment methods for BFT, in particular to inform advice in 2016.
- Identification of important uncertainties in state and productivity of the two stocks, including: the form of the stock-recruitment relationship for both stocks, population structure and connectivity among East and West management units, and the nature of the relationship between stock abundance and the available abundance indices (i.e. CPUE). The respective recommendations request that the SCRS provide advice on the sensitivity of the current and 2016 advice to these uncertainties via MSE.
- Re-iterate quantitative objectives for the rebuilding plans of the respective stocks, including desired levels of performance and the need to revisit these in light of the 2016 assessment and, possibly, the MSE.
- Request the SCRS advice on: i) what constitutes a "serious threat of stock collapse" and ii) the potential utility of time-area closures in the management of the bluefin spawning stocks.

The Group thanked Dr. Pillarès for her summary, noting that the outcomes of the Commission provided considerable guidance for the Modelling and MSE work program. The specifics of the relevant Commission and SCRS outcomes as they related to the Modelling and MSE work program were revisited in detail under item 9.

5. **Update on progress, current status and funding of ICCAT GBYP**

The GBYP coordinator provided an overview of progress of the relevant ICCAT GBYP activities, which can be useful for the development of MSE. The full and detailed description of the updated GBYP activities is on the document SCRS/2014/051.

The Group was informed about the data mining and data recovery activities, specifying the data that are already quality checked, controlled and included in the ICCAT BFT database. The trade, auction and market data sets are now validated and should be included in the ICCAT BFT database as soon as possible, after setting a proper format in the ICCAT data base. These data are available for SCRS uses, and the few ancient trap data sets obtained in the last part of Phase 4 are still to be checked and are likely to form only a small part of the historical Task I series, dating from 1512, is already available.

The group reviewed the summary of data collected by the three GBYP aerial surveys on spawners and the plan for future aerial surveys under Phase 5. The Group was advised about the tagging activities (both conventional and electronic) and the initial results about evidence of mixing both between the east and the west and within the Mediterranean. The results of the biological work were also presented, including the preliminary results of the genetic and microchemistry analyses, showing the possible presence of multiple populations and the variable W/E mixing in some areas with relevant inter-annual variability.

The group discussed the available sources of evidence of bluefin tuna movements in different parts of the ICCAT area which were assembled by GBYP in the first four Phases and which could be considered in the MSE development. This discussion was picked up in the review of the work program, in particular the proposed workshop to review in detail alternative hypotheses for population structure and connectivity and the priority for a comprehensive analysis of the individual and combined sources of information available through the GBYP and various related national research initiatives (see Table 1 of revised work program and task description for analysis and workshop).

6. Overview of draft Work Program for Stock Assessment and Management Strategy Evaluation for Bluefin Tuna

The Modelling and MSE Coordinator provided an introduction and overview of the draft work program. The draft circulated to the Group (Davies, 2014) had been updated for the outcomes of the SCRS meeting, but not the Commission. The Coordinator recalled the objectives for Modelling and MSE component of the GBYP:

1. Collate, manage and synthesise new data and information collected through GBYP Program and other appropriate sources;
2. Facilitate consultation and capacity building on Reference Points, Harvest Strategies and MSE for Bluefin for the SCRS and Commission;
3. Develop, document and maintain an integrated MSE modelling platform for:
    a. Examining the relative plausibility of alternative hypotheses about the population structure and dynamics of BFT and fisheries;
    b. Developing and testing new stock assessment approaches;
    c. Evaluating alternative harvest strategies and reference points, and;
    d. Building capacity and understanding of the role of reference points, harvest strategies and MSE in the fisheries monitoring, assessment and management system.
4. Facilitate the evaluation, selection and adoption of harvest strategies for bluefin that meet the objectives of ICCAT, as specified by the SCRS and Commission.

That the work program has been structured in five components:

1. Data collation, management and synthesis
2. Review and selection of alternative stock assessment models
3. Development of MSE modeling platform
4. Capacity building in Harvest Strategies, Reference Points and MSE (see: http://iccat.int/Documents/Meetings/Docs/2014-SWGSM_ENG.pdf)
5. Consultation and engagement in design and evaluation of Harvest Strategies.

The Core Modelling Group has been convened to provide expert advice and guidance on the development and implementation of the work program and to assist the implementation of the program through the BFT Species Group, SCRS and Commission, as appropriate.

The Group reviewed the Terms of Reference and name of the group previously approved by the GBYP Steering Committee. The group considered that the TORs as drafted were appropriate, although it was noted that the current title and the fact that participation in this 1st meeting of the Group was restricted to members and *ex-officio* participants had raised concerns that participation in future meetings of the group may be to narrow, and that this was undesirable in the context of transparency and the capacity building objectives of the process.

The Chair clarified that this was not the intention; the limited participation in this first meeting of the Group was to facilitate the focused technical discussions required to refine and finalise the work-program and consider the role of the Group and its relationship with the BFT Species Group and SCRS and other working groups more generally.

It was agreed that:

- future meetings and activities of the Group will generally be open to participants in the BFT Modelling and MSE work program;
- the group shall be retitled "GBYP Modelling and MSE Group"; and
- the secondary role of the group and the BFT Modelling and MSE work program in contributing to broader capacity development in stock assessment, reference points, HCR and MSE across ICCAT will be promulgated through the SCRS and relevant working groups by the SCRS Chair and Rapporteurs.

The Group re-affirmed the objectives and proposed structure of the work program and Terms of Reference for the operation of the GBYP Modelling and MSE Group and recommended the name of the Group be revised as proposed to emphasise it's open, inclusive and transparent operation.

7. **Presentation of the initial deliverables under the Modelling Contract 2014-2**

GBYP 2014-2 includes three principal deliverables:

(1) A design document that details an object orientated (OO) design with code based on C++ and/or S4 classes for i) a multi-population OM that can be conditioned on a variety of data sets and hypotheses and ii) an Observation Error Model (OEM) that can be used to evaluate different data collection regimes e.g. aerial survey, tagging programs, catch and catch per unit effort (CPUE) and size to age conversions.

To address this deliverable, Report 1 of the contract includes a full description of the preliminary MSE framework including diagrammatic representations of the relationship of objects, the definition of these classes and their related methods (See XX GBYP\Modelling and MSE).

(2) Summary of alternative management procedures including alternative stock estimation procedures with coding requirements and appropriate code, libraries and packages. For example there are a variety of stock assessment methods already coded up and these may need modification to be used within a common MSE framework or adapted to use GBYP data and BFT stock assessment assumptions.

In collaboration with the MSE Modelling Group a simulation evaluation study was carried out on a total of 26 potential management procedures. The approach and results have been summarized in a draft peer-reviewed paper that was made available for the meeting (Carruthers et al 2014b).

(3) MSE demonstrator for use with stakeholders to illustrate the impact of uncertainty on management objectives and collaboration on a manuscript describing these results.

A streamlined demonstration of the preliminary BFT MSE was made available to the group including the fully specified Bayesian belief network for dynamic investigation of the preliminary MSE results. All code for the MSE framework was shared with the group and is available for the GBYP Modelling and MSE program. The group discussed the relative merits of software for communicating MSE concepts and results to wider audiences. While Bayesian Belief Networks (BBN) may be suitable for other scientists or more technically oriented stakeholders they may not necessarily be appropriate for Commission members and other higher-level decision makers.

Other potentially suitable tools include ‘shiny’, which is an online presentation tool used by the International Pacific Halibut Commission to explore MSE outputs, and/or further development of the presentation approaches developed as part of the previous risk and uncertainty perception (Leach *et al*., 2014). The group noted that there was a general need for presentation and communication approaches for science and non-technical audiences as part of the MSE, reference points and HCR processes running across multiple RFMOs and that there would be both capacity building and process efficiencies. It was agreed that this should be recommended as an agenda item for the proposed meeting of the MSE technical advisory group associated with the GEF-FAO-WWF sustainable tuna ABNJ currently planned for the middle of 2015.

Dr. Kell presented preliminary results of simulation testing of assessment models as a basis for understanding the behaviour and estimation properties of statistical models that might be considered for use in a Management Procedure (MP) or Harvest Strategy (HS). This test case explored the mismatch in assumptions between data simulated from an age-structured model, with an implied production function that is asymmetrical, and a biomass dynamic model with symmetrical production function. The mismatch in assumptions only biased estimation by the “assessment model” for certain target exploitation rates and was largely independent of the choice of harvest control rule. This simple example clearly demonstrates that the interaction between “truth”, sampling error and the structural assumptions of an “assessment model” used in an MP can be subtle and counter-intuitive. This underscores the value of using simulation testing to explore the statistical properties of candidate “assessment models” for inclusion in management procedures. This work will be completed by Kell, Kimoto et al., and published in 2015 (see Kell *et al*., 2015)

Cross-validation (also known as retrospective testing) was noted as an alternative approach to simulation testing assessment approaches that might be considered for use in MPs, or as alternatives to the current VPA assessment used for BFT. This involves sequentially removing historical data and the re-running the assessment model to test its ability to predict the data that has been removed. This approach may be a useful preliminary test of candidate assessment methods for BFT because it is simple, transparent and based on real data that familiar to scientists working on BFT and is less time and resource intensive than full simulation evaluation.

Dr. Kell initiated a discussion on the graphical representation of MP performance using plot from Kell *et al*. (2014, ‘Exorcising the Spectre...’) as a straw man example. The multiple panel plot allows users to compare results from multiple assessment models, reference points and/or management procedures that satisfy a particular level of performance for multiple performance metrics. In the approach precented, each alternative was equally weighted. The group agreed that model weighting is a central step in the MP evaluation process and a substantive, in-principle discussion is required to scope out and agree a process and consider the details of alternative technical methods for the BFT MSE.

The group discussed future developments of the MSE modelling framework for 2015. The group considered the identification and selection of a range of “assessment models” and associated data that were considered most likely to be used in model-based/empirical MPs in the short term to be a high priority. While there are a range of potential candidates, including current and previous approaches used for BFT (e.g. extended survivorship analysis (XSA), virtual population analysis, statistical catch-at-age assessment, statistical catch-at-length assessment, spatial surplus production models and spatial delay-difference models) it was noted that a) not all would be suitable for inclusion in MPs and c) it would not be possible to evaluate them all by MSE within the time and resources available before the scheduled advice to the Commission in 2016. It was noted that the draft work program included a workshop, either associated with or shortly after the scheduled BFT data meeting in 2015, to identify candidate assessment approaches, agree on the testing criteria and ensure that the required data sets would be available for the MSE work program. The current rules for inclusion of new software in the ICCAT software catalogue was agreed as an appropriate basis for candidate assessment models for inclusion in MPs.

The other high priority deliverables that were identified were:

- the development of a spatial operating model that can be empirically fitted to the range of fishery, tagging and genetics and otolith micro-constituent data that are available for BFT, or are likely to become available within the duration of the current work program; and
- confirmation of the methods for raising of catch composition data to the total catch-at-age dataset required by virtual population analyses and extended survivorship analyses.

The group agreed that imputation approaches developed for tropical tunas under previous contract (Carruthers XX, 2012) should be investigated in the context of BFT in order to understand the impact on assessments and to better characterize observation models for such data for data generation in operating models.

The group thanked Dr. Carruthers for his presentation and work delivered through GBYP 2014-2. This represents a substantial contribution to the tools available for the BFT modelling and MSE program for evaluation of assessment approaches and development and testing of harvest strategies and reference points. The group also complimented Dr. Carruthers on the thoroughness of the documentation and examples provided with the code, which would be of considerable assistance to other users. In this regard, the group noted that while these MSE tools have been developed under GBYP, their generic and flexible nature means that can be readily apply to other species and stocks and, as such, will assist in advancing the HS, reference point and MSE work program across ICCAT more generally.

8. **Review of previous work under GBYP Modelling and MSE**

There are a few projects relevant to MSE that have been conducted to support western BFT assessments and management. John Walter (NMFS) and Mark Maunder (IATTC) are collaborating to apply the MSE approach developed for Pacific Albacore (Maunder, 2014), which uses two linked SS3 models for Atlantic BFT. Lisa Kerr and Steve Cadrin are working with Nathan Taylor's MAST model to serve as an operating model for an MSE as well (Kerr *et al*., 2012; Kerr *et al*., 2014; Galuardi *et al*., 2014) and have a proposal to the 2014 NSF round to extend this work.

A new candidate for an alternative modeling approach for BFT stock assessments, based on applying Statistical-Catch-At-Length (SCAL) (Butterworth and Rademeyer, 2014a, 2014b, 2014c), was presented at the 2014 stock assessment of the Western and Eastern stocks of BFT. The SCAL model could also be considered as a candidate for an operating model for a MSE. Prof. Butterworth has advised the group (through the Chair) that they intend continuing the refinements of these models for the consideration in the 2016 assessment and use as an operating model for evaluation of MPs as part of the MSE program. The Chair also noted, that Prof. Butterworth has commented that he considered empirical harvest control rules likely to be more appropriate for BFT than model-based MPs, but this would be determined through MSE testing of potential candidates.

US scientists from NMFS (John Walter, Matt Loretta), VIMS (Jan McDowell, John Graves) and University of New Hampshire (Molly Lutcavage) are collaborating with CSIRO scientists (Campbell Davies, Peter Grewe and Mark Bravington) on a pilot project to determine the design of an application of the Close-kin Mark Recapture (CKMR) to assessment of BFT, in the first instance to the Western stock. This approach has been successfully applied to Southern Bluefin tuna (Bravington *et al.*, 2014) to the extent it is being considered for long-term monitoring of the stock. It is expected that if this approach is successful for western BFT it will provide the first estimates of spawning stock abundance that are independent of fishery data. The group considered it may be important to use an MSE approach to evaluate the value of such new method to management of BFT.

9. **Review and detailed discussion of tasks for stock assessment modelling and MSE 2015-2016**

9.1. Overview and proposed priorities given 2014 Commission decisions

The Group reviewed the draft detailed work program provided in Table 1 of Davies, 2014, in light of the relevant reported outcomes of the Commission, the status of the GBYP and the work completed to date under the Modelling and MSE program.

The Group noted:

- The outcomes and deliverables achieved to date under the GBYP Modelling and MSE program to date, in particular, the deliverables provided through project 2014-2 men that the program is well placed to complete delivery of the operating models, candidate management procedures and new assessment approach 9es) required to improve the scientific basis for advice on bluefin tuna.
- That while this program was focussed on bluefin, the flexible nature or the tools and comprehensive review of harvest control rules drawn from a range of tropical and temperate tunas and other stocks, means that the tools, capacity and knowledge developed through this GBYP program would be of great value to the wider reference points, harvest control rules and implementation of the Precautionary approach in ICCAT more generally.
- The request for new stock status and management advice in 2016 would place considerable strain on available stock assessment and modelling capacity among the CPCs. Hence, the dedicated coordination, advice and technical support of the MSE Coordinator and Expert Technical Assistant would be essential in meeting the requests of the Commission and the objectives of the program. Continuity of expertise was considered a high priority to maintain current *momentum* and meet the timelines requested by the Commission.
- The expectation of “new data” and “new modelling approaches” to inform SCRS advice to the Commission in 2016 (14-04 and 14-05) and 2017 (14-04) means confirming and addressing the priority data collation tasks for the March 2015 BFT data preparatory meeting and consolidation and analysis of the available tagging, Genetics and micro-constituent data were a high priority and urgent task for 2015.
- The important of engaging the wider BFT Species Group and SCRS in the work program and delivery of essential tasks as soon as possible.

- To the extent possible, meetings of the Modelling and MSE Group should be scheduled to coincide with existing meetings (e.g. Species Groups, Methods Working Group) and/or larger workshops to minimise additional travel costs and increase the opportunity for participation and capacity building for CPC scientists.
- It was important for transparency and acceptability of the final outcomes that the dedicated technical workshops were open to participation of external experts and scientists with particular expertise in bluefin biology and ecology and design and evaluation of management strategies.
- The desirability of initiating regular dialogues with commissioners, scientific advisors, industry, NGOs and others interested parties on reference points, harvest control rules and MSE from early in the process to build understanding, confidence and engagement in the development and evaluation process.
- The SWG-SM was the natural forum for engaging in this more informal dialogue, assuming this is considered appropriate by the Commission and the Chair of the SWG-SM.

9.2. Testing and evaluation of alternative assessment approaches for 2016 BFT Assessment

The current assessment for BFT is done with a VPA approach. Other assessments methods that have been used include SCAL, iScam and SS3 for the eastern stock. In addition, a biomass dynamics approach has recently been developed for the western stock. A variety of alternative management procedures are available for consideration for BFT (e.g. Carruthers *et al*., 2014). As noted by the group above, not all of these are likely to be appropriate for use as “assessment models’ in MPs and not all have been tested in to determine whether they meet the requirements of the ICCAT software catalogue.

There is a range of related aims that can be addressed through simulation modelling using a operating models, including testing the statistical properties and predictive abilities of assessment models, evaluation of reference points, harvest control rules and management procedures. Kell *et al*., 2006, for example, used the current (at the time) stock assessment model to test its ability to estimate the population parameters using data generated by the same population model. While the use of the assessment model as the operating model seems to imply that the assessment model describes the underlying reality almost perfectly, if an assessment model cannot perform well when the underlying reality is effectively identical to itself (i.e no model/structural uncertainty), it is unlikely to perform adequately for more comprehensive representations of the uncertainty. Kimoto, Kell and others are working on the four assessment methods prepared for the 2014 BFT assessment update to examine in more detail why they provide different results and to determine the extent to which they could be used as alternative operating models for the BFT MSE.

The other extreme is when the emphasis is on expert beliefs and other *a priori* information about the processes that may affect the behaviour of management systems in the future (i.e. the focus is on the future, not on fitting historical data). This is a less data-, and more hypothesis-orientated approach.

For example, climatic change studies may show that a regime shift is possible (even though one has never been seen in the historical data sets) and should be taken into account when selecting ways to provide management advice (e.g. Ravier and Fromentin, 2001; Dufour *et al*., 2010; Fromentin *et al*., 2010, 2013). Alternatively management has resulted in past fisheries data being unreliable and unrecoverable. It is important therefore that OMs are flexible so that they can deal with such factors.

9.3. Review of current status and ongoing work

The Secretariat made an extensive summary of a variety of modelling tasks completed so far. Prior to the GBYP several peer review papers related to bluefin MSE have been published (e.g. Kell *et al*., 2003) and the evaluation of the robustness of maximum sustainable yield based management strategies to variations in carrying capacity and migration pattern for bluefin (Kell and Fromentin, 2007; Fromentin and Kell, 2007).

Under phases II, III and IV of the GBYP, additional progress was made in support of the MSE process, with SCRS and peer review papers published and proposed. These include Risk Analysis, example MSEs, development of Operating Models (OMs) Observation Error Models (OEMs) and Management Procedures (MPs). SCRS papers have also been written on diagnostics and presentation of advice and software has been developed in R (e.g. Kell et al., 2007). An example MSE based on the CCSBT Harvest Control Rule (HCR) has also been evaluated Kell et al. (2014). This will aid in developing and running the MSE. Most of the assessment tasks for bluefin have already automated using R scripts. All software and code will be open source and made available on the ICCAT cloud server.

A review of historical uncertainty (Fromentin *et al*., 2014) and a qualitative Risk Assessment have been conducted with members of the SCRS and the Commission (Leach *et al*., 2014). Following these papers a quantitative analysis (Kell, 2014b) was used to identify the main sources of uncertainty that could be developed for the Operating Model and ways of weighting then proposed (Levontin *et al*., 2014).

The secretariat also identified work in progress, including elasticity analysis, a review of population hypotheses and stock assumptions, alternative management procedures, cross-validation of stock assessment methods and the use of PID control systems.

A summary of the t-RFMO MSE working group was also provided. A variety of related activities are being conducted under the tRFM-MSE WG, e.g. the Review of Kobe Strategy Matrix, comparative studies (e.g. across species or across RFMOs), MSE-lite, Communication, Code sharing repositories, Parallel Computing, and developing Glossary of terms and bibliography repository. It is proposed to have a meeting in the 2nd-3rd quarter of 2015, under the GEF ABNJ umbrella to agree future activities. Activities under GEF are aimed to build capacity amongst stakeholder groups, while that of the tRFMO-MSE group is to build capacity with tRFMO scientific committees. Additional intra-regional collaboration is also being developed, as agreed under the Strategic Plan, for example on Social Economics factors as required by the SWGSM Standing Working Group on Science and Managers), with ICES and EU.

9.4. Considerations for Modelling and MSE in context of 2016 BFT stock assessment

The next eastern Atlantic Bluefin tuna stock assessment is scheduled in 2016. This assessment is scheduled to be a new (not just an update) assessment, incorporating new information and improved assessment approaches as well as updated fishery data. The Atlantic-wide Research Program for Bluefin tuna (GBYP) and various National programs have produced a wide range of new information on the biology and fisheries for bluefin tuna. This information was reviewed in the 2014 BFT data preparatory meeting, aiming to incorporate the new fishery information in ICCAT databases as well as introducing some new pre-analysis and assessment modelling approaches. However, it was evident during the 2014 assessment that some of the available data has yet to be fully processed and reviewed, and the proposed modelling frameworks are not yet fully developed or tested.

Additional progress will be evaluated during the 2015 Data preparatory meeting. The main data issues for that meeting are related to the revision of Task II data by validating and integrating the catch at size statistics with new information from farms, both data during harvesting as well as that coming through the stereo-video cameras, as well as other sources of information.

Additional tasks to be achieved during the 2015 data preparatory meeting are to review past and recent tagging data, review progress on developing age-length keys, and review progress on life history studies such as maturity and fecundity schedules, stock structure and mixing rates (using otolith microchemistry, genetics, electronic tagging etc.). The Modelling group considered it would be important, as part of the agenda of the data preparatory meeting, to include an item on the development and testing of new assessment approaches being considered for use in the 2016 assessment. The Group recommended this include two components:

- The assessment methods to be considered for use in 2016 and appropriate criteria for determining their suitability for use an assessment models in 2016; and
- Consideration of a process for comparative evaluation of the alternative methods and how this may be completed as part of the longer term work program beyond the immediate need for assessment advice in 2016.

During the species group meetings, the Bluefin working group is expected to update fishery indicators (i.e. catch rates), as well respond to Commission requests as in the 2014 Commission report (not available at the time of drafting this report).

During the last couple of years, several alternative modelling approaches have been developed, including SCAL, iScam and SS. These approaches are expected to further be developed during 2015-2016 and considered for use in the 2016 assessment. The group, following earlier recommendations from the WGSAM, noted the need to validate and catalogue any new software used to evaluate stocks. Recommended approaches for validation of assessment methods include those of considered at SISAM (Deroba et al. 2014), cross-validation and simulation evaluation using an Operating Model, as recommended in the draft Modelling and MSE work program. The group noted, however, that simulation evaluation was resource and time intensive and that it would not be possible to complete such a detailed evaluation prior to 2016.

The group noted that these alternative assessment approaches could be useful for conditioning OMs in the MSE framework developed by Dr. Carruthers. However, the current methods/codes are likely to require additional refinement in order to run reliably in a simulation context and to provide more realistic representations of dynamics and uncertainty. Additional considerations include: complex subpopulation structure, temporal shifts in targeting and biological features and/or environmental influences on BFT population dynamics (e.g. Fromentin *et al*., 2014; Arrizabalaga *et al*., 2014).

The Group recommended that it would be necessary for proponents/developers of alternative approaches to provide the code and data and parameter inputs to the Expert MSE Technical Assistant so that the code could be refined and optimised for inclusion in the MSE modelling platform. This would ensure consistency and transparency of approach and provide a platform for consistent testing and comparison of assessment methods proposed for use in harvest strategies/management procedures. This was considered a priority task that should be completed by the Expert MSE Technical assistant in 2015 for consideration at the 2015 meeting of the BFT Species Group. This would require attendance by the Expert MSE Assistant at the 2015 BFT Data Preparatory meeting to ensure that the data required for likely candidates was going to be available and in the form required for evaluation.

Finally, during the last decades, within the GBYP and other national and international research programs, important amounts of new biological information has been generated, especially on population structure and mixing (e.g. see the report of the meeting on Biological parameters in Tenerife, 2013). This information is especially valuable to inform the development and specification of alternative hypotheses and scenarios for the MSE process, in particular to parameterize plausible population structure and mixing hypotheses.

As the new data and hypotheses are based on different sources of data and methodologies (e.g. electronic tagging, microchemistry, genetics…) and in many cases the raw data is not held by ICCAT, the Modelling group recommended that consolidated analyses be conducted through a coordinated project (in 2015) and workshop in late 2015 or early 2016. The objectives of such a task and dedicated workshop would be to confirm the plausible hypotheses to be used in MSE, as discussed in the 2013 Tenerife meeting, parameterize the spatial structure and connectivity in the MSE operating models, and engage the wider scientific community in the BFT Modelling and MSE process. The group agreed that, while analysis based on the primary datasets is desirable, it may be difficult to reach agreement on data sharing and analysis arrangements. A default position in the case that data access cannot be achieved would be for the Group to request specific and simple queries on estimated transition probabilities from the relevant research groups. This may be sufficient to start parameterize the spatial structure and mixing hypotheses in the OM for the MSE in the short-term.

The Group recommended that the Chair of the GBYP Modelling and MSE Group contact each of the relevant research groups and invite them to participate in the development of the OMs through the provision of data, analysis results and participation in the planned proposed workshop. This should be done as early in 2015 as possible in order to provide sufficient time for analyses of the new data and organization of the workshop in late 2015-early 2016.

10. **Detailed review and refinement of work program for evaluation of management frameworks**

The results of the detailed review of the work program are given in Table 1.

The recommended meetings to be attended by the MSE and Modelling Coordinator and MSE Expert Technical Assistant are:

1. ICCAT Methods Working Group meeting: 16-20 February 2015. Campbell Davies (MSE and Modelling Coordinator) to potentially attend in conjunction with Tuna ABNJ meeting in Panama.
2. ICCAT BFT data preparatory meeting: 2-6 March 2015. Tom Carruthers (Expert MSE Technical Assistant) to attend.
3. ICCAT Species Group meetings: 23-25 September 2015. Campbell Davies (MSE and Modelling Coordinator) to attend. Need for Expert MSE Technical Assistant to attend to be confirmed, pending outcomes of Data Preparatory meeting
4. Population structure and connectivity work shop with 2nd GBYP MSE and Modelling Group meeting. December 2015/January 2016. Both Campbell Davies (MSE and Modelling Coordinator) and Tom Carruthers (Expert MSE Technical Assistant) to attend.

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Table 1. Draft Budget for BFT MSE work program 2014-2018.

Year	LEAD	Item/Activity	Indicative Budget
2014	MSE – Coordinator	i) Review work program; ii) Convene Core Modelling Group (CMG); iii) Develop revised Modelling and MSE program.	34,000
	MSE – Tech Expert	i) Preliminary scoping and coding of Operating Model; ii) Review and evaluation of potential harvest control rules iii) MSE *Geni* demonstrator model. See Carruthers et al 2014a.	53,500
	MSE – Coordinator	CMG Meeting 1 - Review MSE modeling platform, SCRS & Commission outcomes, MSE demonstrator, HCR review and general MSE progress and refine detailed work program (1-4 December, Madrid). See terms of reference CMG.	7,5000
	MSE – Tech Expert	Paper: Preliminary evaluation of performance of range of HCR for BFT. See Carruthers et al 2014b.	
			95,000
2015	ICCAT - GBYP	MSE & Modelling Coordinator Contract (0.2 FTE). See terms of reference 1.	52,000/yr[1]
	ICCAT – GBYP	MSE Tech Expert Contract (1.0 FTE) . See terms of reference 2.	125,000/yr[2]
	MSE Coordinator	In cooperation with GBYP Coordinator, coordinate collation and analysis of electronic tag data for parameterization of population structure and connectivity hypotheses. See TORs for analysis project	
	Pop Dyn Expert	Glossary for technical terminology associated with Precautionary approach, MSE, HCR and Reference Pts. Paper to Methods Working Group meeting. See terms of reference X.	
	SCRS Chair/Pop Dyn Expert	Stock Assessment Methods Working Group meeting (16-20 February, Miami). i) Communicating BFT Modelling and MSE work program; contribution to wider MSE, HCR and Ref Pts program across ICCAT. BFT Modelling Coord to attend. Part travel costs met by ABNJ capacity building project	1000 MMC attendance
	MSE Coordinator	MSE Tech Expert Tasks – Dec 2014-Mar 2015 i) Incorporation of candidate assessment methods in MSE modeling platform ii) Effects of data imputation on assessment uncertainty. iii) Papers for consideration at BFT Data preparation meeting. See Task X1	

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[1] This would be the cost to ICCAT with 30% of full cost being met by CSIRO.
[2] Expected cost per year for 2015 and 2016 based on EoI from T.Carruthers.

	SCRS Chair/Pop Dyn Expert	BFT Data Preparatory meeting 2-6 March, France – MSE Tech Expert to attend Papers and presentations on assessment and imputation; technical contributions to development of specific tasks associated with evaluation and selection of candidate assessment methods for 2016.	2,500
	SCRS Chair/Pop Dyn Expert/BFT Rapp	BFT Species Group meeting and SCRS – X-X September, Madrid i) Update on progress with Modelling and MSE Program (SCRS Chair). ii) Pop Dyn Expert papers on cross-validation methods for stock assessment (see Kell et al XX). iii) Final papers on: data imputation; Precautionary Approach, Ref points and MSE; simulation evaluation of assessment methods for BFT (MSE Tech Expert; MSE Coord). Attendance of MSE Coord contingent on final agenda and outcomes of BFT Data prep and SWG-SM: default is non-attendance.	2,500 (5,000 for MMC)
	MSE Coordinator	MSE Modelling Workshop – Seattle/Glouster/Miami/Madrid? – early December 2015. i) Population structure and movement for operating modeling and MSE ii) Results of comprehensive analysis of population structure and connectivity project. iii) Invited papers and presentations. Attendance by 1 invited expert in spatial population modelling. See draft scope and agenda 3.	30,000
	MSE Coordinator	BFT-MMSE Meeting 2 – As per workshop, early December 2015, (One day prior and 1-2 days post workshop.) i) Review OM population structure, connectivity and fishery structures; ii) Review proposed approach to conditioning spatial MSE operating models.	Included in workshop budget
			213,000
2016	ICCAT - GBYP	MSE & Modelling Coordinator Contract (0.3 FTE) – 2016	78,000/yr
	ICCAT – GBYP	MSE Tech Expert Contract (1.0 FTE) – 2016	125,000
	BFT Rapp	BFT Data Preparatory meeting for 2016 Assessment.	5,000

		MSE Tech Expert to attend. MSE Coordinator TBC. i) Papers and presentation on preliminary conditioning of OMs, and; ii) Evaluation of implications of current assessment assumptions and management objectives for consideration in context of 2016 assessment process. iii) Preliminary consideration of criteria “serious threat of fishery collapse”	
	SCRS Chair	Standing Working Group on Science and Management, date and location TCB i) Participation in SWG-SM by Modeling coordinator.ii) ii) Facilitated session on objectives and performance measures based on outcomes of work presented at Data preparatory meeting.	5,000
	SCRS Chair	BFT Species Group meeting, X-X September, Madrid MSE Coord and Tech Expert participation, i) Presentations ii) Particpate in assessment review and present update on MSE program, in particular relative performance of alternative assessment approaches, and; iii) Present and facilitate discussion on updated conditioning of OMs for MSE work in 2017.	12,500
	MSE Coordinator	MSE Modelling Workshop – (Bilbao? – late Nov/Early Dec). i) Review of conditioning of OM, including population and fishery structure and mixing hypotheses; ii) Initial consideration of candidate Harvest Strategies. iii) Initial selection of reference set and Robustness tests for MSE based on outcomes of 2016 assessment process and Population structure and Connectivity workshop outcomes.	30,000
	MSE Coordinator	BFT-MMSE Meeting 3 - Review OM conditioning, candidate HCR and potential objectives and performance measures from SWGSM/Commission; (In conjunction with MSE modeling workshop)	

			255,500
2017	ICCAT - GBYP	MSE & Modelling Coordinator Contract (0.2 FTE) – 2017	55,000/yr
	ICCAT – GBYP	MSE Tech Expert Contract (0.6 FTE) – 2017	75,000
	ICCAT – GBYP/MSE Coord	Participation in SWG-SM (Mar?, location TBC) i) Session on OM with performance of alternative harvest strategies and assumptions/hypotheses ii) Facilitated discussion for refinement objectives, performance measures and operational requirements for final evaluation of candidate harvest strategies	7,500
	MSE Coordinator	MSE Modelling Workshop – Review of final conditioning of OM and selection of final harvest strategies based on Commission guidance on objectives and performance measures (TBC- Apr).	30,000
	MSE Coordinator	BFT-MMSE 4- Review OM conditioning, candidate harvest strategies and potential objectives and performance measures from SWGSM/Commission; (Sept, Madrid)	
	ICCAT – BFT Rapp	MSE Coord and Tech Expert participation, briefing for delegations and presentations to BFT Sp Gp and/or SCRS (Sept, Madrid)	10,000
			177,500
2018	ICCAT - GBYP	MSE & Modelling Coordinator Contract (0.2 FTE) – 2017	55,000/yr
	ICCAT – GBYP	MSE Tech Expert Contract (0.6 FTE) – 2017	75,000
	MSE Coordinator	MSE Modelling Workshop – Final testing, selection and tuning of selected harvest strategy to Commission's objectives (Morocco? - Apr).	30,000
	ICCAT – BFT Rapp	MSE Coord and Tech Expert participation, briefing for delegations and presentations to BFT Sp Gp and/or SCRS (Sept, Madrid)	10,000
	ICCAT – SCRS Chair	SCRS Chair and MSE Coord - Consultations and presentation to Commission of final recommendation for harvest strategy for BFT.	5,000
	MSE Coordinator	BFT-MMSE Meeting 5 - early December, Madrid Debrief and review meeting of BFT MSE & Modelling Group to document outcomes and lessons	10,000
			185,000

Annex 1: Membership of GBYP Modelling and MSE Group and participants at 1st meeting, 1-4 December 2015, Madrid.

Name	**Position**	**Role**	**Attendance at 1st Meeting**
Campbell Davies	Consultant	Chair & Modelling and MSE Coordinator	Y
Polina Levontin	Independent Scientist	Member	N
Richard Hillary	Independent scientist	Member	N
Toshihide Kitakado	CPC MSE Expert	Member	Y
Yukio Takeuchi	CPC BFT assessment scientist	Member	Y
Haritz Arrizabalaga	CPC BFT assessment scientist	Member	Y
Doug Butterworth	CPC MSE Expert	Member	N
Tom Carruthers	Consultant	Expert MSE Technical Assistant	Y
Clay Porch	WBFT Rapporteur	*Ex-Oficio*	N
Sylvain Bonhommeau	EBFT Rapporteur	Ex-Oficio	N
Laurie Kell	Population Dynamics Specialist	Ex-Oficio	Y
David Die	SCRS Chair	Ex- Oficio	Y
Paul De Bruyn	Secretariat Statistical Dept.	Ex-Oficio	Y
Antonio Di Natale	GBYP Coordinator	Ex- Oficio	Y
Pilar Pillarès	Scientific Coordinator	Ex- Oficio	Y

Annex 2: Agenda for 1st Meeting of the GBYP Modelling and MSE Group

ICCAT GBYP Modelling and MSE Sub-Program

1st Meeting of Core Modelling Group
1-4 December 2014,

ICCAT Secretariat, Calle Corazón de Maria 8, 28002 Madrid, Spain

Draft Annotated Agenda

Day 1, 1 December

9:00 Welcome and Introductions (Campbell Davies, Modelling Coordinator)

9:05 Opening of meeting (Driss Meski, ICCAT Executive Secretary)

Priority of MSE process for Commission

Specific issues from the Commission for the CMG

9:15 Confirmation of agenda

Start and finish times

Group Dinner

Departure details

9:25 Nomination of Rapporteur(s)

1. Stock assessment
2. MP development
3. Data collation and synthesis
4. Engagement and capacity building
5. Collation and editing of final draft detailed work program (Davies)

9:30 Update on progress, current status and funding of ICCAT GBYP (Antonio Di Natale, GBYP Coordinator)

Summary of outcome of Commissions consideration and decisions on the GBYP in general and Modelling and MSE work program in particular.

Approved budget for 2015 and provisional budget for 2016-18

Priority deliverables for SCRS and Commission 2015-16.

Dates for meetings that have already been agreed.

10:00 Draft Work Program for Stock Assessment and Management Strategy Evaluation for Bluefin Tuna (Campbell Davies)

Short presentation and initial discussion of the draft work program and budget developed by Dr Davies in consultation with MSE Technical Assistant and Secretariat. See Table 1, Davies 2014, *Draft work plan for Management Strategy Evaluation for Atlantic Bluefin Tuna.*

The focus of this session is: i) the overall scope and structure of the work program; ii) whether there are any major missing elements; and, in particular the timing of essential elements and decision points (e.g. data cut offs, model structures and final conditioning of operating models/stock assessments).

A key consideration is the practical feasibility of developing and conditioning a multi-population assessment and/or operating models within the schedule requested by the Commission and reaching agreement on the final reference set of models. This issue, amongst others, will be picked up in throughout the meeting but, in particular detail on day 2 and 3 in the sessions on stock assessment, MSE and data synthesis and collation.

In addition, the group should reflect on the TORs and composition of the Core Modelling Group and whether there is the need to consider any refinements to its mandated purpose and operation going forward.

Output of this session is a list of substantive outstanding issues/details that need to be resolved at this meeting for the work program to be finalised.

11:00 Morning break

11:30 Presentation of the initial deliverables under the Modelling Contract 2014-2 (Tom Carruthers)

GBYP Tender 02/2014 – Modelling approaches to support BFT stock assessment appointed Dr Tom Carruthers (UBC, Canada) as the Expert MSE Technical Assistant to assist the Modelling and MSE Coordinator and complete three initial pieces of work to substantially advance the MSE modelling program: i) Development of flexible code and documentation for operating models; i) Review and code a range of alternative forms of management procedure/harvest control rules; and, iii) an MSE demonstrator model to facilitate understanding of purpose and concepts underpinning evaluation of alternative management approaches (i.e. MSE).

This and the following two sessions will review the draft outputs of this contract and provide feedback for their finalisation (as part of this contract) and further development (as part of the future work program). Outputs of this session will include: i) a set of topics/tasks for further detailed technical discussion and specification of resources and responsibilities (Day 3, morning Day 4) and ii) points of interaction/linkage with the stock assessment and population dynamics review to be picked up in Day 2.

- MSE simulation framework: Flexible object orientated code for operating and observation models

See Carruthers *et al*, Draft Final Report “Evaluating Management Strategies for Atlantic Bluefin Tuna” and the following link:
https://drive.google.com/folderview?id=0B0HYOP0BN5RPdUYxQzVFcDh3dUE&usp=sharing

13:00 Lunch

14:30 Continuation of the presentation of deliverables (Tom Carruthers)

- Preliminary simulation testing of existing and new Harvest Control Rules

See Carruthers *et al* a, Draft Final Report *Evaluating Management Strategies for Atlantic Bluefin Tuna* and Carruthers *et al* b, Draft Manuscript *Performance Review of Simple Management Procedures*

- Potential use of Bayesian Belief networks for MSE demonstration

  See Carruthers *et al* a, Draft Final Report *Evaluating Management Strategies for Atlantic Bluefin Tuna*

15:30 Afternoon break

16:00 Review of previous work under GBYP modelling contracts and tasks agreed at Gloucester 2013 (Laurie Kell)

- Risk assessment
- Review of updated separate assessment approaches
- Review of initial mixed stock models and refinement of alternative mixing structure scenarios
- Tool for visualizing movement
- Meeting including stakeholders (finalise at 2013 Commission meeting)

17:30 End Day 1

Day 2, 2 December

9:00 Opening of Day 2 and Recap from Day 1 (Campbell Davies)

9:10 Review and detailed discussion of tasks, schedule and resourcing of Stock Assessment Work Program (2015-2016) (Sylvain Bonhommeau)

11:00 Morning break

11:30 Review and detailed discussion of tasks, schedule and resourcing of Stock Assessment Work Program (2015-2016) in context of GBYP Modelling Program (Clay Porch)

13:00 Lunch

14:30 Data and synthesis requirements for Stock Assessments and MSE (Paul Debruyn?)

15:30 Afternoon break

16:00 Refinement of Draft Work Program - Stock Assessment (Laurie Kell & David Die)

17:30 End Day 2

Day 3, 3 December

9:00 Opening of Day 3 and Recap from Day 2 (Campbell Davies)

9:10 Review of steps required to conduct an MSE (Campbell Davies)

11:00 Morning break

11:30 Detailed review and update of Technical Workplan to accomplish MSE under GBYP (Tom Carruthers & Campbell Davies)

13:00 Lunch

14:30 Detailed review and update of proposed engagement strategy with SCRS, COMM and CPCs

- Building capacity (Technical and Understanding)
- Clarifying Harvest Control Rules, Harvest Strategies and Performance Measures
- Processes for specifying objectives and performance measures and eliciting trade-offs

15:30 Afternoon break

16:00 Refinement of Draft Work Program - MSE modelling and Engagement (Campbell Davies)

17:30 End Day 3

Day 4, 4 December

9:00 Opening of Day 4 and Recap from Day 3 (Campbell Davies)

9:10 Small group detailed discussions on each component of the work program and agreement on specific tasks and responsibilities:

- stock assessment and MSE modelling
- data collation and synthesis
- Capacity building and engagement

11:00 Morning break

11:30 Update, circulate and review revised work program and budget (Davies, Di Natale, Porch, Bonhommeau, Die, Kell) & small group discussions (others)

13:00 Lunch

14:30 Review and adopt revised detailed work program, including list of tasks and responsibilities

15:30 Afternoon break

16:00 Summary of outcomes, immediate tasks and next steps (Campbell Davies)

16:30 Meeting close

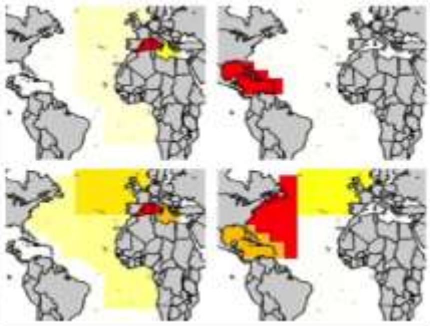
Annex 3: Final Report for GBYP Phase IV, project 2014-2.

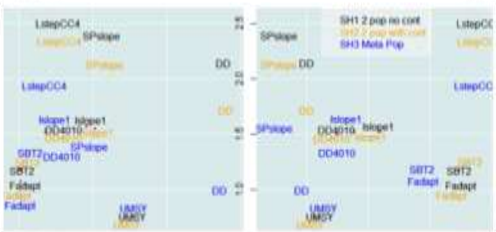
Evaluating Management Strategies for Atlantic Bluefin Tuna

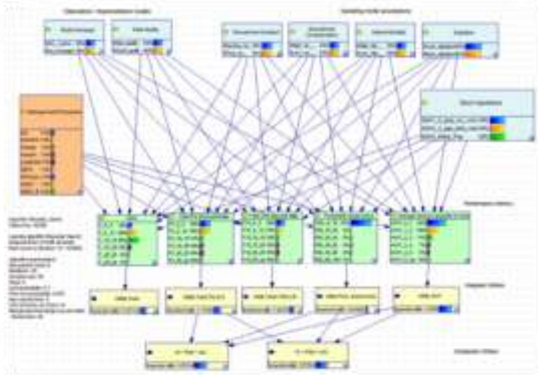
Report 1 (Draft)

November 2014

SHORT-TERM CONTRACT FOR MODELLING APPROACHES: SUPPORT TO BFT ASSESSMENT (GBYP 02/2014) OF THE ATLANTIC-WIDE RESEARCH PROGRAMME ON BLUEFIN TUNA (ICCAT-GBYP – Phase 4)







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Executive Summary

We describe a preliminary MSE for Atlantic Bluefin Tuna (ABT) that can be used to evaluate management procedures over a wide range of ecological, data collection and management hypotheses. The MSE design makes use of Object-Oriented Programming (OOP) to improve development efficiency and organisation.

A set of operating models were defined that encompass credible sub-population scenarios for the eastern Atlantic stock and the core uncertainties regarding ABT population dynamics. A series of management procedures (MPs) were tested and incorporated in the MSE framework that include simple stock assessments and rules used in the management of southern bluefin tuna.

A set of 55 thousand simulations were identified that covered the core uncertainties in addition to alternative data quality levels and quota overages. In this report we present the main results of the preliminary ABT MSE and introduce Bayesian Belief Networks as a tool in making ABT MSE outputs accessible to a wider group of stakeholders. MP performance was evaluated with respect to metrics that have been previously identified for ABT.

Our early results indicate that alternative stock-structure hypotheses may determine management performance as strongly as conventional sources of uncertainty such as population growth rate, recruitment and natural mortality rate. The effect of increasing sub-population structure was often counter-intuitive which underlines the important role of simulation evaluation of MPs. Simple delay-difference assessments appeared to outperform the other MPs under most circumstances.

In this report we provide a detailed description of the preliminary operating model structure. We discuss the preliminary ABT MSE results, the limitations of the current MSE design and highlight areas for future development. We also report on progress with respect to project deliverables.

Contents

1 Introduction

The Atlantic-Wide Research Programme on Bluefin Tuna (GBYP) aims to develop a new scientific management framework by improving data collection, knowledge of key biological and ecological processes, assessment models and management. A critical component of the GBYP is the construction of a robust advice framework consistent with the precautionary approach (GBYP 2014).

Management Strategy Evaluation (MSE) offers a solution that is increasingly applied in the management of fisheries (Cochrane et al. 1998, Butterworth and Punt 1999). Figure 1 provides an illustration of a possible MSE for Atlantic bluefin tuna. MSE differs from stock assessment in that detailed fishery data are used to condition an Operating Model (OM); a simulation model that represents plausible hypotheses about fishery and population dynamics. These simulations are then used to tune and evaluate procedures for updating management recommendations that are typically simpler than a conventional stock assessment. These rules are referred to as Management Procedures (MP) and generally operate on recent information regarding trends in abundance and catch data. Instead of using stock assessment as the primary source of management advice, the MSE approach makes routine management decisions using MPs while the operating model is updated to accommodate new data.

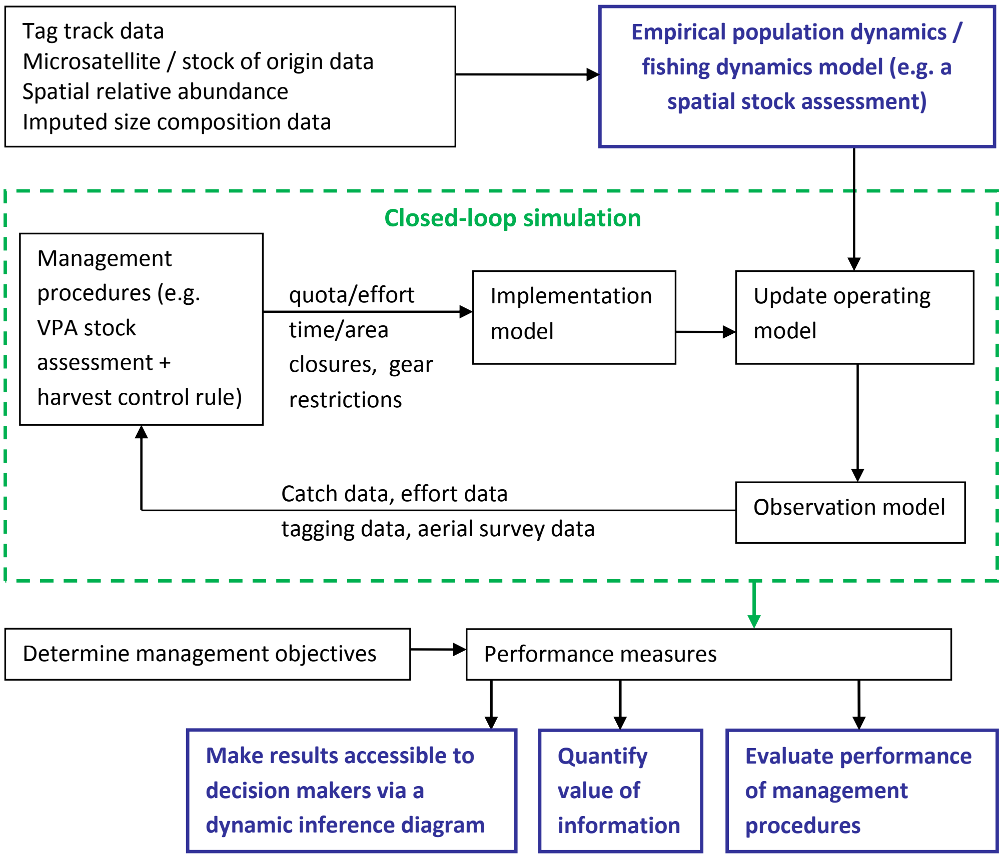

Figure 1. A possible MSE for Atlantic bluefin tuna.

MSE can add stability to the management decision process by first identifying realistic management objectives through stakeholder participation followed by a thorough evaluation of trade-offs achievable under alternative harvest strategies when accounting for different sources of uncertainty (e.g. Rockmann et al. 2012). MSE can also be used to guide the scientific process by identifying where the reduction of scientific uncertainty will improve performance in achieving management objectives and so help to ensure that expenditure is prioritised to provide the best research, monitoring and enforcement (Fromentin et al. 2014). While a stock assessment assumptions may vary over time due to the expert judgement of scientists (Hilborn, 2003) that can have impacts on management recommendations, the MSE paradigm is intended to instil greater constancy. Additionally since the MSE approach is simulation based it should detect overly complex assessment approaches (management procedures) that can lead to biased management recommendations. This is important as there is increasing evidence that simple MPs can perform as least as well as conventional stock assessments (Geromont and Butterworth 2014b)

In recognition of the potential benefits of MSE for Atlantic bluefin tuna management, the 2013 meeting of the Bluefin Stock Assessment Methods working group (Gloucester, MA; SCRS 2013) recommended Management Strategy Evaluation (MSE) as an approach to building a robust advice framework. Constructing a fully-featured MSE can be broken down into prerequisites and tasks. Two important prerequisites include agreement on performance measures (e.g. long-term stability in yield, probability of underfished status subject to underfishing, Leach et al. 2014, Levontin et al. 2014) and identification of axes of uncertainty for the operating model (e.g. spatial structure, temporally varying growth, Kell et al. 2012, Kell 2014, Fromentin et al. 2014). The most important tasks include the acquisition and processing of data to inform the operating models, the programming of the operating models and the identification and implementation of a range of candidate management procedures (i.e. Carruthers et al. 2014b).

Atlantic bluefin tuna (*Thunnus thynnus*) is an ideal candidate for MSE because a range of data are available to support various stock mixing and sub-stock structure hypotheses that are likely to determine the success of candidate management procedures. For example Arrizabalaga et al. (2014) identify 5 distinct stock hypotheses that include multiple sub-populations for the Eastern stock. Additionally, MSE may be particularly useful in progressing Atlantic bluefin tuna science by quantifying value of information: the performance of a management procedure may be characterized in terms of the uncertainty in inputs leading to the identification of the most critical information gaps (e.g. stock mixing, number of genetically distinct stocks, temporal shifts in maturity or growth).

In this report we describe the development and testing of a preliminary MSE framework for Atlantic bluefin tuna (Section 2). We describe a preliminary set of simulation scenarios in order to demonstrate the functionality of the MSE framework (Section 3). The central results of these preliminary simulations are presented in Section 4 and include a summary of the main sensitivities, MP performance trade-offs and value-of-information analysis. In Section 5 a demonstration Bayesian belief network (a type of inference diagram) is presented that allows for rapid summarization and dynamic investigation of the MSE results by a wide range of stakeholders. The implications of the preliminary results are discussed in the context of wider management considerations in Section 6 which also includes a summary of possible future MSE developments and research priorities. We summarize progress with respect to core project deliverables in Section 7.

2 Designing of an MSE framework for Atlantic bluefin tuna

2.1 Object – Oriented programming (OOP)

In order to maximise flexibility and minimize development time we adopt an object-oriented programming (OOP) approach. OOP involves the definition of objects that are data structures with a variety of *attributes* for the organization of data and functions. For example a stock object may have attributes for the name of the species, catch data and natural mortality rate. In this case we have defined an *object class* 'stock' with three attributes. The advantage of the OOP approach is that standard functions, referred to as *methods*, may be developed that will operate on any given instance of an object of a particular class. For example a stock assessment method applied to any given stock object.

OOP is particularly appropriate for MSE development because of the hierarchical, multiple scenario nature of MSE. For example MSE may require a standardized data input to an empirically fitted operating model (an object class), an empirical operating mode (a method), graphical representation of the fitted operating model (a method), observation error scenarios (an object class), a range of implementation error models (a function class), the range of candidate management procedures (methods), etc.

2.2 The structure of the preliminary ABT MSE

The preliminary ABT MSE includes several object classes, methods and function classes that are listed in Table 1. The relationship between the object classes and function classes is illustrated in Figure 2.

The operating model may be defined by either a user-specified definition object (*OMd*) or an empirically fitted assessment model or a combination of both. The rationale for the '*OMd* to *OM*' approach was to create a rapid means of investigating alternative stock hypotheses and MP performance without having to fit a detailed assessment model to data which was beyond the scope of this preliminary MSE. The *OMd* is pseudo-empirical in the sense that it includes population parameter inputs, stock size and depletion estimated by recent stock assessments (SCRS 2012). Additionally the '*OMd* to *OM*' step allows for the development of a fully featured MSE framework ahead of the more intensive process of empirical OM testing and conditioning.

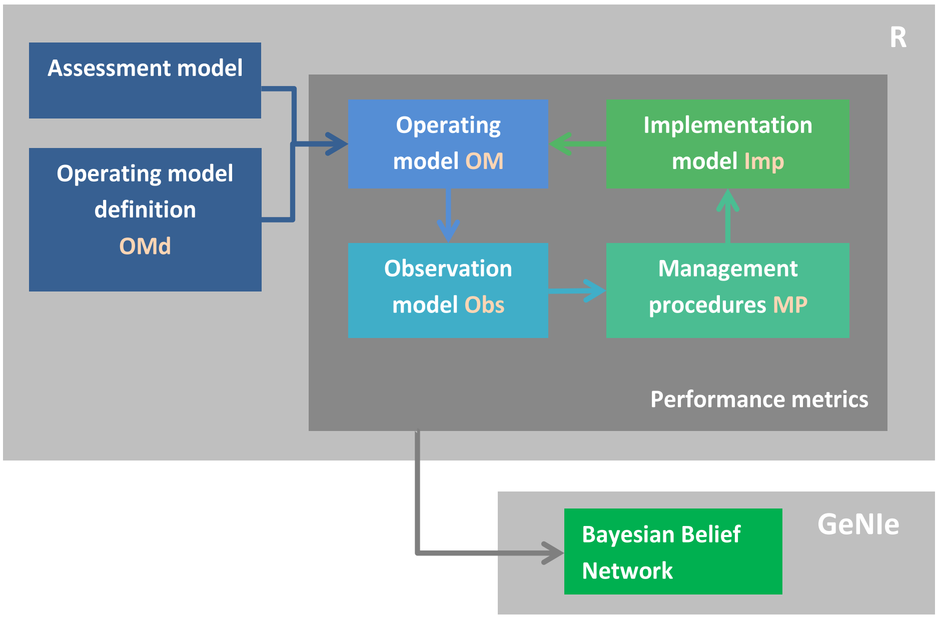

Figure 2. The MSE design.

Table 1. The object classes, methods and function classes of the preliminary ABT MSE

Object classes	
OMd	(Operating Model definition) User specified inputs can completely define an operating model
OM	(Operating Model) A specified OM inc. all sampled parameters and calculated reference points
Obs	(Observation error model) User-specified levels of imprecision and bias for the inputs to MPs
MSE	(Management Strategy Evaluation) Summary of MSE simulations including results
Methods (core)	
new(*OM*)	Create new instance of an operating model
new(*MSE*)	Create a new instance of an MSE
Methods (ancillary)	
plot(*OMd*)	Plot the area definitions of the OMd object
plot(*OM*)	Plot the spatial distribution implied by the movement of the OM object
summary(*MSE*)	Summarize the results / performance of the MSE
Function classes	
Imp	(Implementation error model) functions that control mismatch between fleet dynamics and management recommendations
MP	Management procedures (e.g. simple algorithms or assessments paired with harvest control rules)

The *OMd* object class is a concise summary of ranges of inputs for various parameters (for a full description of all the attributes of the *OMd* object and other objects see Appendix 9.1). For example one attribute is the vector of mean natural mortality rate by age and a possible range in natural mortality rate. Because the *OMd* object contains a random seed attribute, this very small file (typically less than 35KB in size) may be easily passed among users from which ultimately the same MSE results can be obtained.

The *OM* object class is a full description of all operating model variables and reference points (e.g. sampled natural mortality rate, sampled fishing mortality rate trajectory over time). These are values for parameters and variables (e.g natural mortality rate current fishing mortality rate) as opposed to ranges as in the *OMd* object. The construction of the *OM* object is computationally intensive and includes the calculation of MSY reference points and optimization for fleet specific catchability coefficients that match user-specified stock depletion. By separating this computation from the rest of the closed-loop simulation, new forward projections may be carried out without having to recalculate reference points. Since the central attributes of the *OM* object have a dimension for simulation number, any input can be replaced by the outputs of an empirically fitted operating model. For example these could be posterior samples of natural mortality rate, stock recruitment compensation, numbers at age or a grid of assumptions for robustness trials (e.g. the MSE of Southern Bluefin Tuna, CCSBT 2011). *OM* objects may also be saved, exchanged among users and used as reference cases for future MSE work.

The *Obs* object class contains the parameters of the observation model. These control the quality of data generated by the operating model that is used by the management procedures (for example bias in estimates of natural mortality rate, precision and bias in historical catches). Since the performance of various MPs may be strongly affected by the quality of their respective data inputs, the observation model is often amongst the most important factors contributing to the performance ranking of MPs.

The *Imp* function class controls how well management recommendations are followed and can simulate a range of phenomena from overages to effort reductions at low catch rates. Implementation models could include maximum fishing mortality rates, declines in fishing effort with expected catch rates (response to declining profits), persistent quota overages or missed quota.

The *MP* function class are management procedures that are the focus of the MSE simulation testing. These represent the complete process from data to management recommendation that may include simple algorithms based on trajectories in catch rates to complex data filtering methods linked to detailed stock assessment models with harvest control rules.

The *MSE* object class stores all the outputs of the MSE closed-loop simulations and has attributes for variables such as population numbers, movement, mortality rate, fishing selectivity, exploitation rate and catches. This object is generally large (>50Mb) and is the focus of a range of methods for summarizing MSE results.

2.3 Operating model population dynamics

The operating model is structured by age, space, sub-year and population (the equations of the population dynamics model are included in Appendix 9.2.1). The operating model includes movement by population, age and sub-year allowing for multiple sub-population hypotheses, seasonal movement, ontogenetic movement and aggregation by mature fish in spawning locations. Natural mortality rate, growth, maturity and recruitment are also specific to population and may be time varying. This allows for the evaluation of key hypotheses for ABT including changes in recruitment strength and natural mortality rate over time (Levontin et al. 2014).

Table 2. The variables of the population dynamics model. 'Structured by simulation' indicates that the MSE was designed to operate on multiple scenarios for a particular variable. Population refers to an individual breeding population that could be a sub-population of the eastern stock spawning in the Mediterranean for example.

Variable	Structured by:
Natural mortality rate	Simulation, population, age, year
Movement	Simulation, population, age, sub-year
Maturity	Simulation, population, age, year
Recruitment anomalies	Simulation, population, year
Growth rate	Simulation, population, year
Recruitment compensation	Simulation, population
Stock size (unfished recruitment)	Simulation, population
Depletion (biomass relative to unfished)	Simulation, population

2.4 Operating model fleet dynamics

The operating model can account for the exploitation of multiple fleets with time varying effort (see Appendix 9.2 for equations). Fleets were modelled that had temporally constant fishing efficiency, spatial targeting and age-selectivity. This preliminary fleet dynamics model either allows the fleet to maintain its current spatial distribution or alternatively to dynamically alter its spatial distribution relative to vulnerable biomass.

Table 3. The variables of the fleet dynamics model. 'Structured by simulation' indicates that the MSE was designed to operate on multiple scenarios for a particular variable.

Variable	Structured by:
Effort	Simulation, fleet, year, sub-year
Spatial targeting	Simulation, fleet
Fishing efficiency	Simulation, fleet
Age selectivity	Simulation, fleet, age

2.5 Software

The MSE framework is implemented in the statistical environment R (R core team, 2014) which is freely available, provides OOP through S4 classes, includes a wide range of presentation tools and provides support for cluster computing.

3 Scenarios for a preliminary MSE for Eastern Atlantic bluefin tuna

3.1 Overview

Papers summarising the central uncertainties in stock assessments Fromentin et al. (2014) and the core uncertainties for MSE robustness trials (Levontin et al. 2014) have focused on population structure, natural mortality rate, population growth and recruitment. For the purposes of this MSE we use these as principal ecological/biological factors over which to evaluate the performance of MPs (Table 4). Following Levontin et al. (2014) and Carruthers et al. (2014) we also add scenarios for implementation error (catch under-reporting), observation models that control data quality and stock depletion (spawning stock biomass relative to unfished). Based on the analysis of Carruthers et al. (2014b) we identify eight MPs and evaluate their performance over each combination of factor levels.

Table 4. The factors and levels of the factorial MSE design. BC refers to the parameterization of the recent 'Base Case' stock assessment (SCRS 2012). In combination, these factors represent a total of 192 sets of assumptions.

Stock structure	Natural mortality rate	Recruitment Compen-sation	Recruitment trajectory	Implement-ation bias	Data quality	Depletion
SH1 (Two pop. no contingents)	Low (80% BC)	Low (0.28-0.52)	Flat (0% y-1)	Accurate (100% quota)	Good	Low (2.5-17.5%)
SH2 (Two pop. with contingents)	High (125% BC)	High (0.44-0.81)	Declining (-0.5% y-1)	Overage (120% quota)	Bad	High (5%-40%)
SH3 (Meta-population)						

3.2 Ecological/biological factors

We identify three levels of the factor stock structure that provide alternative sub-population hypotheses for the Eastern Atlantic stock (Arrizabalaga et al. 2014, Figures 3-5), two levels of the natural mortality rate factor that are 4/5 and 5/4 the base case stock assessment natural mortality rate at age (SCRS 2012), two levels of recruitment compensation (population growth) that specify different ranges for steepness of the Beverton-Holt stock-recruitment curve (based on the inferred S-R curves of recent assessments, SCRS 2012) and two levels of temporal trajectory in recruitment that include either a flat trend or a declining trend (1/2 % y^{-1}).

A core finding of previous MSE research (e.g. Carruthers et al. 2014a) is that starting level of stock depletion can have a large impact on the relative performance of MPs. Therefore two levels of stock depletion are also considered that represent the upper and lower ranges estimated from recent stock assessments (SCRS 2012).

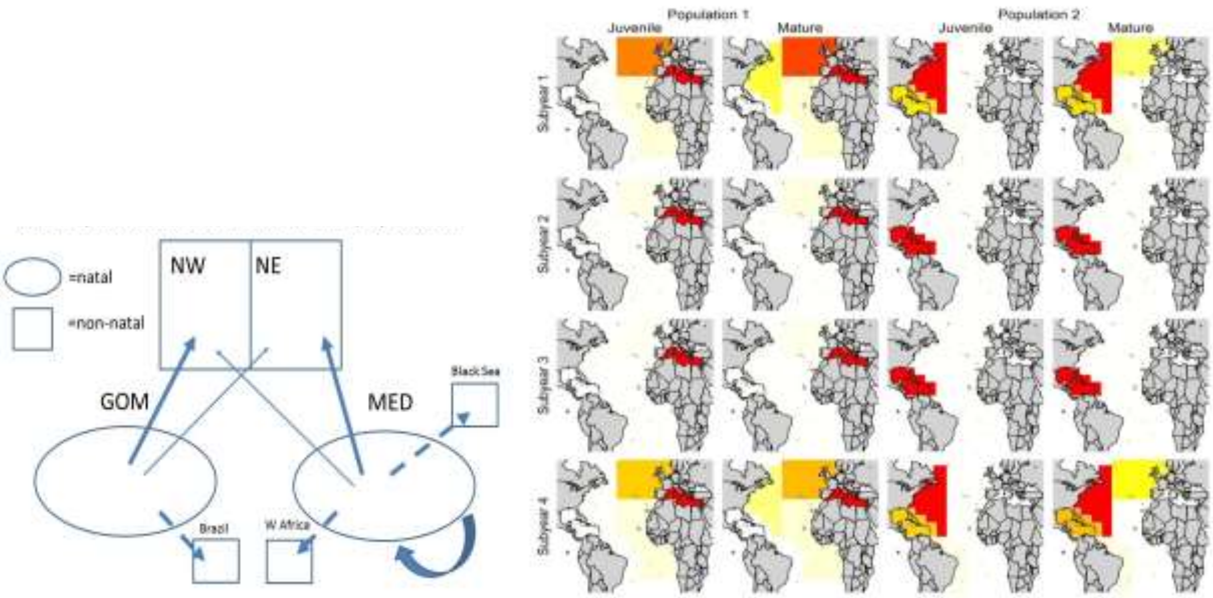

Figure 3. The two population model with no sub-populations (Arrizabalaga et al. 2014, SH1)

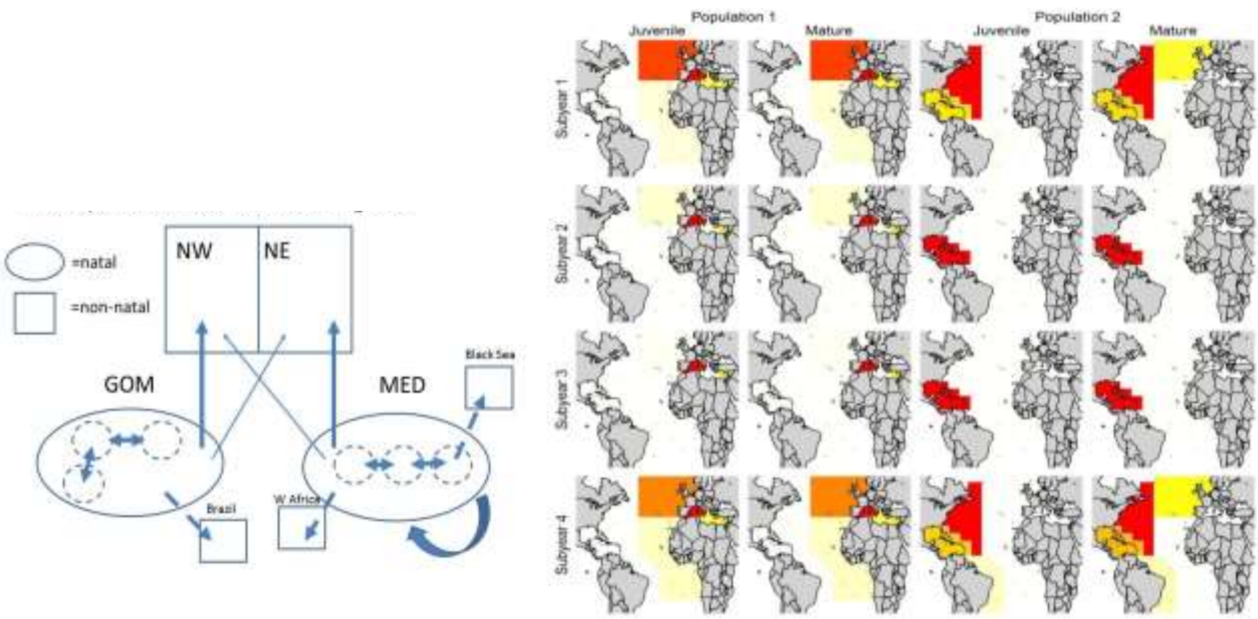

Figure 4. The two population model with contingents (Arrizabalaga et al. 2014, SH2)

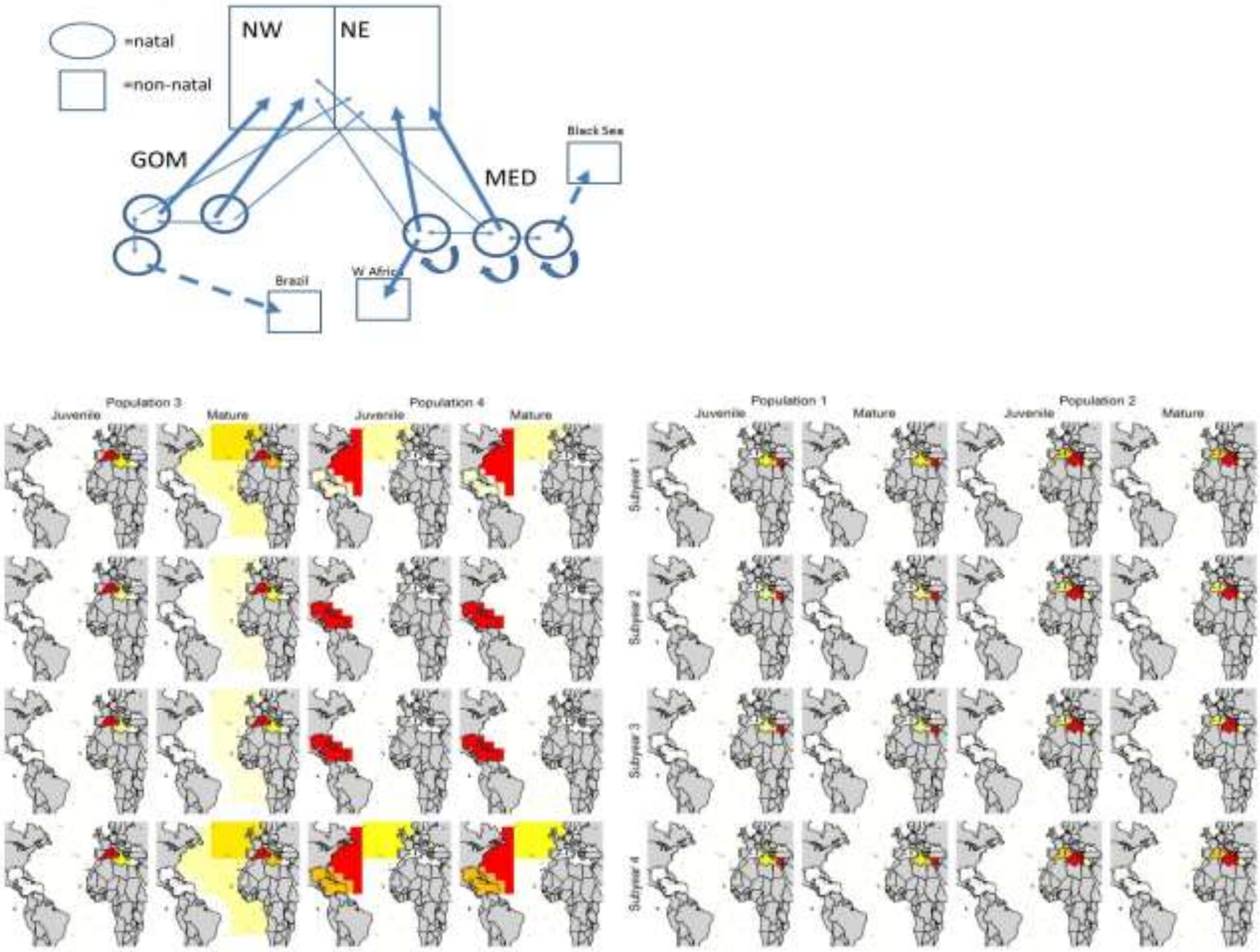

Figure 5. The metapopulation model (Arrizabalaga et al. 2014, SH3). A model with three separate Mediterranean sub-populations.

3.3 Implementation and observation models

The preliminary MSE includes two levels of implementation bias (accurate and 20% quota overages) to evaluate the relative importance of potential overages.

Management procedures can make use of a wide range of fishery data that are likely to be subject to observation error and potential biases. For example extended survivorship analysis (XSA, Shepherd 1992) requires input values for natural mortality rate, catch-at-age data and a relative abundance index, whereas slope MPs (e.g. 'Islope1', Geromont and Butterworth 2014b) makes use of just recent CPUE and aggregated annual catch data. It follows that the quality of these data will affect the relative performance of the respective MPs. It follows that it is important to recreate credible bias and imprecision in data. In this preliminary MSE we include two observation error models that simulate relatively bad and relatively good quality data (Table 5).

Data were simulated from observation models that could include both bias (e.g. observations of historical catches that are 10% over those actually taken) and imprecision (e.g. observation error or 'noise' in annual estimates of catch)(Table 5).

Table 5. The two observation models used to generate two levels of relative data quality 'good' and 'bad'.

Data quality		Good	Bad
Catch observation error log-normal CV	σ_C	0.1 - 0.3	0.2 -0.5
Catch bias log-normal CV	Υ_C	0.2	0.4
Number of Catch-at-age observations per year	n_{CAA}	2000-5000	1000-2000
Length observation error lognormal CV	σ_L	0.025 - 0.05	0.05 - 0.1
Hyperstablity / hyperdepletion in index	β	3/4 - 5/4	2/3 - 3/2
Abundance index observation error	σ_I	0.1 - 0.3	0.2 - 0.5
Bias in M	Υ_M	0.2	0.4
Bias in FMSY	Υ_{FMSY}	0.1	0.2
Current biomass observation error log-normal CV	σ_B	0.1 - 0.3	0.2 - 0.5
Current biomass bias log-normal CV	Υ_B	0.5	1
Bias in target CPUE (BMSY)	Υ_{CPUE}	0.3	0.4
Bias in target catch (MSY)	Υ_{MSY}	0.2	0.4

3.4 Management procedures

Based on the results of Carruthers et al. (2014b) we selected a shortlist of 8 management procedures to investigate in this preliminary MSE (Table 6). These include the index slope MP applied to Southern Bluefin Tuna (*SBT2*, CCSBT 2012, Kell et al. 2014), the index slope and average catch MPs (*Islope1* and *LstepCC4*) of Geromont and Butterworth (2014a), the adaptive FMSY MP (*Fadapt*) that is a hybrid of Maunder's (2014) surplus production seeking MP (*SPslope*), and fishing at a fixed fishing mortality rate (*UMSY*).

We also include a delay-difference stock assessment *DD,* fitted to historical catch and CPUE data. A second version of the delay-difference model includes the 40-10 harvest control rule (*DD4010*). Under the 40-10 rule the stock is not fished when stock size is below 10% unfished biomass and fished at FMSY above 40% of unfished biomass. Between 10% and 40% unfished levels exploitation rate follows a linear increase from 0 to 100% FMSY.

Table 6. The equations of the 8 candidate management procedures. Q is a quota recommendation, C is a total annual catch observation, B is an absolute annual biomass estimate, I is an annual relative abundance index or catch rate (CPUE) observation, R is an estimate of recruitment strength, y^* refers to the first year in which the MP was implemented, *MSY, FMSY* and *UMSY* are catches, instantaneous exploitation rate and harvest rate at Maximum Sustainable Yield subject to imperfect information.

MP Name	Quota calculation
SBT2 CCSBT 2011	$Q_y = \frac{1}{2}C_{y-1} + \delta MSY$, $\delta = \begin{cases}\Delta^{7/4} & \Delta < 1 \\ \Delta^{1/4} & \Delta > 1\end{cases}$, $\Delta = R^{ave}/R^{hist}$ $R_y^{ave} = \frac{1}{5}\sum_{t=y-4}^{y} R_t$, $R_y^{hist} = \frac{1}{10}\sum_{t=y-9}^{y} R_t$
Islope1 Geromont and Butterworth 2014a	$Q_{y*} = 5\sum_{t=y*-4}^{y*} C_t$ $Q_{y+1} = Q_y(1 + 0.4s_y)$ where s is the gradient of log CPUE over the last 5 years
LstepCC4 Geromont and Butterworth 2014a	$Q_{y+1} = Q_y \pm \frac{1}{20} C_{y+1}$, $Q_{y*} = 0.7C_{y*}$, $C_{y+1} = 1/5\sum_{t=y-4}^{y} C_t$
Fadapt Carruthers et al. 2014	$Q_y = F_y B_y$, $F_y^{try} = F^L + logit^{-1}(W_y - G_y)(F^U - F^L)$ $W_y = \begin{cases} logit\left(\frac{F_y^{ave} - F^L}{F^U - F^L}\right) & F^L < F_y^{ave} < F^U \\ 2 & F_y^{ave} < F^L \\ 2 & F^U < F_y^{ave} \end{cases}$ G is the slope in S, with biomass over the last 7 years, $F^L = \frac{FMSY}{2}$ $F^U = 2FMSY$
SPslope Carruthers et al. 2014	$Q_y = \begin{cases} \left\| 0.5(B_{y-4} - B_y)/B_{y-4} \right\| C_y^{ave} & \Delta^B < 9/10 \\ \frac{9}{10}S_{y-1} & \Delta^B > 11/10 \\ C_{y-1} & 9/10 < \Delta^B < 11/10 \end{cases}$ $\Delta^B = B_y/B_{y-4}$, $S_y = B_y - B_{y-1} + C_{y-1}$, $C_y^{ave} = 1/4\sum_{t=y-3}^{y} C_t$
UMSY NPFMC 2012	$Q_y = UMSY \cdot B_y$
DD Carruthers et al. 2014	Delay-difference stock assessment fitted to annual catch and catch rate data
DD4010 Carruthers et al. 2014	As DD with a 40-10 harvest control rule superimposed

3.5 Performance diagnostics

Following Leach et al. (2014) we evaluate performance according to three metrics: (1) probability of maintaining the stock in the green Kobe quadrant (F/FMSY <1, B/BMSY>1), (2) magnitude of maximum continuing catch and

(3) Stability of yield. In the absence of a defensible effort dynamics model and economic model it was not possible to include the fourth and fifth performance metrics of Leach et al. (2014) that were stability of effort and maintaining high employment.

Probability of ending in the Green Kobe (PGK) and average annual variability in yield (AAVY) are easily calculated and represent metrics 1 and 3, respectively (Table 7). Maximum continuing catch is more of a challenge because it is important to maintain meaning across simulations that may obtain very different absolute yields due to circumstance other than MP selection (e.g. a depleted stock with low future recruitment versus a less depleted stock with strong future recruitment). In order to maintain comparability among simulations, depletion scenarios, natural mortality scenarios and stock hypotheses we calculate a relative yield metric, which is the average catch obtained by an MP relative to fishing at UMSY given the same simulated conditions. The yield metric was calculated given 0%, 5% and 10% discount rates (Y, Y5 and Y10).

Table 7. Performance metrics of this simulation evaluation and their derivation.

Performance		Derivation per simulation
Yield 0% discount rate	Y	$Y = \frac{1}{n_y}\sum_{y=1}^{n_y} C_y / \frac{1}{n_y}\sum_{y=1}^{n_y} C_y^{FMSY}$
Yield 5% discount rate	Y5	$Y5 = \frac{1}{n_y}\sum_{i=1}^{n_y} (19/20)^y C_y / \frac{1}{n_y}\sum_{y=1}^{n_y} (19/20)^y C_y^{FMSY}$
Yield 10% discount rate	Y10	$Y10 = \frac{1}{n_y}\sum_{y=1}^{n_y} (9/10)^y C_y / \frac{1}{n_y}\sum_{y=1}^{n_y} (9/10)^y C_y^{FMSY}$
Average annual variability in yield	AAVY	$AAVY = \frac{1}{n_y - 1}\sum_{y=2}^{n_y} \left\lvert C_y - C_{y-1} \right\rvert \Big/ \frac{1}{n_y}\sum_{y=1}^{n_y} C_y$
Probability of Green Kobe	PGK	$PGK = \begin{cases} 0 & \frac{B_{ny}}{B_{MSY}} < 1 \; or \; \frac{F_{ny}}{F_{MSY}} > 1 \\ 1 & \frac{B_{ny}}{B_{MSY}} > 1 \; and \; \frac{F_{ny}}{F_{MSY}} < 1 \end{cases}$

where n_y is the number of projected years and C are the true simulated catches of an MP n_i is the number of simulations, B_{ny} is the biomass in the final year of the simulations, and B_{MSY} is the true simulated biomass at maximum sustainable yield.

3.6 Configuration of preliminary analysis

The preliminary MSE was used to undertake 55,296 simulations composed of 32 replicate simulations for 9 MPs (including the perfect information UMSY MP used to calculate yield) over each combination of the stock hypotheses, observation models, implementation models, initial stock depletion, recruitment compensation, recruitment trajectory and natural mortality rate (192 combinations). Using parallel processing, a single quad-core Intel i7 finished the closed loop simulations in around 20 hours.

4 Results of preliminary MSE

4.1 Drivers of performance: the role of MPs, operating model assumptions, observation and implementation models.

Across all simulations, MP selection had the strongest impact on performance with respect to Y, AAVY and PGK (Figures 6 and 7). Of the operating model variables, recruitment compensation (steepness, h), natural mortality rate and stock depletion were the principal drivers of performance differences among methods. The influence of these factors was more pronounced when focusing on one of the better performing MPs such as the delay-difference model (DD, Figure 7). Alternative stock hypotheses generally had little effect on yield but impacted AAVY and PGK in the delay-difference simulations (Figure 7). Simulating 20% overages in quota appeared to have little impact on the performance metrics.

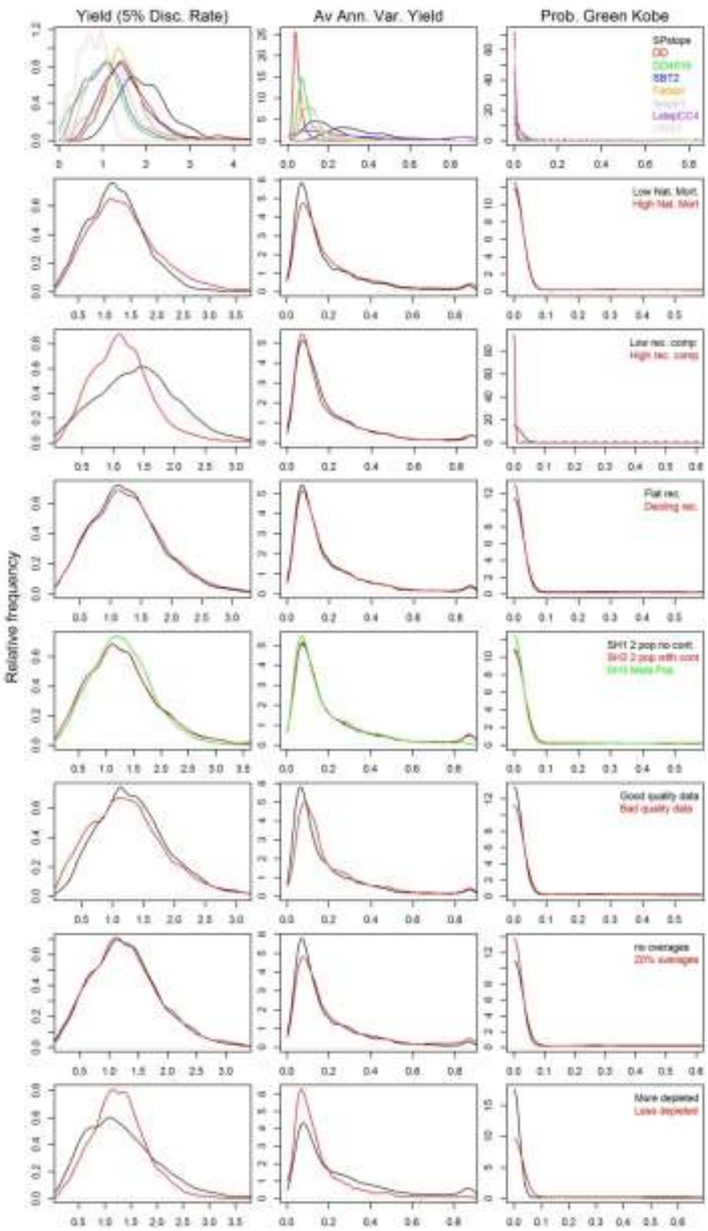

Figure 6. The distribution of performance metrics for all simulations separated marginally by the various simulation factors.

Recruitment trajectory had an unexpected impact on the PGK scores for the delay-difference MP (Figure 7). In simulations where recruitment strength was simulated to decline 0.5 % per year the delay difference model was more likely to rebuild the stock leading to higher PGK scores. This is likely due to the estimation of a more depleted stock that can withstand lower fishing rates. Catch recommendations were therefore downward biased to a greater extent than the decline in future productivity due to the downward trend in future recruitment.

The higher resilience (higher PGK scores) of the metapopulation model (SH3) was less surprising when considering the fishing dynamics that were simulated. Since fishing is directed to areas of higher vulnerable biomass and the spatial distribution of the sub-populations are distinct (Figure 5), the fleet moves opportunistically and provides a refuge from fishing for sub-populations as they become increasingly depleted.

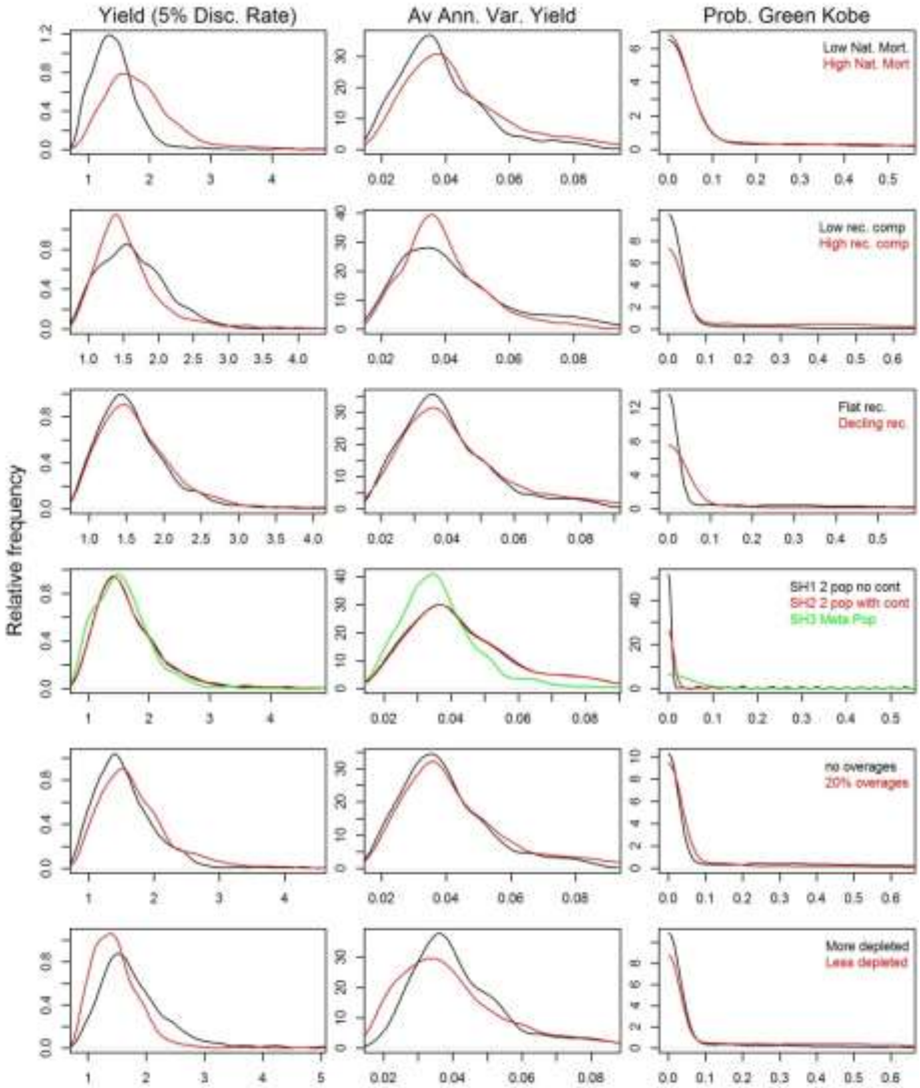

Figure 7. The distribution of performance metrics for delay-difference simulations given good quality data separated marginally by the other simulation factors.

4.2 Performance trade-offs

It was possible for MPs to obtain mean yield scores (given a 5% discount rate) that were well above fishing at FMSY levels (perfect information) but this appears to come at the cost of lower PGK scores. There was not a clear trade-off in performance metrics among the MPs and some methods (e.g. DD) outperformed others in all three metrics.

The delay-difference MP appeared to offer the best balance of performance in terms of Y5, PGK and AAVY (Figure 8), however the Y5 metric was much lower compared to other MPs where natural mortality rate and recruitment compensation was high. The delay-difference model performance with respect to Y5 appears to be more sensitive to stock hypotheses than the other MPs (Figure 8).

The LstepCC4 MP performed well in terms of Y5 but less well with respect to PGK and AAVY. SPslope could provide high yields with modest PGK scores and low AAVY. A surprising result was the relatively poor performance of the fixed fishing rate strategy UMSY, which in other simulation evaluations has ranked highly (Carruthers *et al*. 2014a/b).

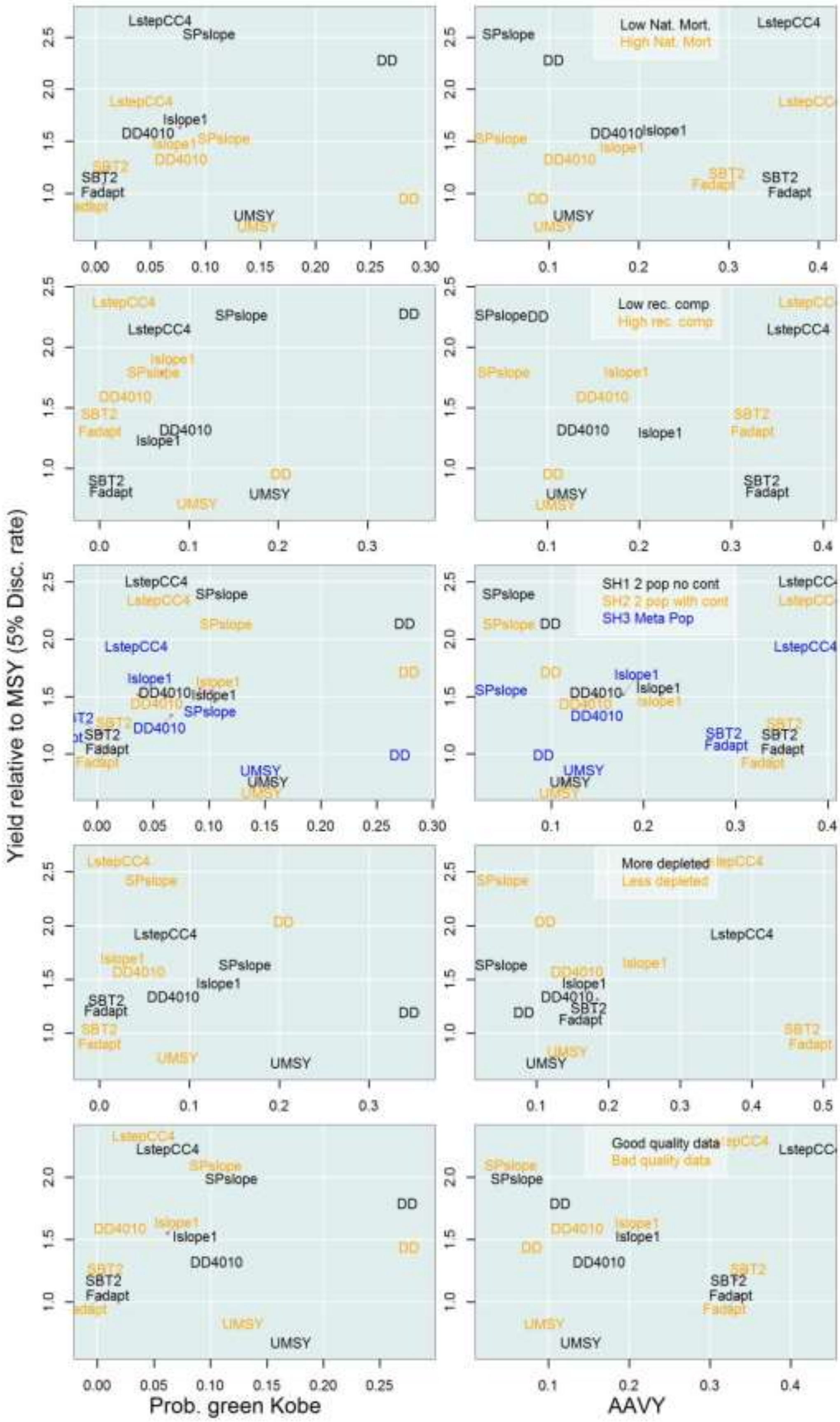

Figure 8. The performance of the candidate MPs given different subdivisions of the simulations.

4.3 Sensitivity analysis / value of information

Multiple regression analysis (Tables 8a and 8b) confirms the performance picture presented in Figures 6-8. The lack of significance of the recruitment compensation factor implies covariance with other simulated parameters and requires further investigation. A surprising inclusion in the significant explanatory variables is implementation error which has a relatively minor effect on yield but was found to be significant for all MPs combined (Table 6a) and the delay-difference MP in isolation (Table 6b)

Table 8a. Effect of simulation conditions on yield (5% discount rate) across all MPs. The results of a linear model fitted to expected yield. 'Estimate' refers to the average difference in yield relative to the UMSY perfect information MP (ie in units of yield of the UMSY MP). Components marked with asterisks had p-values less than 5%. The intercept represents the effect of all level 1 factors combined.

Component	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept	1.73	0.05	38.27	2.54E-316	
SH2 2 pop with contingents	-0.10	0.04	-2.80	5.18E-03	*
SH3 meta population	-0.31	0.04	-8.35	7.09E-17	*
Depletion (more depleted)	0.25	0.03	8.20	2.52E-16	*
Natural mortality rate (low M)	-0.39	0.03	-12.94	3.18E-38	*
Recruitment compensation (low h)	0.02	0.03	0.66	5.07E-01	
Recruitment trajectory (flat)	-0.05	0.03	-1.65	9.80E-02	
Observation model (good data)	0.03	0.03	0.94	3.45E-01	
Implementation error model (20% overag	-0.18	0.03	-5.88	4.15E-09	*

Table 8b. As Table 8a but for the delay-difference MP only.

Component	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept	3.01	0.16	18.48	3.00E-74	*
SH2 2 pop with contingents	-0.26	0.13	-1.97	4.87E-02	*
SH3 meta population	-0.84	0.13	-6.29	3.32E-10	*
Depletion (more depleted)	0.79	0.11	7.27	4.15E-13	*
Natural mortality rate (low M)	-1.00	0.11	-9.24	3.19E-20	*
Recruitment compensation (low h)	-0.47	0.11	-4.36	1.34E-05	*
Recruitment trajectory (flat)	-0.09	0.11	-0.86	3.87E-01	
Observation model (good data)	0.08	0.11	0.73	4.63E-01	
Implementation error model (20% ove	-0.54	0.11	-5.00	6.00E-07	*

5 Bayesian belief networks

The factorial nature of the preliminary MSE analysis is well suited to presentation in a Bayesian Belief Network. BBNs are inference diagrams that represent the connectivity of factors. They can be adapted to include multiple utility functions. Perhaps their biggest potential benefit is that they allow a wider audience to gain an intuition of MSE behaviour by dynamically adjusting assumptions and viewing impacts on utility in real-time.

To demonstrate the possible benefits of this approach we constructed a BBN in the software GeNIe (2014) (Figure 8) which is freely available and provides a range of tools for calculating utility, illustrating sensitivities and determining value-of-information.

This trial BBN includes 'nodes' for management procedures, observation and implementation error and the conditions of the operating model. The user can alter 'evidence' in the BBN to change the weighting of assumptions to investigate the impact on performance metrics and additive utility functions (similar to Levontin *et al* .,2014).

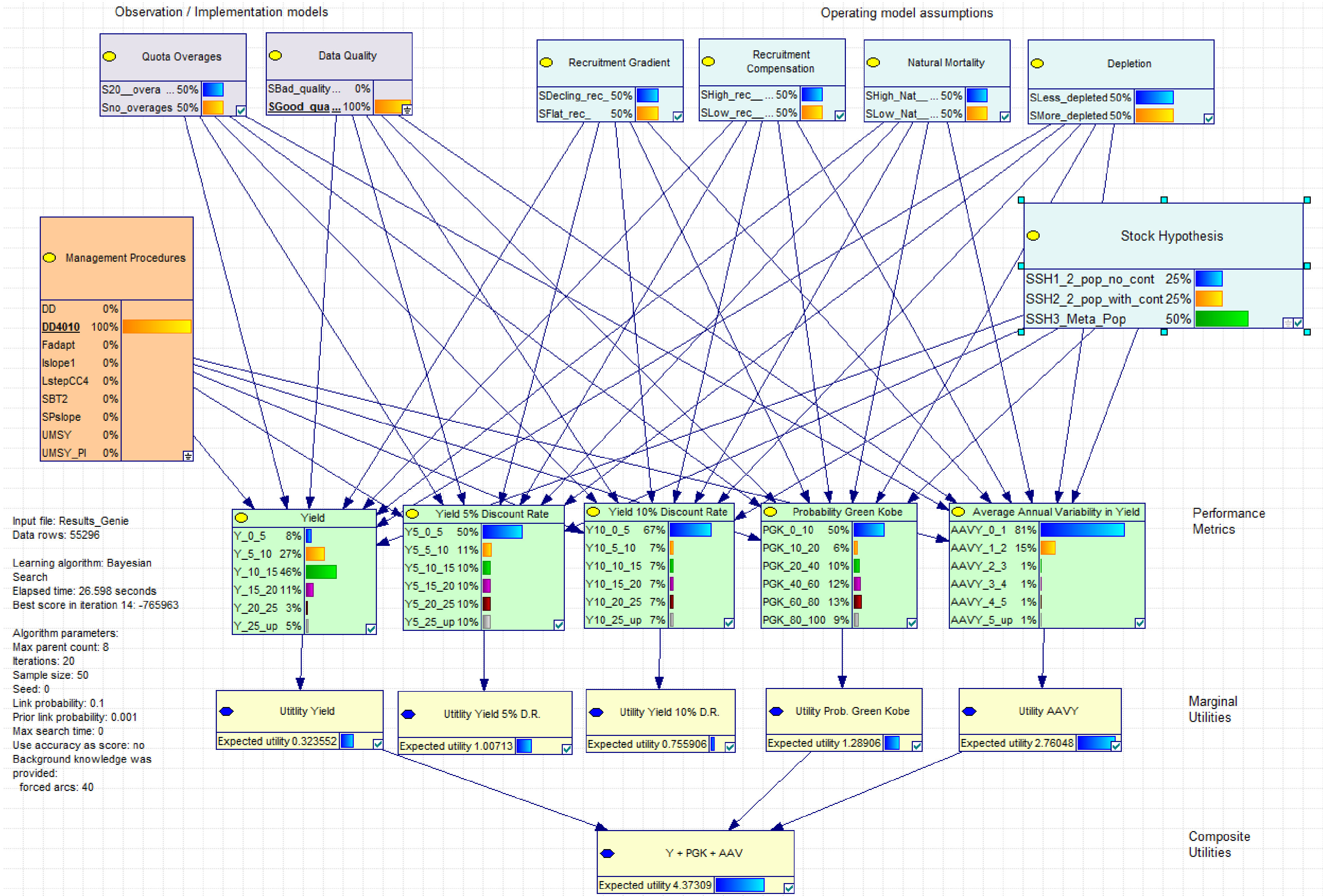

Figure 8. A screenshot of the Genie Bayesian Belief Network summarizing the findings of the preliminary MSE.

6 Discussion

6.1 Preliminary MSE results

Fromentin *et al*. (2014) identify population structure, natural mortality rate, population growth and recruitment as the primary sources of uncertainty for ABT. Our early results confirm that alternative stock hypotheses (population structure) may determine the likelihood of meeting management objectives (e.g. probability of green Kobe, PGK) as strongly as alternative hypotheses for natural mortality rate, population growth (recruitment compensation rate) and recruitment (trajectory in recruitment).

Our simulations indicate that sub-population structure can lead to unpredictable results. The metapopulation hypothesis (SH3) was more likely to recover to be underfished and subject to underfishing (higher PGK) than simulations with smaller number of sub-populations. This may be a product of simulating overly simplistic spatial population distribution and spatial fishing dynamics. Nonetheless this result underscores the important role of simulation evaluation in revealing the behavior of complex systems. A similar example was the higher PGK scores of the delay-difference MP for declining recruitment trajectory. The bias in estimated parameters of the DD MP over the 50 year historical simulation was strong enough to counter the future loss in productivity from declining recruitment. Without undertaking closed-loop MSE simulation it is not possible to reveal these often counter-intuitive dynamical properties.

In this analysis we consider MSY reference points and depletion by stock and essentially aggregate all eastern sub-populations when calculating these reference points and related performance metrics. The risk of extinction to subpopulations (relevant only to the meta-population model SH3) is not used in the evaluation of performance and when monitored is likely to reveal added risks to smaller less productive stocks (Kell et al. 2012). An important future step in MSE development is characterizing stakeholder utility with respect to the depletion of one or more sub-populations.

Simple stock assessment models such as the delay-difference MP appear to offer the best overall performance. However it should be noted that in future applications many of the other candidate MPs will be tuned to a training set of operating model simulations and may offer substantially improved performance. Simple MPs such as SPslope have provided mixed performance in other simulation studies (Carruthers et al. 2014b). However SPslope appeared to perform much better given the particular performance metrics and spatial dynamics simulated here. This finding suggests that caution should be taken in the wider interpretation of simulation studies particularly if there are large discrepancies in operating model assumptions or defined objectives.

The relative lack of sensitivity to data quality may be a product of observation models that were too similar and did not span a credible range of bias and imprecision in data inputs to MPs. Consultation with experts and more comprehensive simulation of data-gathering protocols is likely to improve the credibility of future observation models. These should include models for aerial survey, catch-composition, microsatellite, genetics and pop-off satellite archival tagging data.

In general, performance was not sensitive to 20% overages in quotas, including yield metrics. This indicates that unless it is substantially larger, implementation bias may be a less critical determinant of management performance than the choice of MP. It should be noted that historical overages and catch under-reporting may have been substantially higher (Fromentin, 2009)

6.2 Future MSE development

Amongst the most important future steps in MSE development is the definition of management goals and performance measures to quantify the extent to which those goals have been achieved (Fromentin et al. 2014, e.g. Kell et al. 2013). Interactive tools such as Bayesian belief networks offer stakeholders the opportunity to focus on their core objectives and construct meaningful utility functions. It may be necessary to construct economic models to represent the full range of performance metrics that have been identified for ABT such as employment and inter-annual variability in fishing effort (Leech *et al.*, 2014). A related task is the construction of credible models for fleet dynamics as these are required to model the response in fishing mortality rate to the spatial distribution of the population and the level of stock depletion. The preliminary effort dynamics and implementation error models presented here are overly simplistic and likely to strongly determine the relative performance of the various MPs. In future analyses it may be necessary to allow for time varying age selectivity and changes in fishing efficiency.

The identification of hypotheses that may impact performance was discussed by Fromentin et al. (2014) and our preliminary MSE was designed specifically to accommodate such hypotheses. The next stage is the development and testing of a spatial operating model that may be fitted to the data that are available for ABT. This is technically the most demanding of the tasks required for implementing a full MSE for ABT. A particular challenge is informing statistical models that include multiple sub-stocks. This may require allocating data to sub-stocks based on time, location and other covariates. The processing of up-to-date electronic tagging data and survey data are also priorities for the conditioning of an empirical operating model, although data that are already available in the conditioning of previous spatial models may be sufficient to bracket a range of credible movement scenarios (e.g. Taylor *et al.*, 2011)

Given the body of MSE work that has been carried out for other fish stocks including Southern Bluefin Tuna, there is already a wide range of candidate MPs available. Many of these are easily incorporated in future analyses as they were tested in the peer-reviewed paper that was drafted in parallel to this document (Carruthers et al. 2014b). Since Virtual Population Analysis (VPA) is an assessment that has traditionally been applied to ABT it would have been desirable to test a related MP. In this preliminary MSE a VPA assessment using Fisheries Library in R was investigated. While the MP would operate in over 95% of simulated situations the procedure led to errors in a small fraction of cases. Future testing and development of this MP is necessary to ensure it is sufficiently robust to a range of simulated conditions (for example a stock that has crashed and catches have remained low for several years).

Other MPs that should be considered are statistical catch-at-age models (e.g. Stock Synthesis, Methot and Wetzel 2013) and statistical catch-at-length models (e.g. MULTIFAN-CL, Fournier et al. 2012) that are commonly used to assess other tuna resources. As in the case of the VPA assessment the core challenge is making the more complex MPs robust to a wide range of simulated conditions, that can violate fundamental assumptions of the approaches (e.g. stationary stock productivity, growth, fully mixed stock dynamics).

Many MPs are designed to be tuned to a training set of simulations. This is followed by robustness trials in which frailties in the candidate MPs are revealed with respect to the core uncertainties. The current MSE framework can be easily adapted to include robustness trials by tuning MPs to the empirical operating model (informed by a spatial assessment model for example) and then using the MSE framework to investigate alternative scenarios for the primary sources of uncertainty. Once an empirical operating model has been defined, the preliminary MSE framework can also be used to conduct retrospective tests of performance in which MPs are evaluated given the historical estimates of population dynamics (e.g. Geromont and Butterworth, 2014b).

The demonstration Bayesian Belief Network illustrates how new software developments may be used to help a wider range of stakeholders understand and interact with the complex results of an MSE analysis. Future work should investigate other decision theoretic approaches such as dynamic inference diagrams and continuous BBNs such as Hugin Expert. Following feedback from the core modelling steering group it would be beneficial to build the ABT-MSE framework into an R package along with supporting documentation and walkthroughs to maximize the opportunity for stakeholder participation and feedback.

7 Progress relative to deliverables

Develop well documented, object-oriented C++ source code for the operating model consistent with the recommendations of the Modelling Coordinator, ICCAT population dynamics specialist and the Core Modelling Steering Group; as part of *this development, the successful bidder shall participate in two documents co-authored with others:*

7.1 Design document (D1)

A design document that details an object orientated (OO) design with code based on C++ and/or S4 classes for i) a multi-population OM that can be conditioned on a variety of data sets and hypotheses and ii) an Observation Error Model (OEM) that can be used to evaluate different data collection regimes e.g. aerial survey, tagging programs, catch and catch per unit effort (CPUE) and size to age conversions.

The design of the MSE framework, the relationship of objects, the definition of these classes and their related methods are all detailed in this report. The code for the MSE framework is available at ABT MSE 2014 (https://drive.google.com/folderview?id=0B0HYOP0BN5RPZmhWeXFJSmpDbnc&usp=sharing&tid=0B0HYOP0BN5RPdUYxQzVFcDh3dUE) including a walkthrough of a typical MSE analysis. If necessary a dedicated MSE design document can be produced.

7.2 Summary of alternative Management Procedures (D2)

Summary of alternative management procedures including alternative stock estimation procedures with coding requirements and appropriate code, libraries and packages. For example there are a variety of stock assessment methods already coded up and these may need modification to be used within a common MSE framework or adapted to use GBYP data and BFT stock assessment assumptions.

In collaboration with the Core Modelling Steering Group a simulation evaluation study was carried out on a total of 26 candidate management procedures. The approach and results have been summarized in a draft peer-reviewed paper. The latest version of the draft paper is available at ABT MSE 2014 (https://drive.google.com/folderview?id=0B0HYOP0BN5RPZmhWeXFJSmpDbnc&usp=sharing&tid=0B0HYOP0BN5RPdUYxQzVFcDh3dUE)in the subfolder 'submissions'.

7.3 MSE demonstrator (D3)

MSE demonstrator for use with stakeholders to illustrate the impact of uncertainty on management objectives and collaboration on a manuscript describing these results

A streamlined demonstration of the preliminary ABT MSE is available at ABT MSE 2014 (https://drive.google.com/folderview?id=0B0HYOP0BN5RPZmhWeXFJSmpDbnc&usp=sharing&tid=0B0HYOP0BN5RPdUYxQzVFcDh3dUE). Users can follow the

R walkthrough 'RScripts/Example script.r' (see Appendix 9.3). Additionally users may install the GeNIe (2014) software and load the Bayesian Belief Network 'Genie/ABT_MSE.xdsl' to investigate the preliminary MSE results.

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9 Appendix

9.1 Object classes and attributes (slots)

Table 9. The attributes of the OMd (Operating Model definition) object class that provides a rapid way of defining a range of simulations for the ABT operating model. Attributes highlighted in red are currently not used in the MSE.

Slot / attribute	Class	Dimension	Dist.	Description
Dimensions				
Name	character	1		The name of the object e.g. "Base case 10 area"
Date	character	1		Date that the object was created
Author	character	1		Who made the object
Notes	character	1		Any important notes regarding the object
PrimarySource	character	1		A reference to the most important paper or report used to make the object
nsim	integer	1		Number of MSE simulations
npop	integer	1		Number of discrete populations (sub populations)
nages	integer	1		Maximum number of ages
nyears	integer	1		Number of historical simulation years (prior to closed loop simulation)
nsubyears	integer	1		Number of subyears (e.g. 4 seasons, 12 months)
nareas	integer	1		Number of discrete spatial areas
proyears	integer	1		Number of years used in projections (for closed-loop simulation)
Biological model				
Magemu	numeric	npop, nages		Mean expected natural mortality rate at age
Mrange	numeric	npop, 2	U	Range of a mulitplier for mean natural mortality rate e.g. c(0.9, 1.1)
Msd	numeric	npop, 2	U	Range in interannual variability in M (lognormal CV) e.g. c(0.05,0.1)
Mgrad	numeric	npop, 2	U	Range of gradient in mean M (% y^{-1}) e.g. c(-0.25, 0.25)
SRrel	integer	npop		Functional form of the stock-recruit relationship (1=Beverton Holt, 2=Ricker)
h	numeric	npop, 2	U	Range of steepness (recruitment compensation) of the stock recruit-relationship
recgrad	numeric	npop, 2	U	Range of gradient in recruitment deviations (% y^{-1})
Reccv	numeric	npop, 2	U	Range in interannual variability in recruitment deviations (lognormal CV) e.g. c(0.2,0.5)
AC	numeric	npop, 2	U	Auto-correlation in recruitment (fraction of recruitment from previous year)
Recsubyr	integer	npop		The subyear in which spawning is assumed to take place (e.g 2 = Apr-Jun)
Linf	numeric	npop, 2	U	Range in sampled maxmum length (von B. L-infinity in cm) e.g. c(310, 330)
K	numeric	npop, 2	U	Range in sampled maximum growth rate (von. B K parameter) e.g. c(0.08,0.09)
t0	numeric	npop		Theoretical age at zero length
Ksd	numeric	npop, 2	U	Range in interannual variability in growth rate K (lognormal CV)
Kgrad	numeric	npop, 2	U	Range of gradient in growth rate K (% y^{-1})
Linfsd	numeric	npop, 2	U	Range in interannual variability in Linf (lognormal CV)
Linfgrad	numeric	npop, 2	U	Range in gradient in Linf (% y^{-1})
a	numeric	npop		Weight-length parameter a $W=aL^b$
b	numeric	npop		Weight-length parameter b $W=aL^b$
ageM	numeric	npop, 2	U	Range for age at 50% maturity (inflection point of logistic model)
ageMsd	numeric	npop, 2	U	Range for interannual variability in the inflection point of logistic model (lognormal CV)
ageMgrad	numeric	npop, 2	U	Range of mean gradient in ageM (% y^{-1})
D	numeric	npop, 2	U	Range of current stock depletion (spawning stock biomass relative to unfished levels)
R0	numeric	npop, 2	U	Range of unfished recruitment (controls relative magnitude of each simulate population)
Size_area	numeric	2, nareas		The size each area (habitat size)
mov	numeric	npop, nages, nyears,		The movement probability matrix for juvenile fish
Mmov	numeric	nsubyears, nareas,		The movement probability matrix for mature fish
movvar	numeric	npop	U	Range of variability in the movement matrix among simulations (juvenile fish)
movsd	numeric	npop, 2	U	Range of interannual variability in movement (juvenile fish)
movgrad	numeric	npop, 2	U	Range in trajectory of regional gradients (juvenile fish)
Mmovvar	numeric	npop	U	Range of variability in the movement matrix among simulations (mature fish)
Mmovsd	numeric	npop, 2	U	Range of interannual variability in movement (mature fish)
Mmovgrad	numeric	npop, 2	U	Range in trajectory of regional gradients (mature fish)
excl	numeric	npop, nareas		Spatial exclusion matrix for each stock (1= an area it inhabits, 0 = area it does not inhabit)
Fishing model				
nfleets	integer	1		Number of fleets fishing
age05	numeric	nfleets, 2	U	Age at 5% vulnerability (ascending limb of the double-normal selectivity curve)
Vmaxage	numeric	nfleets, 2	U	Selectivity of the oldest age class (descending limb of the double-normal selectivity curve)
AFS	numeric	nfleets, 2	U	Age at full selection (joint point of the double-normal selectivity curve)
Fsd	numeric	nfleets, 2	U	Range in the interannual variability in fishing effort
Fgrad	numeric	nfleets, 2	U	Trajectory in effort over the final 50% of historical fishing (% y^{-1})
Frat	numeric	1		Relative proportion of fishing mortality per fleet (e.g. for two stocks 0.5 would be equal)
Spat_targ	numeric	nfleets, 2	U	Range of spatial targetting. distribution of F is proportional to (vulnerable biomass)$^{Spat\_targ}$
Area_names	character	nareas		Names of the areas
Area_defs	list	nareas		Polygon objects defining each area
Other				
targpop	integer	undefined		A vector representing populations of interest (MSY calcs, user specified depletion, etc)
seed	numeric	1		A random seed to be passed through the MSE to ensure results can be replicated

Table 10. The attributes of the OM (operating model) object class that stores the simulated values of operating model parameters and variables including derived reference points. Attributes highlighted in red are currently not used in the MSE

Slot / attribute	Class	Dimension	Dist.	Description
As OMd				
Name, Date, Author, Notes, PrimarySource, nsim, npop, nages, nyears, nsubyears, nareas, proyears, SRrel, Recsubyr, t0, a, b, Size_Area, excl, Area_names, Area_defs, Frat, Spat_targ, targpop, seed				
Biological parameters				
Mrange	numeric	nsim, npop		A multiplier to mean mortality at age
Msd	numeric	nsim, npop	LN	Interannual variability in M (lognormal CV)
Mgrad	numeric	nsim, npop		Gradient in mean M (% y^{-1})
h	numeric	nsim, npop		Steepness (recruitment compensation) of the stock recruit-relationship
recgrad	numeric	nsim, npop		Gradient in recruitment deviations (% y^{-1})
Reccv	numeric	nsim, npop	LN	Interannual variability in recruitment deviations (lognormal CV)
AC	numeric	nsim, npop		Auto-correlation in recruitment (fraction of recruitment from previous year)
Linf	numeric	nsim, npop		Maxmum length (von B. L-infinity in cm)
K	numeric	nsim, npop		Maximum growth rate (von. B K parameter)
Ksd	numeric	nsim, npop	LN	Interannual variability in growth rate K (lognormal CV)
Kgrad	numeric	nsim, npop		Gradient in growth rate K (% y^{-1})
Linfsd	numeric	nsim, npop	LN	Interannual variability in Linf (lognormal CV)
Linfgrad	numeric	nsim, npop		Gradient in Linf (% y^{-1})
ageM	numeric	nsim, npop		Age at 50% maturity (inflection point of logistic model)
ageMsd	numeric	nsim, npop	LN	Interannual variability in the inflection point of logistic model (lognormal CV)
ageMgrad	numeric	nsim, npop		Gradient in ageM (% y^{-1})
D	numeric	nsim, npop		Current stock depletion (spawning stock biomass relative to unfished levels)
R0	numeric	nsim, npop		Unfished recruitment (controls relative magnitude of each simulate population)
mov	numeric	nsim, npop, nages, nyears,		The movement probability matrix for juvenile fish
Mmov	numeric	nsubyears, nareas, nareas		The movement probability matrix for mature fish
movvar	numeric	nsim, npop		Variability in the movement matrix among simulations (juvenile fish)
movsd	numeric	nsim, npop		Interannual variability in movement (juvenile fish)
movgrad	numeric	nsim, npop		Trajectory of regional gradients (juvenile fish)
Mmovvar	numeric	nsim, npop		Variability in the movement matrix among simulations (mature fish)
Mmovsd	numeric	nsim, npop		Interannual variability in movement (mature fish)
Mmovgrad	numeric	nsim, npop		Trajectory of regional gradients (mature fish)
Fishing model				
age05	numeric	nsim, nfleets		Age at 5% vulnerability (ascending limb of the double-normal selectivity curve)
Vmaxage	numeric	nsim, nfleets		Selectivity of the oldest age class (desc. limb of the double-normal selectivity curve)
AFS	numeric	nsim, nfleets		Age at full selection (joint point of the double-normal selectivity curve)
Fsd	numeric	nsim, nfleets	LN	Interannual variability in fishing effort
Fgrad	numeric	nsim, nfleets		Trajectory in effort over the final 50% of historical fishing (% y^{-1})
Spat_targ	numeric	nsim, nfleets		Spatial targetting. distribution of F is proportional to (vulnerable biomass)$^{Spat\_targ}$
Simulated variables				
E	numeric	nsim, nfleets, nyears		Fishing effort
dFfinal	numeric	nsim, nfleets		The gradient in fishing effort at the last historical year
q	numeric	nsim, nfleets		Numerically optimized catchability (F=qE) to reach user-specified depletion D
sel	numeric	nsim, nfleets, nages		Age selectivity of fishing
mat	numeric	nsim, fleets, nages, nyears		Probability mature at age
Recdevs	numeric	nsim, npop, nyears		The recruitment deviations (anomalies from deterministic recruitment)
M	numeric	nsim, npop, nages, nyears		Natural mortality rate
Linf	numeric	nsim, npop, nyears		Maximum length (von B, L infinity)
K	numeric	nsim, npop, nyears		Maximum growth rate
Idist	numeric	nsim, npop, nages, nareas		Unfished fraction of each population in each area (juvenile fish)
MIdist	numeric	nsim, npop, nages, nareas		Unfished fraction of each population in each area (mature fish)
MSY	numeric	nsim		Maximum sustainable yield
BMSY	numeric	nsim		Biomass at MSY
VBMSY	numeric	nsim		Vulnerable biomass at MSY
SSBMSY	numeric	nsim		Spawning stock biomass at MSY
UMSY	numeric	nsim		Harvest rate corresponding to MSY
FMSYa	numeric	nsim		Apical fishing mortality at MSY (most vulnerable age class)

Table 11. The attributes of the MSE object class that stores all of the results of the closed-loop simulation.

Slot / attribut	Class	Dimension	Dist.	Description
As OM				
Name, Date, Author, Notes, PrimarySource, nsim, npop, nages, nyears, nsubyears, nareas, proyears, targpop				
Observation model				
Cimp	numeric	nsim	LN	Imprecision in annual catch observations (lognormal CV)
Cb	numeric	nsim		Persistant bias in catch observations
Cerr	numeric	nsim, nyears		Annual catch error
Iimp	numeric	nsim	LN	Imprecision in annual relative abundance estimates (lognormal CV)
Ibeta	numeric	nsim		Beta parameter controlling hyperstability (Iobs |proportional to| $I^{beta)}$
Ierr	numeric	nsim		Index error
nCAAobs	integer	nsim	MN	The number of annual catch-at-age observations
nCALobs	integer	nsim	MN	The number of annual catch-at-length observations
Lcv	numeric	nsim	LN	Length observation error (lognormal CV)
Mb	numeric	nsim		Bias in observed M
Kb	numeric	nsim		Bias in observed growth rate K
Linfb	numeric	nsim		Bias in observed maximum length
LFCb	numeric	nsim		Bias in observed length at first capture
LFSb	numeric	nsim		Bias in observed length at full selection
FMSYb	numeric	nsim		Bias in observed fishing mortality rate corresponding with MSY
FMSY_Mb	numeric	nsim		Bias in observed ratio of fishing mortality rate to natural mortality rate
BMSY_B0b	numeric	nsim		Bias in observed ratio of biomass at MSY relative to unfished levels
ageMb	numeric	nsim		Bias in observation of age at 50% maturity
Dimp	numeric	nsim	LN	Imprecision in observations of stock depletion (B relative to unfished)
Db	numeric	nsim		Bias in observations of current depletion (biomass relative to unfished)
Derr	numeric	nsim, nyears		Depletion error
Btimp	numeric	nsim	LN	Imprecision in observations of current stock biomass (lognormal CV)
Btb	numeric	nsim		Bias in observations of current stock biomass
Bterr	numeric	nsim, nyears		Current biomass error
Ftimp	numeric	nsim	LN	Imprecision in observations of current fishing mortality rate
Ftb	numeric	nsim		Bias in observations of current fishing mortality rate
Fterr	numeric	nsim, nyears		Current fishing mortality rate error
hb	numeric	nsim		Bias in observations of steepness of the stock-recruit relationship
IMSYb	numeric	nsim		Bias in observation of the relative abundance index at BMSY
MSYb	numeric	nsim		Bias in observation of MSY
BMSYb	numeric	nsim		Bias in observation of biomass at MSY
Projection				
nMPs	integer	1		Number of management procedures used in
MPs	characte			Names of the management procedures
C	numeric	nMPs, nsim, nfleets,		Simulated annual catches (by weight)
D	numeric	nMPs, nsim, nfleets,		Simulated stock depletion
B_BMSY	numeric	nMPs, nsim, nyears		Simulated biomass relative to MSY levels
F_FMSY	numeric	nMPs, nsim, nyears		Simulated fishing mortality rate relative to MSY levels
TAC	numeric	nMPs, nsim, nyears		TAC recommendations of the MPs

Table 12. The attributes of the Obs (observation model) object class that defines the level of precision and bias in observed data that are used by the various MPs.

Slot / attribute	Class	Dimension	Dist.	Description
Name	Character	1		Name of the observation model e.g. "imprecise / biased"
Ccv	numeric	2	U	Range of catch observation error (lognormal CV)
Cbcv	numeric	1	LN	Lognormal CV from which to sample bias in catch observations
nCAAobs	numeric	2	U	Range of number of annual catch-at-age observations
nCALobs	numeric	2	U	Range of number of annual catch-at-length observations
Lcv	numeric	2	U	Range of length observation error (lognormal CV)
Ibeta	numeric	2	UL	Range of the beta parameter controlling hyperstability in index observations
Icv	numeric	2	U	Range of the relative abundance observation error (lognormal CV)
Mbcv	numeric	1	LN	Lognormal CV from which to sample bias in M observations
Kbcv	numeric	1	LN	Lognormal CV from which to sample bias in von B. K observations
Linfbcv	numeric	1	LN	Lognormal CV from which to sample bias in von B. Linf observations
LFCbcv	numeric	1	LN	Lognormal CV from which to sample bias in length at first capture observations
LFSbcv	numeric	1	LN	Lognormal CV from which to sample bias in length at full selections observations
FMSYbcv	numeric	1	LN	Lognormal CV from which to sample bias in FMSY observations
FMSY_Mbcv	numeric	1	LN	Lognormal CV from which to sample bias in ration of FMSY to M observations
BMSY_B0bcv	numeric	1	LN	Lognormal CV from which to sample bias in BMSY relative to unfished observations
ageMbcv	numeric	1	LN	Lognormal CV from which to sample bias in observations of age at 50% maturity
Dbcv	numeric	1	LN	Lognormal CV from which to sample bias observations of current depletion
Dcv	numeric	2	U	Range of observation error in current depletion (lognormal CV)
Btbcv	numeric	1	LN	Lognormal CV from which to sample observations of current stock biomass
Btcv	numeric	2	U	Range of observation error in current stock biomass level (lognormal CV)
Ftbcv	numeric	1	LN	Lognormal CV from which to sample bias in in current fishing mortality rate observations
Ftcv	numeric	2	U	Range of observation error in current fishing mortality rate (lognormal CV)
hbcv	numeric	1	LN	Lognormal CV from which to sample bias observed steepness
Recbcv	numeric	1	LN	Lognormal CV from which to sample bias in observations of recent recruitment strength
IMSYbcv	numeric	1	LN	Lognormal CV from which to sample bias abundance index at BMSY
MSYbcv	numeric	1	LN	Lognormal CV from which to sample bias observations of MSY
BMSYbcv	numeric	1	LN	Lognormal CV from which to sample bias in observations of BMSY

9.2 Operating model equations

9.2.1 Population dynamics

An age-structured, seasonally structured, multiple population model was used to simulate population and fishery dynamics. A range of parameters and variables are allowed to vary among simulations for a given stock (*e.g.*, M, gradient in recent fishing effort, targeting). All parameters that vary as random variables across simulations are denoted with a tilde (*e.g.*, $\tilde{\mu}$). Hence, each parameter or variable denoted with a tilde represents a different simulated value specific to each population. This convention alleviates the need for a simulation and population subscript for every parameter or variable described below. For example, the symbol $\tilde{\mu}$ represents $\tilde{\mu}_{p,i} \sim f\left(\theta_p\right)$ which is the sample of the parameter $\tilde{\mu}$ corresponding with the i^{th} simulation for population p, drawn from a distribution function $f()$, from the population-specific parameters θ_p.

The numbers of individuals recruited to the first age group $N_{y,a=1,r}$ in each year y, subyear s, and area r is calculated using a Beverton-Holt stock-recruitment relationship with log-normal recruitment deviations:

1) $$N_{y+1,s=sr,a=1,r} = \exp\left(P_{y,a,r} - \frac{\tilde{\sigma}_{proc}{}^{2}}{2}\right)\frac{0.8R_0\tilde{h}\,SSB_{y+1,sr-1,r}}{0.2SSB_0(1-\tilde{h}) + (\tilde{h}-0.2)SSB_{y,sr-1,r}}$$

where *sr* is the subyear in which recruitment occurs, *h* is the steepness parameter, R_0 is the recruitment given unfished conditions, $SSB_{y,r}$ is spawning stock biomass in the previous year and SSB_0 is the spawning stock biomass under unfished conditions. The process error term *P*, was randomly sampled from a standard normal distribution that has a standard deviation, σ_{proc}:

2) $$P_{y,a,r} \sim N(0, \tilde{\sigma}_{proc})$$

The spawning stock biomass, *SSB*, is given by:

3) $$SSB_{y,s,r} = \sum_{a=1}^{n_a} m_{y,a} W_{y,a} N_{y,s,a,r}$$

where m_a is the maturity-at-age *a* and year *y,* and the maximum age n_a is specific to each stock. Maturity-at-age is assumed to follow a logistic relationship with age and changes over time according to the slope of the transition from immature to mature. This is determined by a temporally variable precision parameter, where 50% of individuals are mature at $\tilde{A}_m$:

4) $$m_{y,a} = \frac{1}{1+\exp\left(\left(\tilde{A}m_y - a\right)/\sigma_A\right)}$$

Numbers at age are converted to length using the von Bertalanffy growth equation:

5) $$L_a = \tilde{L}nf_y\left(1-e^{-\tilde{K}_y(a-t_0)}\right)$$

where L_a is the length of an individual of age *a*, the asymptotic length is *Lnf*, and *K* is the slope at the theoretical age at zero length t_0.

Weight at age W_a, is assumed to be related to length by:

6) $$W_a = \beta L_a{}^{\alpha}$$

For ages greater than 1, fishing mortality is assumed to occur before natural mortality and the numbers-at-age are calculated by the equations:

7) $$N_{y,s,a,r} = \begin{cases} \left(N_{y,s-1,a-1,r} - C_{y,s-1,a-1,r}\right)\exp\left(-\tilde{M}_{y,a}\right) & s>1 \\ \left(N_{y-1,s=n_s,a-1,r} - C_{y-1,s=n_s,a-1,r}\right)\exp\left(-\tilde{M}_{y,a}\right) & s=1 \end{cases}$$

where $\tilde{M}$ is the rate of natural mortality. No "plus group" is modelled, and instead the maximum age is set to 32 after which survival is less than 1% under unfished conditions.

Movement is assumed to be constant over time and age of individuals, and to occur instantaneously at the end of each subyear. For example, for individuals of age *a*, moving from area *r*, to area *k* for any year *y*:

8) $$N^{after}_{y,s,a,k} = \sum_r N^{before}_{y,s,a,r} \psi_{s,r,k}$$

where ψ is the probability of an individual moving from area *r*, to area *k* (Equation 24).

9.2.2 Fishing dynamics

To describe fishing dynamics of the model it is necessary to include the population subscript *p*, and the fleet subscript *f*.

The vulnerability at age, ω_a, was calculated using a double normal curve with age at maximum selectivity *ms*, an ascending limb standard deviation of σ_1 and a descending limb standard deviation σ_2. These standard deviations were determined for each simulation by numerically solving for two user-specified quantities: (1) the minimum age at 5% vulnerability $\tilde{\omega}_5$, and (2) the vulnerability of the oldest age class $\tilde{\omega}_{32}$.

The ascending limb age selectivity A_a (before normalization to a maximum value of 1) is given by:

9) $$A_{f,a} = \frac{1}{\sqrt{2\pi\tilde{\sigma}_{1f}^{\ 2}}} \exp\left(-\frac{(a - ms_f)^2}{\tilde{\sigma}_{1f}^{\ 2}} \right)$$

The descending limb vulnerability D_a is given by:

10) $$D_{f,a} = \frac{1}{\sqrt{2\pi\tilde{\sigma}_{2f}^{\ 2}}} \exp\left(-\frac{(a - ms_f)^2}{\tilde{\sigma}_{2f}^{\ 2}} \right)$$

For any given fleet *f*, the vulnerability at age is given by:

11) $$\omega_{f,a} = \begin{cases} A_{f,a} / \max(A_f) & a \le ms_f \\ D_{f,a} / \max(D_f) & a > ms_f \end{cases}$$

Catch in numbers is calculated by:

12) $$C_{p,y,s,a,r,f} = N_{p,y,s,a,r}\left(1 - \exp\left(-\omega_{f,a} T_{y,s,r,f} F_{y,s,a,f}\right)\right)$$

where *F* is the instantaneous fishing mortality rate (Eqn. 15) and *T* is a variable controlling spatial targeting (Eqn. 22).

Observed catch is calculated by multiplying simulated catch in numbers-at-age by weight-at-age and adding observation error:

13) $$C_y^{obs} = \exp\left(\varepsilon_y - \frac{\tilde{\sigma}_{obs}^{\;2}}{2}\right)\sum_p\sum_f\sum_s\sum_q\sum_r C_{p,y,s,a,r,f}\, W_{p,y,a}$$

The error term ε, was drawn from a standard normal distribution whose standard deviation σ_{obs} was sampled at random in each simulation:

14) $$\varepsilon_y \sim N(0, \tilde{\sigma}_{obs})$$

Fishing mortality rate F, may increase relative to effort (E) over the historical period according to catchability q modified by a percentage increase in fishing efficiency each year $\tilde{\Delta}q$:

15) $$F_{f,y} = \tilde{q}_f E_{f,y}\left(1 + \tilde{\Delta}q_f / 100\right)^{y-1}$$

Total effort was not related to biomass levels and in historical and future projections could remain high even at very low biomass levels. The maximum fraction of the population that could be caught in any given year was restricted to a maximum of 60% to prevent the simulation of single year stock collapses from TAC recommendations that are occasionally very high.

Log-normal variability in effort was added to a general effort trend V:

16) $$E_{f,y} = \exp\left(\varphi_{f,y} - \frac{\tilde{\sigma}e_f^{\;2}}{2}\right)V_{f,y}$$

The effort variability term φ_y was randomly sampled from a standard normal distribution that has a standard deviation, σe drawn at random for each simulation:

17) $$\varphi_{f,y} \sim N(0, \tilde{\sigma}e_f)$$

A range of effort variability was sampled. The general trend in effort was determined by a linear model of change in effort over time with slope aE, and intercept $\tilde{b}E$:

19) $$\frac{dV_{f,y}}{dy} = aE_f\, y + \tilde{b}E_f$$

This functional form allows effort to increase, decrease or remain flat over time. This effort model was constrained by sampling positive $\tilde{b}E$ values (effort was increasing at the start of the time series). The final annual change in effort $\tilde{\Delta}E$, is specified by the user to control the sampling of increasing, neutral and decreasing final effort trajectories:

20) $$\tilde{\Delta}E_f = \frac{dV_{f,final}}{dy}$$

For any simulated effort time series, the slope could then be calculated from the total number of years in the time series n_y, and the sampled intercept $\tilde{b}_E$:

21) $$aE_f = \left(\tilde{\Delta}E_f - \tilde{b}E_f\right)/n_y$$

Effort time series with negative values were discarded. All of the stocks had the same underlying variability in temporal effort dynamics.

In any given year, spatial fishing effort is assumed to be proportional to the distribution of the vulnerable biomass in the previous year, modified by a targeting parameter λ, that controls how strongly fishing effort will be distributed in relation to vulnerable biomass:

22) $$T_{y,s,r,f} = \left(\sum_p \sum_a \omega_{f,a} W_{p,a} N_{p,y,s,a,r}\right)^{\lambda_{y,f}} \Bigg/ \sum_r \left(\sum_p \sum_a \omega_{f,a} W_{p,a} N_{p,y,s,a,r}\right)^{\lambda_{y,f}}$$

The values for T average 1 in any year y, and subyear s, so they can be used to distribute total effort $E_{y,s}$ across areas in each subyear such that mean F among areas is the same as total annual F. Fishing is distributed evenly regardless of the vulnerable biomass in the previous year when the targeting parameter λ is zero. Spatial fishing will be distributed in favour of areas of high vulnerable biomass when λ is positive and distributed away from such areas when λ is negative. When λ =1 fishing distribution is proportional to vulnerable biomass. Targeting was assumed to remain constant over time.

9.2.3 Movement and spatial distribution

The initial biomass in each area is initialized according to an equilibrium assumption regarding age and spatial structure:

23) $$N_{p,y=1,s=1,a,r} = R0_p \left(e^{-\sum_{j=1}^{a} \tilde{M}_{p,j}}\right) d_{p,r}$$

where $R0$ is unfished recruitment, $d_{p,r}$ is the initial spatial distribution proportion, and the $d_{p,r}$ sum to 1 over r. Note that the age structure is assumed to be the same across areas. The initial distribution vector of the stock over areas, $d=[d_1,\ldots,d_n]$, is the stationary distribution satisfying the condition:

24) $$d_p = \psi_p d_p$$

where d is determined numerically by repeatedly multiplying an initial distribution for d by ψ. The probability ψ of moving from area r, to area k, is specific to each stock, age class and sub-year. The numerical process essentially

9.3 An example run of the demonstration MSE

```
#
================================================================================================
# ==== ABT MSE ==== Atlantic Bluefin Tuna Management Strategy Evaluation
==========================
#
================================================================================================

# --- Object-Oriented Management Strategy Evaluation using parallel processing
------------

# --- Tom Carruthers   UBC
# --- Laurie Kell      ICCAT
# --- Campbell Davies  CSIRO

# Version alpha (preliminary)
# 27th November 2014

# Prerequisites
===========================================================================

rm(list=ls(all=TRUE))              # Remove all existing objects from
environment
setwd("H:/ABT-MSE/")               # Set the working directory
source("Source/MSE_source.r")   # Load the source code
sfInit(parallel=T,cpus=8)          # Initiate the cluster

# Define Operating model
====================================================================

load("Objects/SCRS SH2")           # Load an operating model definition (OMd)
object
OMd@nsim<-as.integer(8)            # For demonstration do a small number of
simulations
plot(OMd)                          # Plot the spatial definition of areas

# Create an Operating Model
=================================================================

OM<-new('OM',OMd)                  # Initialize a new operating model (OM) object
```

```
plot(OM)                    # Plot the spatial distribution of mature and
immature fish

# Load Observation model
================================================================
=====

load("Objects/Good_Obs")         # Load the precise and unbiased observation
model ('Good')

# Undertake closed-loop simulation
=============================================================

tmse<-new('MSE',OM,Obs,MPs<-
c("DD","DD4010","UMSY","UMSY_PI"),interval=3,IE="Umax")

# Summarize results
================================================================
==========

plot(tmse)                   # Plot results
summary(tmse)                 # Tabulate results
```

Annex 4:
Draft Manuscript on the performance of a range of existing Harvest Control Rules.

Performance Review of Simple Management Procedures
(submitted to ICES Journal)

Authors:

Tom Carruthers, Laurence Kell, Doug Butterworth, Mark Maunder, Helena Geromont, Carl Walters, Murdoch McAllister, Richard Hillary, Toshihide Kitakado, Campbell Davies, Polina Levontin.

Abstract

Using a management strategy evaluation approach, we compare a range of new and established management procedures (MPs) for setting catch-limits in fisheries. Performance was evaluated with respect to fish life-history type, level of stock depletion, auto-correlation in recruitment strength and data quality. We identify the core sensitivities of each management procedure with respect to simulated population dynamics and observation processes. Methods that made use of current absolute biomass or stock depletion offer the best overall performance and that this is consistent across life-history types, data qualities and stock depletion levels. Simple MPs could outperform conventional approaches in both data-limited and data-rich assessment settings. In general methods are most sensitive to biases in reported catches, the selectivity to fishing of older age classes and relatively small temporal changes in somatic growth parameters. Our results indicate that in many cases tuning MPs to specific stock circumstances is important, though this may not be viable in data-poor assessment scenarios.

Keywords

Management strategy evaluation, management procedure, stock assessment, simulation, fisheries management, data-poor, data-limited

Appendix A. Operating model

A.1 Simulating stock dynamics

A standard age-structured, spatial model identical to that of Carruthers et al. 2014 was used to simulate population and fishery dynamics. A range of parameters and variables are allowed to vary among simulations for a given stock (*e.g.*, natural mortality rate *M*, gradient in recent fishing effort, targeting). All parameters that vary as random variables across simulations are denoted with a tilde (*e.g.*, $\tilde{\sigma}$). The probability distributions from which these parameters are sampled are detailed in Table App.A.1. Hence, each parameter or variable denoted with a tilde represents a sample from a distribution specific to each stock. This convention alleviates the need for a simulation and stock subscript for every parameter or variable described below. For example, the symbol $\tilde{\sigma}$ represents $\tilde{\sigma}_{s,i} \sim f(\theta_s)$ which is the sample of the parameter $\tilde{\sigma}$ corresponding with the i^{th} simulation for stock *s*, drawn from a distribution function *f*(), from the stock specific parameters θ_s.

The numbers of individuals recruited to the first age group $N_{y,a=1,r}$ in each year *y*, and area *r* is calculated using a Beverton-Holt stock-recruitment relationship with log-normal recruitment deviations:

App. A.1) $$N_{y,a=1,r} = \exp\left(P_{y,a,r} - \frac{\tilde{\sigma}_{proc}{}^2}{2}\right)\frac{0.8R_0\tilde{h}SSB_{y,r}}{0.2SSB_0(1-\tilde{h})+(\tilde{h}-0.2)SSB_{y,r}}$$

where *h* is the steepness parameter, R_0 is the recruitment given unfished conditions, $SSB_{y,r}$ is spawning stock biomass in the previous year and SSB_0 is the spawning stock biomass under unfished conditions. The process error term *P*, is an autocorrelated random variable:

App.A.2) $$P_{y,r} = v \cdot \kappa_{y,r} + (1-v) \cdot P_{y-1,r}$$

where, v controls the level of autocorrelation in recruitment deviations and κ is a normally distributed random variable of mean zero:

App.A.3) $$\kappa_{y,r} \sim N\left(0, \tilde{\sigma}_{proc}\right)$$

The spawning stock biomass, *SSB*, is given by:

App.A.4) $$SSB_{y,r} = \sum_{a=1}^{n_a} m_a W_a N_{y,a,r}$$

where m_a is the maturity-at-age a, and the maximum age n_a is specific to each stock. Maturity-at-age is assumed to follow a logistic relationship with age; the slope of the transition from immature to mature is determined by the precision parameter, where 50% of individuals are mature at $\tilde{A}_m$:

App.A.5) $$m_a = \frac{1}{1 + \exp\left(\left(\tilde{A}_m - a\right) / \sigma_A\right)}$$

Numbers at age are converted to biomass using the von Bertalanffy growth equation:

App.A.6) $$L_a = \tilde{L}_{\inf}\left(1 - e^{-\tilde{K}(a - t_0)}\right)$$

where L_a is the length of an individual of age a, the asymptotic length is L_{inf}, and K is the slope at the theoretical age at zero length t_0. L_{inf} and K are assumed to be time-varying with mean percentage gradient Δ_{Linf} and Δ_K. Inter-annual variability in L_{inf} and K is simulated from log-normal distributions with mean 1, and standard deviations sd_{Linf} and sd_K.

Weight at age W_a, is assumed to be related to length by:

App.A.7) $$W_a = \beta L_a{}^{\alpha}$$

For ages greater than 1, fishing mortality is assumed to occur before natural mortality and the numbers-at-age are calculated by:

App.A.8) $$N_{y,a,r} = \left(N_{y-1,a-1,r} - C_{y-1,a-1,r}\right)\exp\left(-\tilde{M}\right)$$

where $\tilde{M}$ is the rate of natural mortality. No "plus group" is modelled; instead the maximum age is set sufficiently high that survival to the maximum age is less than 1% under unfished conditions.

Movement is assumed to be constant over time and age of individuals, and to occur instantaneously at the end of each year. For example, for individuals of age *a*, moving from area *r* to area *k* for any year *y*:

App.A.9) $$N_{y,a,k}^{after} = \sum_{r} N_{y,a,r}^{before} \psi_{r,k}$$

where ψ is the probability of an individual moving from area *r*, to area *k* (Equation App.A.27).

A.2 Simulating fishery dynamics

The selectivity at age ω_a, was calculated using a double normal curve with age at maximum selectivity m_{sel}, an ascending limb standard deviation of σ_{sel1} and a descending limb standard deviation σ_{sel2}. These standard deviations were determined for each simulation by numerically solving for two user-specified quantities that are more intuitive: (1) the minimum age at 5% maximum selectivity $\tilde{a}_{0.05}$, and (2) the selectivity of the oldest age class $\tilde{\omega}_{old}$.

The ascending limb age selectivity A_a (before normalization to a maximum value of 1) is given by:

App.A.10) $$A_a = \frac{1}{\sqrt{2\pi\tilde{\sigma}_{sel1}^{\ 2}}} \exp\left(-\frac{(a - m_{sel})^2}{\tilde{\sigma}_{sel1}^{\ 2}} \right)$$

The descending limb selectivity D_a is given by:

App.A.11) $$D_a = \frac{1}{\sqrt{2\pi\tilde{\sigma}_{sel2}^{\ 2}}}\exp\left(-\frac{(a-m_{sel})^2}{\tilde{\sigma}_{sel2}^{\ 2}}\right)$$

The selectivity at age is given by:

App.A12) $$\omega_a = \begin{cases} A_a / \max(A) & a \le m_{sel} \\ D_a / \max(D) & a > m_{sel} \end{cases}$$

Refuges from fishing are simulated here by a regional availability variable R that is 1 for at least one area*:*

App.A.13) $$\begin{array}{ll} R_r = 1 & r = 1 \\ R_r \sim \text{dBern}\left(1-\left(\tilde{p}_R \frac{n_r}{n_r - 1}\right)\right) & r > 1 \end{array}$$

where R is the regional availability of the stock to fishing, p_R is the Bernoulli probability of failure (“failure to fish successfully” or “probability of a refuge”, Table App.A.1.) pre-specified for each stock.

Catch in numbers is calculated by:

App.A.14) $$C_{y,a,r} = N_{y,a,r}\left(1-\exp\left(-\omega_a p_{y,r} R_r F_{y,a}\right)\right)$$

where F is the fishing mortality rate.

Observed catch is calculated by multiplying simulated catch in numbers-at-age by weight-at-age and adding observation error:

App.A.15) $$C_y^{obs} = \exp\left(\varepsilon_{y,a,r} - \frac{\tilde{\sigma}_{obs}^{\ 2}}{2}\right)\sum_a \sum_r C_{y,a,r} W_a$$

The error term ε, is drawn from a standard normal distribution whose standard deviation σ_{obs} is sampled at random in each simulation:

App.A.16) $$\varepsilon_{y,a} \sim N(0, \tilde{\sigma}_{obs})$$

Fishing mortality rate *F*, may increase relative to effort (*E*) over the historical period according to catchability *q* modified by a percentage increase in fishing efficiency each year $\tilde{\Delta}_q$:

App.A.17) $$F_y = \tilde{q} E_y \left(1 + \tilde{\Delta}_q / 100\right)^{y-1}$$

Total effort is not related to biomass levels, and in historical and future projections can remain high even at very low biomass levels. The maximum fraction of the population that can be caught in any given year is restricted to a maximum of 80% to prevent the simulation of single year stock collapses from TAC recommendations that are occasionally very high.

Log-normal variability in effort is added to a general effort trend *V*:

App.A.18) $$E_y = \exp\left(\varphi_y - \frac{\tilde{\sigma}_{eff}^{\ 2}}{2}\right) V_y$$

The effort variability term φ_y is randomly sampled from a standard normal distribution that has a standard deviation, σ_{eff} drawn at random for each simulation:

App.A.19) $$\varphi_y \sim N(0, \tilde{\sigma}_{eff})$$

A range of effort variability is sampled to assess how the degree of auto-correlation affected the performance of stock status classification methods. The general trend in effort is determined by a linear model of change in effort over time with slope a_E, and intercept $\tilde{b}_E$:

App.A.20) $$\frac{dV_y}{dy} = a_E y + \tilde{b}_E$$

This functional form allows effort to increase, decrease or remain unchanged over time. This effort model is constrained by sampling positive $\tilde{b}_E$ values (effort is increasing at the start of the time series). The final annual change in effort $\tilde{\Delta}_E$, is specified by the user to control the sampling of increasing, constant and decreasing final effort trajectories:

App.A.21) $$\tilde{\Delta}_E = \frac{dV_{final}}{dy}$$

For any simulated effort time series, the slope can then be calculated from the total number of years in the time series n_y, and the sampled intercept $\tilde{b}_E$:

App.A.22) $$a_E = \left(\tilde{\Delta}_E - \tilde{b}_E\right) / n_y$$

Effort time series with negative values were discarded. All of the stocks had the same underlying variability in temporal effort dynamics.

In any given year, spatial fishing effort is assumed to be proportional to the distribution of the vulnerable biomass in the previous year, modified by a targeting parameter λ, that controls how strongly fishing effort will be distributed in relation to vulnerable biomass:

App.A.23) $$p_{y,r} = \left(\sum_a \omega_a W_a N_{y,a,r}\right)^{\lambda_y} \Bigg/ \sum_r \left(\sum_a \omega_a W_a N_{y,a,r}\right)^{\lambda_y}$$

The values for p average 1 in any year so they can be used to distribute total effort E_y across areas in each year such that mean F among areas is the same as total annual F. Fishing is distributed evenly regardless of the vulnerable biomass in the previous year when the targeting parameter λ is zero. Spatial fishing will be distributed in favour of areas of high vulnerable biomass when λ is positive and distributed away from such areas when λ is negative. In order to simulate increases or decreases in targeting, the targeting parameter follows a linear change over time with intercept 0, and final targeting level $\tilde{\lambda}_{cur}$ in the last historical year of the simulation n_y:

App.A.24) $$\lambda_y = \frac{y}{n_y}\tilde{\lambda}_{cur}$$

Targeting is assumed to remain constant over projected years at the same level as the final year of the historical period.

A.3 Initializing the population dynamics model and simulating movement

The initial biomass in each area is initialized according to an equilibrium assumption regarding age and spatial structure:

App.A.25) $$N_{y=1,a,r} = R_0\left(e^{-\tilde{M}}\right)^{a-1} d_r$$

where d_r is the initial spatial distribution proportion, and the d_r sum to 1 over r. Note that the age structure is assumed to be the same across areas. The initial distribution vector of the stock over areas, $d=[d_1,\ldots,d_n]$, is the stationary distribution satisfying the condition:

App.A.26) $$d = \psi d$$

where d is the positive eigenvector of the movement probability matrix ψ, corresponding to the first eigenvalue (this can also be determined numerically by repeatedly multiplying an initial distribution for d by ψ). Two user specified parameters are used to define the movement matrix ψ: the probability of remaining in area 1 between years ($\psi_{1,1}$) and the equilibrium unfished fraction of stock in area 1 (d_1) are used to numerically solve for a matching set of ψ parameters.

A.4 Parameterization of stock dynamics

Given the availability of full stock assessments with which to characterize their stock dynamics, we chose Pacific herring (DFO, 2012), Atlantic bluefin tuna (ICCAT, 2012), and canary rockfish (Wallace and Cope 2011) as case-studies that span a range of longevity. The values of input parameters and the sources of these inputs are detailed in Table App.A.1.

Table App.A.1. Summary of the variables/parameters that define each of the stock simulations, including values and/or the range over which they are sampled. Where two values are provided, variables are sampled from a uniform distribution with the lower and upper bounds listed.

Name		**Pacific herring**		**Eastern Atlantic bluefin tuna**		**Canary rockfish**	
Maximum age	n_a	10		32		64	
Steepness	h	0.4	0.6	0.6	0.9	0.35	0.7
Mean natural mortality rate	μ_M	0.28	0.38	0.12	0.16	0.04	0.08
Interannual variability in natural mortality rate	sd_M	0	0.1	0	0.1	0	0.05
Gradient in natural mortality rate (per cent y^{-1})	α_M	-0.5	0.5	-0.5	0.5	-0.5	0.5
Theoretical age at length zero	t0	-0.025		-0.97		-0.04	
Mean maximum length	μ_{Linf}	25	29	315	325	62	68
Interannual variability in maximum length	sd_{Linf}	0	0.025	0	0.025	0	0.025
Gradient in maximum length (per cent y^{-1})	α_{Linf}	-0.25	0.25	-0.25	0.25	-0.25	0.25
Mean von Bertalanffy growth coefficient	μ_K	0.43	0.53	0.08	0.1	0.122	0.128
Interannual variability in the growth coefficient K	sd_K	0	0.025	0	0.025	0	0.025
Gradient in the growth coefficient K (per cent y^{-1})	α_K	-0.25	0.25	-0.25	0.25	-0.25	0.25
Weight-length parameter a ($W=aL^b$)	α_{WL}	4.50E-06		1.96E-05		1.55E-05	
Weight-length parameter b ($W=aL^b$)	b_{WL}	3.127		3.009		3.03	
Stock depletion, biomass relative to unfished	D	0.025	0.6	0.025	0.6	0.025	0.6
Age at 50% maturity	A_m	1.7	2.3	3.5	5	6.5	9.5
Log-normal recruitment variation	σ_R	0.2	0.4	0.1	0.3	0.2	0.5
Reference		DFO 2012		ICCAT 2012		Wallace and Cope 2011	

Appendix B: Reference methods

B.1 DCAC

In circumstances where the information available is insufficient to derive a catch-limit from stock assessment the NMFS advocates the use of Depletion Corrected Average Catch (DCAC, MacCall 2009). DCAC attempts to calculate average catch accounting for the removal of "windfall harvest" of less productive biomass that may have occurred as the stock became depleted. DCAC requires inputs for M, F_{MSY}/M (or c), B_{MSY}/B_0 (or D) and B_{cur}/B_0 (or B_{peak}). A number of samples are drawn from the following distributions:

App.B.1a) $M_{DCAC} \sim \mathrm{dlnorm}(\mu = M, SD = 0.5)$

App.B.1b) $c_{DBSRA} \sim \mathrm{dlnorm}(\mu = c, \sigma = 0.2)$

App.B.1c) $D_{DBSRA} \sim \mathrm{dlnorm}(\mu = D, \sigma = 0.2)$

where, in keeping with MacCall's (2009) approach, the SDs for M and c are set to 0.5 and 0.2, respectively.. MacCall (2009) states that "unlike the other parameters, the precision of [depletion D] is entirely dependent on the data and method used in its estimation, and there is no clear value of precision that can serve as a default". Subsequently, Dick and MacCall (2011) assume a default distribution with a CV of 0.25. We adopt the same beta distribution for depletion to remain consistent with the assumptions made in simulating DB-SRA (detailed above in management scenario M1), i.e.:

App.B.2a) $D_{DBSRA} \sim \text{dbeta}(\mu = D_{obs}, CV = 0.25)$ where $D_{obs} < 0.5$

App.B.2b) $1\text{-}D_{DBSRA} \sim \text{dbeta}(\mu = 1\text{-}D_{obs}, CV = 0.25)$ where $D_{obs} > 0.5$

For each sample of these parameters, sustainable yield (YS) is calculated by:

App.B.3)

$$YS_{DCAC} = \frac{\sum C_{obs}}{n + (1 - D_{DCAC})/(Bpeak_{DCAC} c_{DCAC} M_{DCAC})} = \frac{\sum C_{obs}}{n + (1 - D_{DCAC})/(0.4 c_{DCAC} M_{DCAC})}$$

where the C_{obs} are annual historical catches and n is the number of years of historical catches.

This stochastic approach produces numerous samples of the derived sustainable yield (YS) that may be used as a catch-limit.

B.5 F_{MSY}/M ratio 'Fratio'

It has been suggested that ratios of F_{MSY}/M (c) may be robust to broad life-history types and fisheries exploitation scenarios. Gulland (1971) proposed a simple method of setting maximum sustainable yield $MSY = 0.5M \cdot B_0$, in doing so assuming that B_{MSY}/B_0 =0.5 and F_{MSY}/M = 1. Subsequent publications have revised this F_{MSY} recommendation downwards. The Fratio MP is simulated by generating imperfect knowledge regarding M, current absolute biomass and the ratio of F_{MSY}/M.

B.6 Delay-difference stock assessment (DD)

The performance of a delay-difference model (Deriso 1980, Schnute 1985) fitted to catch and effort data is evaluated to provide a reference for the performance of the other MPs. The delay-difference model requires additional auxiliary (independent) information regarding the form of the stock-recruit function, the fraction mature at age, somatic growth, M, and the selectivity-at-age curve. The delay-difference stock assessment method provides estimates of B_{curr} and F_{MSY} and therefore direct estimates of an appropriate catch limit.

The delay-difference model is fitted to annual total catch and effort data. The model is parameterized according to: maximum sustainable yield, MSY_{DD} and harvest rate at maximum sustainable yield, $Umsy_{DD}$. The catchability coefficient scaling effort to fishing mortality rate is also estimated. The growth parameters α and ρ of the Ford-Brody growth model ($W_{a+1}=\alpha+\rho W_a$) are approximated from the known weight at age W, for each simulation:

App.B.4) $$\alpha = W_\infty (1-\rho); \qquad \rho = \frac{W_{V_{obs}+2} - W_\infty}{W_{V_{obs}+1} - W_\infty}$$

where W_∞ is the maximum weight of an individual and V_{obs} is the observed age at 50% selectivity determined from the ascending limb of the selectivity curve ω (Eqn. App.A.12). Since bias in the age at 50% selectivity may strongly affect the delay-difference model, V_{obs} is simulated subject to imperfect knowledge (Table App.C.1 3). Survival rate at maximum sustainable yield is given by $Smsy = \exp(-M_{obs})(1-Umsy_{DD})$ so that the number of spawners per recruit, SPR is given by:

App.B.5) $$SPR = \frac{(\alpha \cdot Smsy)/(1-Smsy) + W_{V_{obs}}}{1-\rho \cdot Smsy}$$

The Beverton-Holt parameter α_{rec}, the maximum recruits per spawner as spawner abundance approaches zero, is calculated:

App.B.6) $$\alpha_{rec} = 1/\left((1-Umsy_{DD})^2 (SPR + Umsy_{DD} \cdot \Delta_{SPR})\right)$$

The derivative of yield with respect to harvest rate Δ_{SPR}, evaluated at $Umsy_{DD}$ is given by:

App.B.7)
$$\Delta_{SPR} = -S_0 \frac{p}{1-\rho \cdot Smsy} \frac{SPR+1}{1-\rho \cdot Smsy} \frac{\alpha}{(1-Smsy)} + \frac{Smsy \cdot \alpha}{(1-Smsy)^2}$$

where S_0 is unfished survival rate $S_0 = \exp(-M)$. The Beverton-Holt parameter β_{rec} is calculated as:

App.B.8)
$$\beta_{rec} = \frac{Umsy_{DD} \cdot (\alpha_{rec} \cdot SPR - 1/(1-Umsy_{DD}))}{MSY_{DD}}$$

Unfished recruitment R_0 is allocated to recruitments up to and including the age at recruitment to the fishery V_{obs} and is given by:

App.B.9)
$$R_{1,2\ldots V_{obs}} = R_0 = \frac{\alpha_{rec} \cdot SPR_0 - 1}{\beta_{rec} \cdot SPR_0}$$

where unfished spawners per recruit SPR_0 is calculated using Equation App.B.5 when S_{msy} is replaced by S_0:

It follows that initial biomass B_1 is given by: $B_1 = R_0 \cdot SPR_0$ and initial numbers N_1 is given by $N_1 = R_0 / (1-S_0)$. From this initialization, biomass dynamics are calculated by:

App.B.10)
$$B_{y+1} = S_y (\alpha \cdot N_y + \rho \cdot B_y) + W_V \cdot R_{y+1} \quad ; \quad N_{y+1} = S_y \cdot N_y + R_{y+1}$$

where $S_y = \exp(-E_y q_{DD} - M)$ is the survival rate in year y, N represents stock numbers, B is the biomass, W_k is the weight of an individual at the age at 50% selectivity k, M is the natural mortality rate (assumed to be known exactly), q_{DD} is the estimated catchability, E_{y} is the observed fishing effort during year y, and R_{y} represents the number of recruits during year y:

App.B.11) $$R_{y+k} = \frac{\alpha_{rec}\left(B_y - C_y\right)}{1+\beta_{rec}\left(B_y - C_y\right)}$$

where catches C, are given by: $C_y = B_y\left(1-\exp\left(-q_{DD}E_y\right)\right)$.

The model is fitted to observed (simulated) catches by minimizing a global objective O that is calculated by the sum of the negative log likelihood of the catches:

App.B.12) $$O = \sum_y \left[\frac{\log(2\pi)}{2} + \log(\sigma_c) + \frac{\left(\log\left(C_y^{obs}\right) - \log\left(C_y\right)\right)^2}{2\sigma_c^{\ 2}}\right]$$

where σ_c is the assumed standard deviation (in log space) of the observation error.

Appendix C: Simulating imperfect information

Table App.C.1. Summary of the bias /error parameters and related distributions that control the accuracy and precision of knowledge of the simulated system that is subsequently used by the data-limited methods and harvest control rules. The log-normal distribution described in the table below (~dlnorm(μ,σ) is the exponent of the normal distribution with mean μ and standard deviation σ, parameters: $N\left(-0.5\log\left(1+\sigma^2/\mu^2\right), \sqrt{\log\left(1+\sigma^2/\mu^2\right)}\right)$.

Variable	Symbol	Related functions
The standard deviation of the log-normally distributed bias in natural mortality rate M	Υ_M	$M_{obs} = M \times \mu_M$ $\mu_M \sim dlnorm(\mu=1, \Upsilon_M)$
The standard deviation of the log-normally distributed bias in von Bertalanffy growth rate parameter K	Υ_K	$K_{obs} = K \times \mu_K$ $\mu_K \sim dlnorm(\mu=1, \Upsilon_K)$
The standard deviation of the log-normally distributed bias in biomass at maximum sustainble yield B_{MSY}	Υ_{Bmsy}	$Bmsy_{obs} = Bmsy \times \mu_{Bmsy}$ $\mu_{Bmsy} \sim dlnorm(\mu=1, \Upsilon_{Bmsy})$
The standard deviation of the log-normally distributed bias in biomass at maximum sustainable yield relative to unfished Bpeak (B_{MSY}/B_0)	Υ_{Bpeak}	$Bpeak_{obs} = Bpeak \times \mu_{Bpeak}$ $\mu_{Bpeak} \sim dlnorm(\mu=1, \Upsilon_{Bpeak})$
The standard deviation of the log-normally distributed bias in the ratio of maximum sustainable fishing mortality rate to natural mortality rate F_{MSY}_M	Υ_{FMSY_M}	$c_{obs} = c \times \mu_{FMSY\_M}$ $\mu_{FMSY\_M} \sim dlnorm(\mu=1, \Upsilon_{FMSY\_M})$
The standard deviation of the log-normally distributed bias in the age at first maturity Am	Υ_{Am}	$Am_{obs} = Am \times \mu_{Am}$ $\mu_{Am} \sim dlnorm(\mu=1, \Upsilon_{Am})$
The standard deviation of the log-normally distributed bias in the current level of stock depletion D (B_{cur}/B_0)	Υ_D	$D_{obs} = D \times j_D$ $j_D \sim dlnorm(\mu_D, \sigma_D)$ $\mu_D \sim dlnorm(\mu=1, \Upsilon_D)$
The maximum standard deviation for log-normal error in current stock depletion μ_D for projected years	SD_D	$D_{obs} = D \times j_D$ $j_D \sim dlnorm(\mu_D, \sigma_D)$ $\sigma_D \sim U(0, SD_D)$
The maximum standard deviation for log-normal error in the relative abundance index for projected years	SD_I	$I_y = B_y^{\beta} x\, j_{y,I}$ $j_{y,I} \sim dlnorm(1, \sigma_I)$ $\sigma_I \sim U(0, SD_{maxI})$
The beta parameter controlling hyperstability / hyperdepletion in the abundance index	β	$LN(\beta) \sim U(LN(\beta_{min}), LN(\beta_{max}))$
The standard deviation of the log-normally distributed bias in the current stock level B_{cur}	Υ_{Bcur}	$Bcur_{obs} = Bcur \times j_{Bcur}$ $j_{Bcur} \sim dlnorm(\mu_{Bcur}, \sigma_{Bcur})$ $\mu_{Bcur} \sim dlnorm(\mu=1, \Upsilon_{Bcur})$
The maximum standard deviation for log-normal error in current biomass for projected years	SD_{Bcur}	$Bcur_{obs} = Bcur \times j_{Bcur}$ $j_{Bcur} \sim dlnorm(\mu_{Bcur}, \sigma_{Bcur})$ $\sigma_{Bcur} \sim U(0, SD_{Bcur})$