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Integrated evaluation of management strategies for tropical multi-species long-line fisheries

Wealth from Oceans National Research Flagship

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November 2010

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Australian Government
Fisheries Research and Development Corporation

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Non-technical Summary

2007/017	**Integrated Evaluation of Management Strategies for Tropical Multi-species Long-line Fisheries**

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OBJECTIVES:

1. Evaluate the performance of the individual target species Harvest Strategies developed by the Eastern Tuna and Billfish Fishery - Western Tuna and Billfish Fishery Harvest Strategy Working Group

2. Evaluate the likely relative performance of the Harvest Strategies in meeting the sustainability objectives of the Commonwealth Harvest Strategy Policy.

3. In consultation with DAFF, AFMA, DEH and relevant regional bodies, develop and provide initial evaluations of alternative approaches for incorporating linkages with regional stocks and/or management organisations in the formal harvest strategies for highly migratory, shared stocks.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED TO DATE

The project results facilitated Eastern Tuna and Billfish Fishery (ETBF) Resource Assessment Group (RAG) and Management Advisory Committee (MAC) discussions about the management objectives for the fishery, and allowed a Harvest Strategy (HS) to be adopted for each ETBF target species, thus directly addressing the 2005 Ministerial Direction requirement for the development and simulation testing of harvest strategies for the ETBF. This has led to the adoption of HS-regulated management arrangements for the ETBF under interim Total Allowable Effort (TAE) management arrangements from November 2009 and for quota-management from March 2011.

The development of operating models for the project has helped to identify key uncertainties in the understanding of ETBF target species population dynamics (including the linkages between the domestic and international populations and fleets and the relative value of different data sources), and potential problems which could adversely affect the expected performance of the adopted harvest strategies. This should assist the prioritisation of future research activities to reduce these uncertainties and improve future management performance.

The project has helped to establish a broader dialogue with regional fisheries interests (the Western and Central Pacific Fisheries Commission (WCPFC) Scientific Committee) on how to address joint management concerns for the highly migratory and straddling stock fisheries of the Western and Central Pacific Ocean. This was pursued, and largely achieved, through submission of papers reporting on the ETBF work to the Scientific Committee meetings of the WCPFC and undertaking commissioned projects for the WCPFC on the use of reference points and Management Strategy Evaluation (MSE) in the application of the precautionary approach to management of tropical tuna and billfish stocks. As noted, the ETBF work has identified the spatial structure and connectivity of the tuna stocks to be a primary sensitivity for the performance of the HS. The successful engagement with the WCPFC processes has built the necessary awareness and relationships for future collaborative work.

This report describes a Management Strategy Evaluation for the Australian Eastern Tuna and Billfish Fishery, including: i) the development of single species operating models to represent each of the five target species, ii) the results from the simulation testing of a range of Harvest Strategies (HSs) for each target species, and iii) a description of the stakeholder consultation process that was undertaken with the ETBF Resource Assessment Group and Management Advisory Committee to illustrate trade-offs among management objectives and facilitate selection of the HSs.

The Eastern and Western longline fisheries (ETBF and WTBF) are multi-species fisheries with a number of primary target species (yellowfin, bigeye and albacore tunas, swordfish, and striped marlin), high value by-product species, and a range of species taken as incidental by-catch. The management of these fisheries is complicated by the multi-jurisdictional nature; both involve stocks that are harvested by the Australian domestic fisheries and multiple international fleets. The Western and Central Pacific Fisheries Commission and Indian Ocean Tuna Commission (IOTC) are the Regional Fisheries Management Organisations (RFMOs) responsible for the international management.

The 2005 Ministerial Direction for Commonwealth Fisheries stipulated the development and evaluation of harvest strategies for all Commonwealth managed fisheries. In the case of the ETBF and WTBF, the development of harvest strategies for target species was initially advanced through a dedicated joint working group of the ETBF and WTBF RAGs. The Harvest Strategy Working Group (HSWG) developed a framework for an empirical (i.e. data-based as opposed to model-based) harvest control rule (a pre-agreed decision process for regulating catch or effort) and conducted some initial simulation testing to ensure that the decision rule performance was qualitatively consistent with expectations. This project focuses on the ETBF, because the small number of active vessels in the WTBF (i.e. < 5 for the last several years) means that operational implementation of the HS is not required at this time.

This project was responsible for further development and evaluation of the HSWG framework using a formal MSE approach as specified in the Harvest Strategy Policy (HSP). This includes the following steps: i) identification of management objectives (and related quantitative performance measures), ii) development of candidate HSs (in this case different versions of the HSWG framework), iii) development of operating models for each of the target species through the adaptation of existing stock assessments, iv) simulation testing the HSs, v) selection of an HS for each species, and vi) implementation of the HSs. This project was primarily responsible for the development of operating models, simulation testing of different versions of the HSWG framework and communication of resulting management objective trade-offs in stakeholder consultations. The final selection of a HS for each target species was undertaken by the ETBF RAG and MAC in 2009. The first HS-based recommendations have been made by AFMA following recommendations from the RAG and MAC and are scheduled for implementation in November 2009, coincident with the implementation of the new ETBF Management Plan.

A generic operating model framework was developed and used for the simulation testing of all target species. There were a number of important constraints on what could be achieved within the particular context of the project. The operating models were dependent on the stock assessments conducted for the broader WCPFC (primarily by the Secretariat of the Pacific Community). These models have been developed through many years of iterative international collaboration, and whenever they are updated, considerable time, effort and technical expertise is required to properly handle all of the data requirements and supporting analyses. Unfortunately, most of these assessments do not provide an ideal resolution of the dynamics in the ETBF region, and were not conducted with the explicit objective of quantifying the uncertainty in the system in the context of developing robust harvest strategies. It was beyond the scope of the current project to reconfigure these assessments. As a result it was necessary to adapt the existing assessments into the operating model framework in an ad-hoc fashion. We have varying levels of confidence in how well the different operating models represent reality, and, consequently, how reliable the simulation results are. In addition, we did not test any HSs that differed fundamentally from the HSWG framework (i.e only different parameter combinations were tested). We speculate about alternative HSs that might perform equivalently or better than the HSWG framework, but these alternatives have not been tested at this time and would require further consideration and consultation with AFMA, the RAG and MAC. Consequences of these constraints are discussed in terms of the success of the current project and future priorities.

Operating model issues and harvest strategy results are summarized by species below:
Swordfish. We have the most confidence in the swordfish operating model because the assessment was developed with this MSE project in mind. It is estimated that the ETBF potentially has a considerable impact on the SW Pacific swordfish population relative to the other fleets, and the adopted HS appears to be robust to uncertainty in the stock dynamics.

Striped marlin. The striped marlin assessment is several years out of date, and was considered preliminary at the time. The data and assessment suggest that the ETBF region is the most important part of the fishery historically (the Japanese fleet seems to have largely depleted this population in the 1950s-1960s). Despite the concerns about the assessment, the operating model may provide a reasonable representation of the spatial dynamics in the ETBF region. The simulation testing suggests that current catches are sufficient to have a reasonable probability of continuing to deplete the already low striped marlin stock. The HS adopted by the MAC has the capacity to increase the biomass risk, and, as such, may not be consistent with the HSP. On the basis of these results, we recommend that striped marlin represents a priority species for stock assessment revision.

Bigeye and Yellowfin tuna. The MSE results shared many similarities for bigeye and yellowfin tuna. We have reasonable confidence in the WCPFC stock assessments because they are recent, supported by large amounts of data, and represent several years of iterative development. However, uncertainty about the stock connectivity for yellowfin and bigeye tuna, in particular, raises doubts that the ETBF HS will provide adequate RBC recommendations for the tuna species to meet both stock conservation and economic objectives for the fishery. That is, if the ETBF fleet has a trivial influence on the relevant population unit, then the basic feedback premise of the HS is undermined, and unilateral domestic management actions could have economic impacts on the ETBF, with minimal long-term conservation or economic benefits. The broader WCPO bigeye stock is estimated to be much more depleted than the stock in the ETBF region, less productive than the yellowfin stock and is, presumably, also more vulnerable in the ETBF, if the population is localized. Direct estimates of connectivity between the Coral Sea and broader WCPO stocks of both species are priority for resolving this uncertainty.

Albacore tuna. We have the least confidence in the albacore HS evaluation, because of the underlying stock assessment and lack of agreement with the ETBF standardized CPUE. The results suggest that there may be an appreciable future risk to the albacore biomass as a consequence of effort increases in the WCPO over the past decade, and the ETBF is an important contributor to this risk. However, at this time, we do not have a lot of confidence in the overall assessment, or the resolution of ETBF processes.

Overall, the project was successful in: (i) evaluating a range of candidate HSs derived from the HSWG decision rule framework; (ii) facilitating the discussion of management objectives and HS selection at the ETBF RAG and MAC; and (iii) assisting AFMA in the implementation of the HS as part of the new ETBF Management Plan.

KEYWORDS: Management Strategy Evaluation, Harvest Strategy, Harvest Control Rule, Operating Model, Population Dynamics, Highly Migratory Stocks, Tropical Tunas and Billfish, Swordfish, Bigeye Tuna, Yellowfin tuna, Albacore, Striped Marlin.

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Background

Eastern and Western Tuna and Billfish Fisheries

The Eastern and Western Tuna and Billfish Fisheries (ETBF and WTBF) are multi-species longline fisheries with a number of primary target species (yellowfin, bigeye and albacore tuna, swordfish, and striped marlin), high value by-product species (e.g. southern bluefin tuna) and a range of species taken as incidental by-catch (e.g. seabirds and turtles). Management measures aimed at addressing target, by-product or by-catch species issues associated with one component of the fishery have secondary effects on other aspects of the fishery. The management of these fisheries is further complicated by their multi-jurisdictional nature, involving stocks that are harvested by the Australian domestic fisheries and multiple international fleets. The Western and Central Pacific Fisheries Commission (WCPFC) and Indian Ocean Tuna Commission (IOTC) are the Regional Fisheries Management Organizations (RFMOs) responsible for the international management.

The current status of the target species for both fisheries contain several elements of uncertainty, most notably in relation to the resolution of spatial processes in the Australian regions, and the relationship with populations harvested in the broader regional fisheries. Stock assessments conducted for the WCPFC and IOTC have indicated that there are serious concerns about the current levels of depletion and/or fishing mortality for a number of the target species in both fisheries, particularly bigeye tuna (Langley et al 2008) and striped marlin (Langley et al 2006) in the ETBF, and yellowfin in the WTBF (Anon. 2008). The current uncertainty in the status of the stocks reflects a lack of fisheries independent indices of abundance, limited direct information on the movement dynamics and spatial structure of the target populations (although there is some evidence for resident Coral-Tasman Sea stocks for some target species), and the relatively short time series of the domestic catch and effort time series (relative to the longevity and production dynamics of the populations). Current effort in the WTBF is very low with only a small number of active vessels (less than 5 for the last several years), which means that operational implementation of the HS is not required at this time. In lieu of operational implementation of the HS there are a set of "meta-rules" which relate to the level of catch and effort required to take place in the fishery before implementation would be required.

Commonwealth Fisheries Harvest Strategies Policy

The 2005 Ministerial Direction for Commonwealth Fisheries (McDonald 2005) stipulated the development and evaluation of harvest strategies for all Commonwealth fisheries by January 2007, and initiated the development of the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines* (HSP) (Anon. 2007). The core objective of the policy is "*...the sustainable and profitable utilization of Australia's Commonwealth fisheries in perpetuity through the implementation of harvest strategies* ..." The harvest strategies will seek to "*...i) maintain fish stocks, on average, at a target biomass point (B_{TARG}) equal to the stock size required to produce maximum economic yield (B_{MEY}), ii) ensure fish stocks will remain above a biomass level where the risk to the stock is regarded as too high, that is B_{LIM} (or proxy), and iii) ensure that the stock stays above the limit biomass level at least 90% of the time.*" And "*For a stock below B_{LIM}, a stock rebuilding strategy will be developed to rebuild the stock to B_{TARG}.*" The Guidelines are intended to "*...provide practical advice to facilitate: i) the interpretation* *of the [HS Policy]; and the application of the HSP to Australia's Commonwealth Fisheries.*"

The HSP was intended to "*...ensure that a common approach and framework is applied across Commonwealth fisheries, to the extent possible for such a diverse range of fisheries.*" Toward this end, Management Strategy Evaluation (MSE – described in the Methods section below) was recognized as the most appropriate tool to develop and simulation test the harvest strategies. However, the guidelines explicitly recognized that a uniform process was not appropriate for all fisheries, and the guidelines were not intended to be prescriptive. There are a number of situations identified in the HSP that complicate the implementation of the policy relative to the ideal situation, and which are relevant to the W/ETBF:

1. Highly Migratory/Straddling or joint Authority Fisheries Stocks - "*In the case of fisheries that are managed under the joint authority of the Australian Government and another ...international management body/arrangement, this policy does not prescribe management arrangements. However, the Australian Government will negotiate with the relevant body with an aim of ensuring sustainable fisheries by advocating this policy as an example of best practice in setting sustainable catch levels.*"

2. Multi-species Fisheries – "*...it will be extremely difficult to maintain all species at the TRP* [Target Reference Point] *because not all species can be effectively targeted and some species will be caught as incidental catches of the main target species.*"

3. Reference point definitions – the state of most of the W/ETBF stock assessments, and uncertainty in spatial structure, is such that many reference points (e.g. B_{MEY}, B_{MSY}) are highly uncertain and potentially variable over time (e.g. due to trends in recruitment variability, and episodic migration events caused by oceanographic variability, etc.).

4. Dealing with Uncertainty and Risk – The HSP recognizes that there are potentially many sources of uncertainty in the assessment and management of fisheries (e.g. process errors, observation errors, model selection errors and implementation uncertainty). The policy indicates that probability and risk thresholds should be set in accordance with the precautionary approach (e.g. harvest more conservatively when uncertainty is greater). However, the HSP does not explicitly recognize the subjectivity involved with uncertainty quantification, nor does it offer advice about how the uncertainty should be quantified.

We discuss how these issues were addressed and critique the success of this project in meeting the objectives set out in the HSP.

Harvest Strategy Working Group Decision Rule Framework

In response to the Ministerial Direction, the development of harvest strategies for ETBF and WTBF was initially progressed through a dedicated joint working group of the ETBF and WTBF RAGs (Davies et al, 2008). This Harvest Strategy Working Group (HSWG) included a fishing industry scientific consultant, several scientists from CSIRO and BRS, an AFMA representative and the ETBF RAG executive officer. The terms of reference of the HSWG were to: i) develop harvest strategies for the five principle target species, ii) consider issues associated with the integration of individual single species harvest strategies into a unified framework for recommending a Total Allowable Effort (TAE) for the fishery, and iii) provide recommendations on research and monitoring priorities identified as part of the harvest strategy development process.

The HSWG developed an initial set of harvest strategies for the consideration of the ETBF and WTBF RAGs, MACs and AFMA Board by December 2006 (Davies et al 2008). The working group was able to conduct some initial testing of alternative forms of single species harvest strategies during this development phase due to the availability of a simulation framework developed for other purposes (Basson and Dowling 2008). The generic framework was accepted by the MAC as a template upon which the final harvest strategies would be developed.

The decision rule framework developed by the HSWG as described in Davies et al 2008) is illustrated in Figure 1 (application to real data is illustrated in Campbell 2008). Figure 2 describes the decision rule framework as a decision tree, which many people find easier to interpret. The original decision rule made recommendations on Total Allowable Effort (TAE), but the move to quota-based management has subsequently been approved, and the rule now advises on the Recommended Biological Catch (RBC) instead. It is an empirical decision rule, which uses relative abundance indices and size composition data from the fishery to adjust the RBC relative to the preceding years. In this context, the term *empirical* is used to distinguish a relatively simple data-based rule from a more complicated model-based rule which could involve fitting a fisheries assessment model every time that a management recommendation is required (e.g. Branch and Parma, 2005 provide a summary of candidate empirical and model-based harvest strategies developed for southern bluefin tuna). In the HSWG framework, CPUE and catch-at-size distributions are divided into juveniles (sometimes referred to as recruits), prime-sized and old fish (except for the albacore tuna HS, which only uses the CPUE index aggregated over all size classes). The exact definition of the prime-sized category varies by species, but is intended to include the majority of the preferred market-size fish in the catch-at-size distribution, and excludes the tails of the size distribution. The lower tail of the distribution is referred to as the *recruits*, and is expected to provide some information about the relative size of cohorts that are just becoming vulnerable to the fishery as an indicator of future catches of prime-size fish. The upper tail is referred to as the *old* fish, and is interpreted as an approximation for spawning stock biomass. The exact size thresholds represent a pragmatic balance between defining sub-groups of the population from the desired life history stages, and ensuring that the sub-groups include an adequate fraction of the catch to be reasonably well sampled and, therefore, have reasonable statistical behaviour. In essence, the decision rule was intended to extract various signals about the population abundance and age structure to form a coherent picture of the stock status and trends. It was expected that sensible management actions could be recommended without the need for explicitly fitting age-structured population dynamics models every time that an RBC recommendation is required. This approach also had the advantage of being simple and intuitive and, therefore, more easily communicated and understood by non-stock assessment analysts.

In level 1 of the decision rule, the *target (CPUE-prime)* refers to the standardized catch rate of the prime-sized fish. This target catch rate should be high enough to ensure that the fish population remains at a level that is biologically safe (very small risk of growth and recruitment over-fishing) and economically profitable (ideally consistent with the principles of Maximum Economic Yield, but recognizing that this can be a difficult concept to quantify, particularly in the context of highly migratory stocks harvested by multiple fleets and gears). Over time, the decision rule attempts to steer the fish population in a direction that tends to maintain the target CPUE (i.e. decreasing catches if CPUE declines below the target, and increasing catches if CPUE increases above the target). The lower levels in the decision rule (levels 2-4, often referred to collectively as the "decision tree"), attempt to utilize additional information from the size composition of the catch, to further modify the RBC if there is additional evidence of biological risk related to weak incoming recruits or overly depleted spawning biomass. The decision tree can only act in a conservative direction, i.e. it can only reduce the RBC relative to that recommended by level 1 of the decision rule.

The decision tree has several parameters which act like thresholds for determining which branches of the tree are applied each year (e.g. *Proportion-Old*). These thresholds relate to stock status and were intended to correspond to a stable population at the target level. Some members of the HSWG considered that it would be possible to define a unique set of internally consistent parameters for each population based on the available biological data. The HSWG recommended thresholds derived from a population equilibrated with a Spawner Per Recruit (SPR) ratio of 40% of virgin levels. However, the thresholds explored in this project were not explicitly adopted at this level for reasons defined in the section: *Harvest Strategy Definitions*. Instead of adopting a fixed set of thresholds defined in relation to *a priori* equilibrium population assumptions, a range of alternative thresholds were tested. The results show that the lower levels of the decision tree tends to make the decision rule more conservative, but they could not be shown to improve the performance of the HS in the manner anticipated by the HSWG. There were several reasons why the performance of the HS did not meet up with *a priori* expectations (i.e. particularly in the short-term). As a consequence, the RAG and MAC were discouraged from focusing on the *a priori* expectations of the HS as inferred from the specification parameters, and the participants were instead encouraged to select decision rules based on the outcomes of the simulation testing which were consistent with the criteria of the HSP. These issues are revisited in the *Summary Comments on Harvest Strategy Performance*.

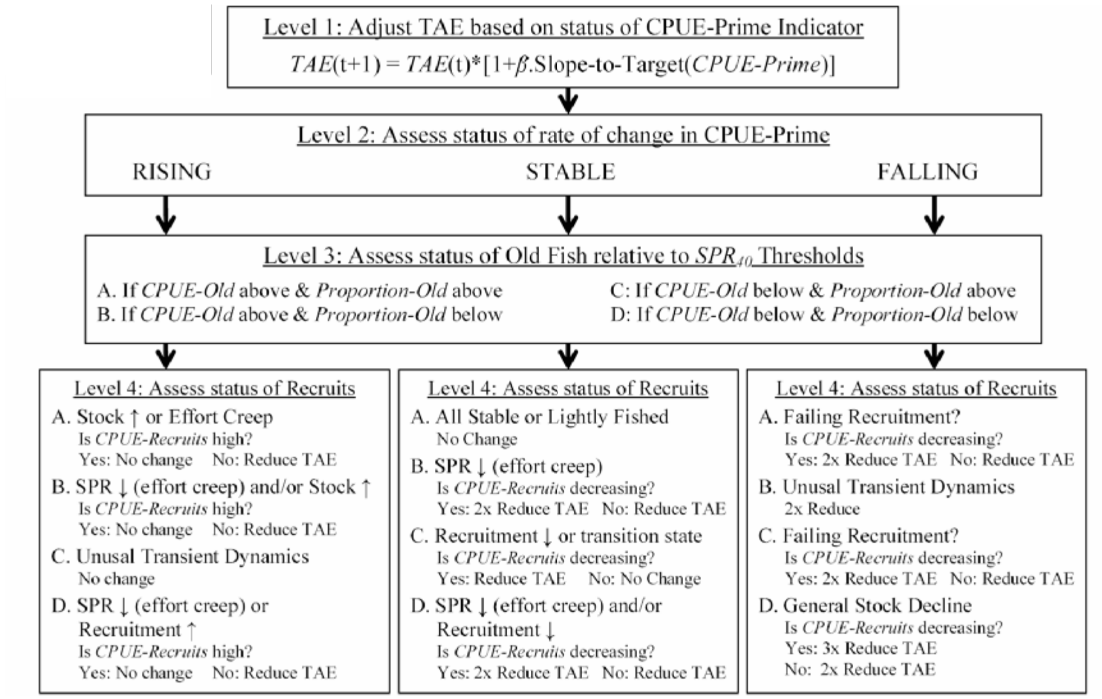


Figure 1. The ETBF Harvest Strategy Working Group decision rule framework (from Davies et al. 2008). Note that Total Allowable Effort (TAE) is replaced by Recommended Biological Catch (RBC) in this report to be consistent with the new ETBF Management Plan. TAE in level 4 of the rule refers to TAE(t+1). Alternatives for Spawner Per Recruit thresholds were adopted for reasons described in the text.

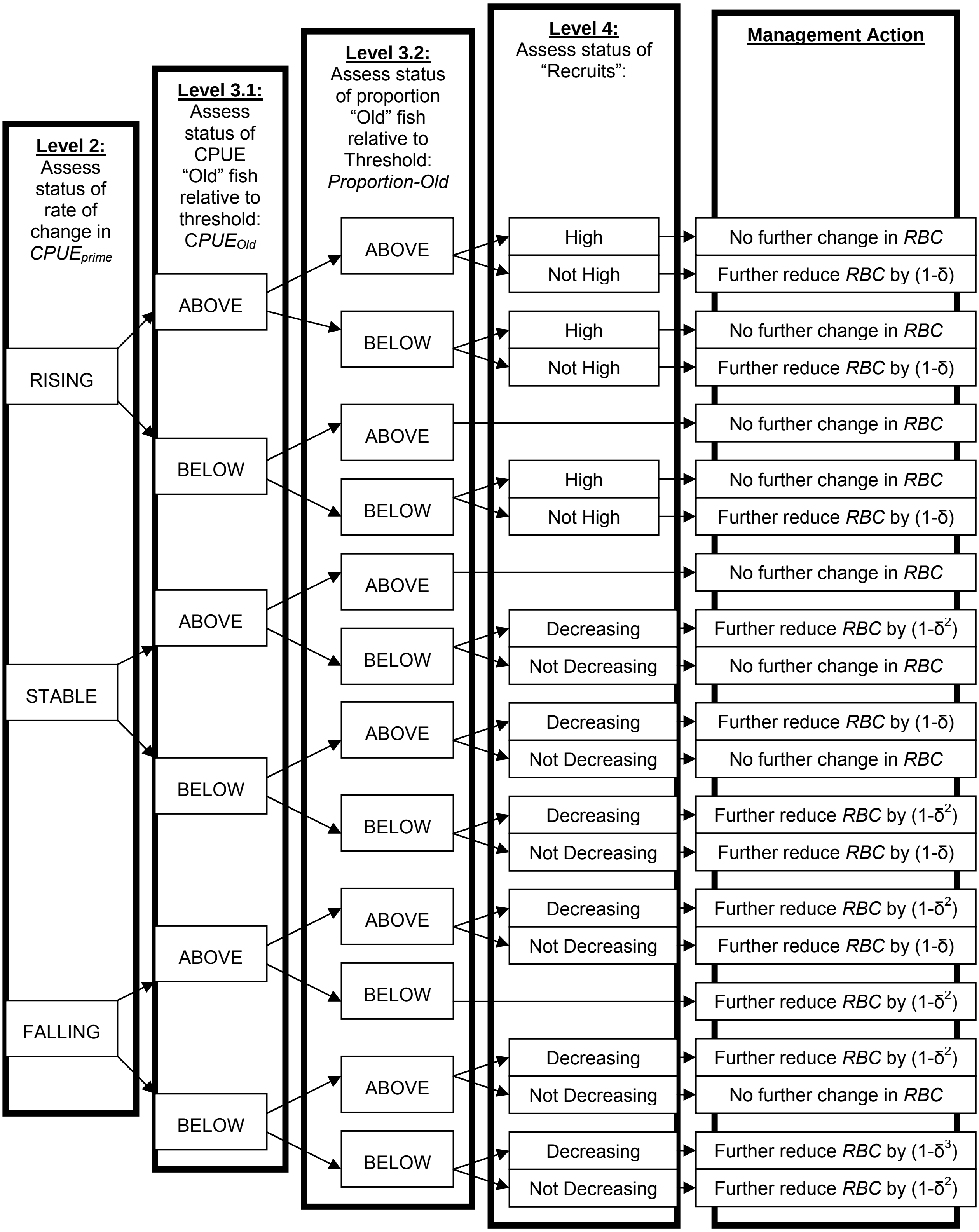


Figure 2. Levels 2-4 of the ETBF Harvest Strategy Working Group decision rule framework expressed as a decision tree. Level 1 sets the RBC which can be further adjusted by levels 2-4 of the tree. Note that Total Allowable Effort (TAE) is replaced by Recommended Biological Catch (RBC) in this report to be consistent with the new ETBF Management Plan.

Davies et al (2008) describe several perceived advantages of the HSWG decision rule framework:

- *The decision framework is target driven, i.e. it is designed to keep stocks near the Target Reference Point, rather than keep stock levels away from being near or below the Limit Reference Point).*
- *Relies on information from the Australian fishery (CPUE and size) to infer and "learn" about economically and ecologically sustainable catch levels.*
- *Including size indicators for growth and recruitment over-fishing through the decision tree makes it more "robust" to potential biases in CPUE.*
- *Should be "robust" to uncertainty about linkages between regional and broader WCP stocks. That is, it should respond to declines and increases in regional stock status, regardless of whether they are generated by domestic or international fleet.*
- *The approach is applicable to all target species and so provides a consistent framework for integrating multi-species considerations.*
- *The HS framework should be cost neutral within current monitoring and assessment processes.*
- *The decision rules are easy to reconcile directly with what the industry is observing in the fishery, and easy to understand for all stakeholders (unlike many model-based decision rules which might include complicated statistical assumptions and opaque mathematical equations).*

This list of perceived advantages and disadvantages are revisited in light of the simulation testing undertaken in this project.

The HSWG provided a promising framework for meeting the E/WTBF single species HS requirements. However, it was beyond the scope of the HSWG project (and the timeline of the Ministerial Direction) to provide comprehensive evaluations of all of the single species harvest strategies, or to examine approaches for incorporating spatial linkages between domestic and broader international fisheries and management arrangements. This project was designed to bridge the gap between the generic HSWG framework development and the adoption of fully-specified harvest strategies. This included the technical requirements of the Management Strategy Evaluation (MSE), illustration of the management performance trade-offs for the RAGs and MACs to facilitate the final HS selection process and introduction of the concepts into the wider WCPFC scientific and management fora. This has been achieved to the extent possible in the available timeframe, however, a number of unresolved issues and future research priorities are identified and discussed.

Harvest Strategy Data Requirements

The HS decision rule requires time series of standardised CPUE for the prime, old and juvenile size groups, and the current proportion of old size fish in the catch. The method for CPUE standardisation and the definition of size groups is specified in Campbell, 2009.

The data requirements for the HS are simple in principle, however, the analyses required to standardize the fishing effort (and examine the representativeness of the catch-at-size data) are not trivial. Ideally, the HS should include the specification of a pre-agreed method for analysing the data, to avoid the troublesome implications that might arise if the analysis turns out to be sensitive to different assumptions. These analyses have been undertaken in a fairly consistent and rigorous manner over the past several years (e.g. Campbell 2009). However, the ETBF fleet has a history of continuous technological and operational change. Many of the changes are known or suspected to have important consequences on fishery catchability and selectivity. As an example of recent innovations in the swordfish fleet, some boats have started to adopt reusable LEDs instead of disposable chemical lightsticks, and circle hooks have widely replaced traditional J-hooks. The effects of LEDs are not known, and anecdotally, industry reports that circle hooks do not retain large swordfish. Neither of these technological changes were anticipated, and they are not recorded in the logbooks. As a consequence, they cannot yet be formally admitted in the CPUE standardization. If industry assertions about differential retention of large swordfish are correct, then there are implications for the size composition data, and the HS assumption that selectivity is constant over time. The ETBF RAG has had some promising discussions in relation to the possibility of industry using a standardized gear configuration in some proportion of sets, to help quantify the effects of technological change. However, until such a procedure is adopted, it seems inevitable that the data analyses required to implement the HS (or any alternative) will continue to require ad hoc analyses and decisions.

One of the main disadvantages of the HS framework was the dependency on commercial longline CPUE (but note that this is potentially a serious problem for most longline fishery assessment models as well). The relationship between CPUE and abundance may be complex and can change over time in ways that are not easily quantified with the data commonly available for these fisheries. The lower levels of the HSWG framework were intended (in part) to also detect risky demographic situations that might not be identified because of these issues associated with CPUE. To examine the efficacy and robustness of the CPUE-based and size-based elements of the decision rules, the simulation testing in this project included a number of scenarios with challenging data characteristics. The simulated CPUE series included serially correlated observation errors (e.g. to mimic gradual targeting shifts that are not completely identified in the effort standardization), and some scenarios included trends in catchability over time (i.e. effort creep leading to hyper-stability in the relationship between CPUE and abundance). The simulated size composition data included sampling biases (tendency to over- or under- sample large fish relative to small fish), with temporal trends. This was intended to mimic the effects of non-random sampling, or (probably more importantly in the ETBF) changing selectivity over time (e.g. due to targeting shifts, gear changes or oceanographic effects on species distributions). These scenarios are discussed further in the section: *The ETBF Generic Operating Model*.

In this project, no attempt was made to explicitly quantify the errors associated with either the CPUE or catch-at-size data. Statistical models for catch rate standardization can provide error estimates for some important factors that affect catchability. They cannot however, even in principle, account for temporal biases that are due to factors that are not recorded in the data. In the simulation testing, we attempted to simulate the net effect of HS data problems in different ways (including serially correlated biases in catch-at-size sampling, serially correlated errors in the CPUE observations, and undetected trends in efficiency that lead to hyper-stability in the relationship between CPUE and abundance). In the absence of independent estimates of abundance or selectivity (e.g. through standardized surveys), there is a large element of subjectivity in the assumptions adopted. While it is difficult to defend the specific assumptions that we adopted, it is useful to demonstrate how the HS performs across a range of assumptions about these data errors, to identify problematic situations that the HS is likely to be robust to.

The CPUE series used in the MSE simulations in this project are described by Campbell (2009) for Striped Marlin, Bigeye, Yellowfin and Albacore, and Campbell et al, (2008) for Swordfish.

Judging the appropriateness of the MSEs and HSWG decision rule

The W/ETBF target species are similar in that they are all highly migratory pelagic populations with broad and overlapping distributions, however, there are many important differences that may affect the success of the HS implementation at this time. In evaluating how appropriate the simulation models are and performance of the HSWG decision rule, we attempt to answer a number of questions for each of the target species in the context of the ETBF:

1) Stock Assessment
    a. How confident are we in the regional stock assessment? i.e. Is it current, and accepted within the WCPFC scientific community?
    b. How well does the model represent the relationship between the fish population in the domestic region (i.e the ETBF) and the broader Pacific?
    c. Is the population currently in an over-fished state or experiencing over-fishing? If so, to what extent is the domestic fishery contributing to the current state of the stock?

2) Deriving Operating Models from stock assessments
    a. What features of the operating model are not adequately quantified by the stock assessment?
        i. Can we approximate the poorly quantified features (e.g. spatial connectivity) without explicitly developing and conditioning new population models?
    b. Is the uncertainty in the population dynamics and stock status adequately represented, to ensure that harvest strategies are sufficiently robust?

3) The HSWG decision rule framework
    a. Does the harvest strategy perform as the HSWG expected?
        i. At a minimum, can we conclude that the feedback-based HS represents an improvement over a constant catch policy?
        ii. Are all elements of the decision rule making a useful contribution, or can the rule be simplified without a loss of performance?
    b. Which elements of operating model uncertainty is the HS sensitive to?

In addressing these questions for each species, we will attempt to i) illustrate how confident we are that the HS is likely to meet the HSP objectives, ii) identify practical means for overcoming outstanding issues with the HS in the short term (i.e. meta-rules on top of the HSWG framework), iii) prioritize further research requirements to improve the population models for assessment and MSE purposes, and iv) critique the conceptual foundations of the HSWG decision rule in light of the simulation testing conducted to date.

Need

This project was developed in relation to the 2005 Ministerial Direction to AFMA that required simulation testing and implementation of harvest strategies for all Commonwealth fisheries by January 2007 (McDonald 2005), as subsequently defined in the Commonwealth Fisheries Harvest Strategy Policy and Guidelines (Anon. 2007). For the ETBF and WTBF, AFMA's response was initially progressed through the establishment of a Harvest Strategy Working Group (HSWG), which was charged with development of individual harvest strategies for the five target species. The HSWG reported to the respective RAGs, MACs and AFMA, the outcomes as described in Davies et al (2008). It was recognized from the outset that the HSWG would not be able to meet all of the expectations of the Ministerial Direction before the January 2007 deadline. The HSWG subsequently also recognised that no further evaluation of WTBF HS are required at this time because of the small number of vessels currently operating. The HSWG reported on some preliminary simulation testing, where the population models only superficially resembled ETBF swordfish and yellowfin populations. An important focus of this FRDC project was to develop simulation models that were explicitly conditioned to the regional WCPFC stock assessments, and to represent the uncertainty associated with these models. The simulation testing was extended to include all of the target species, and to use the formal methods of Management Strategy Evaluation (MSE, as detailed in the methods) to evaluate the HSWG decision rule framework. The project also provided an interface with the RAGs and MACs to illustrate HS management performance trade-offs and to stimulate the discussion which would allow the MAC to ultimately select specific harvest strategies for implementation as part of the ETBF Management Plan.

Objectives

1. Evaluate the performance of the individual target species Harvest Strategies developed by the ETBF-WTBF Harvest Strategy Working Group.

Modifications: Subsequent to the initiation of this project, the evaluation and application of the HSWG framework to the WTBF has been postponed, pending greater levels of activity in the fishery. For the duration of this project, the WTBF has consisted of less than 5 active vessels, providing limited CPUE and catch-at-size data which are likely to not be very informative. In the IOTC, the stock assessments are not as well developed as in the WCPFC, and this has important implications for the conditioning of operating models. It seems unlikely that the small number of WTBF vessels represents a conservation risk to the target species or a risk to exceeding a national allocation that might be negotiated within the IOTC. With these issues in mind, it was recognized that WTBF Harvest Strategies would not be simulation tested until such time as more operators entered the fishery, and unless/until a minimum catch level was exceeded (subject to periodic review in relation to changes in the domestic or international fishery). As a result, this project focussed on the ETBF. However, the conceptual framework and software can be transferred to the WTBF system at the appropriate time and many of the general lessons learned from the evaluations for the ETBF are likely to be relevant to the WTBF.

2. Develop and evaluate approaches to integrating individual target species harvest strategies into a single multi-species harvest strategy.

Modifications: During the course of the project, the AFMA board took the decision to switch the ETBF management from primarily input control (effort in the form of an area-specific hook decrement system) to output control (TAC, ITQ). Under the input control system, methods for integrating the harvest strategies in a multi-species context were essential. Under the ITQ system (which is scheduled to be implemented under the guidance of the harvest strategies in March 2011), industry will have the flexibility to manage the multi-species aspect of the fishery in the manner that they believe to be the most efficient, subject to the quota constraints. As such, this project objective was no longer relevant, and was not pursued. The resources that would have been allocated to this aspect of the project were refocussed on additional sensitivity analyses relating to the spatial structure and connectivity of the main tuna target species which had been identified as important.

3. Evaluate the likely relative performance of input (TAE, ITE) and output (TAC, ITQ) controls in meeting the sustainability objectives of the Commonwealth Harvest Strategy Policy.

Modifications: This objective was not explicitly pursued for the reasons described under point 2 above. However, the simulation testing was undertaken with different levels of RBC implementation error, that qualitatively describe some of the differences that might be expected between TAE and TAC management.

4. In consultation with DAFF, AFMA, DEH and relevant regional bodies, develop and provide initial evaluations of alternative approaches for incorporating linkages with regional stocks and/or management organisations in the formal harvest strategies for highly migratory, shared stocks.

Methods

The general method of Management Strategy Evaluation (MSE) provided the structural framework for this project and is described in the following section. In principle it is described as a sequence of discrete steps, but in practice, most steps are iteratively revisited (e.g. in relation to stakeholder consultations that are an important part of the process). For clarity, the report summarizes the project in a sequential manner that emphasizes the justification for various decisions and the final direction taken (but does not accurately reflect the circuitous path taken to get there). As a consequence, the Methods section is somewhat arbitrarily partitioned from the Results and Discussion. The Methods section provides a conceptual description of the generic ETBF operating model (a technical description is included in Appendix 3), and a timeline of stakeholder consultations (including references to working papers developed under the project). The species-specific implementation details of the operating models have been included in the Results and Discussion, along with the outcomes from the simulation testing.

A Note on Biomass Terminology

The term Biomass (or B) is typically used to describe the size of a fish population and can be used to refer to the total population or a subset, such as the adult biomass. Our understanding of the HSP is that reference points defined as B_{XXX} refer to adult biomass. In this document, we also use the ambiguous term B, to refer to adult or spawning biomass, and try to distinguish between Total Biomass (TB) and Spawning Biomass (SB or SSB) when a specific quantitative definition is relevant.

Management Strategy Evaluation (MSE)

MSE is an increasingly used method for testing alternative fisheries management options using computer simulations (e.g. de la Mare 1986, Butterworth et al. 1997, Smith et al. 1999). In general, the objective is not to identify optimal performance, but to identify management options that are robust to the major uncertainties in the system, with the admission that the probabilities associated with some of these uncertainties cannot be rigorously quantified. MSE is generally recognized as preferable to an *ad hoc* assessment and management process for several reasons, not the least of which is the transparency in decision-making. However, the process cannot be expected to eliminate the need for quality data, and will always be subject to the implications of somewhat arbitrary modelling assumptions (e.g. Kolody et al 2008a, Rochet and Rice 2009). The MSE process as applied to the ETBF HS can be described in a number of steps:

1) Identification of management objectives (and related quantitative performance measures)
2) Development of candidate Harvest Strategies
3) Development of a range of operating models conditioned to real fishery data
4) Simulation testing candidate Harvest Strategies with operating models
5) Selection of a Harvest Strategy on the basis of performance measures from simulation testing
6) Implementation of the Harvest Strategy

Figure 3 is a flowchart of the process. However, it is important to note that not all of the steps are necessarily sequential.

Step 1. Identification of management objectives is primarily the responsibility of fisheries managers. They are required to articulate legislative obligations and institutional policies (from the HSP in this case). However, industry has an important role in the interpretation of the flexible elements of policies which have important practical and economic outcomes. The role of the scientists in this step should be to attempt to illustrate and quantify the relationships among the management objectives. In many cases, this step is difficult and needs to be iteratively revisited. However, fisheries MSE can often proceed without an explicit resolution of this step (e.g. Kolody et al 2008a), as stakeholders might find it easier to conceptualize management objectives if they understand how they are related to one another.

Step 2. The development of candidate HSs is often seen as an area for considerable statistical analysis and modelling (e.g. evaluating and comparing the value of information in different data collection schemes) and creative input (e.g. designing clever decision rules that extract the most useful information, and meet the short and long term management objectives in the most effective way). In practice, for many fisheries, the performance differences between different decision rules might be very limited (e.g. options are tightly constrained by the productivity of the stock, and the data are not very informative). In the W/ETBF case, the candidate HSs all conformed to the HSWG decision rule framework, and as such, all versions represented relatively minor variants on a common theme.

Step 3. The development of operating models is simple to describe conceptually, i.e. simulation testing requires operating models to represent the dynamics of the fishery. The operating model includes several sub-components: i) a fish population model describing recruitment, growth, migration and mortality, ii) an observation model to simulate the data collection process, and iii) a management model describing how the fishery catch is regulated (which usually includes processing of the simulated fishery data). Improved accuracy and precision in the operating model should result in a better indication of the harvest strategy performance. Using comprehensive fisheries assessment models to parameterize the operating models should ensure that the operating models are at least consistent with all of the available data and research currently available. However, it is a real challenge to adequately represent the uncertainties in the system. If the uncertainty is understated, the fish population can quickly reveal itself to be outside of the range which was tested in the MSE, and could result in selection of a HS which performs poorly. Overstatement of uncertainty is probably much less common in fisheries, however, in the context of the precautionary approach, this has the potential to lead to very conservative management and lost economic opportunity.

Step 4. Simulation testing is the most computationally intensive part of the project. The different sub-components of the operating model are linked in an iterative cycle of updating fish population demographics including fishing mortality, collecting simulated observations, and management setting of the decision rule. In this study, the cycle is repeated from the current year to 2030. To represent uncertainty in initial stock status and fishery parameters, the process is conducted from a range of alternative starting assumptions. In this project, the initial stock status (and associated parameters) was based on the Maximum Posterior Density (MPD) estimates from one or more stock assessment models. To represent uncertainty in future processes (e.g. recruitment variability) and observations (e.g. CPUE error), Monte Carlo simulations are used to repeat the simulations numerous times from each set of initial conditions. Additional uncertainty was introduced by over-riding some of the parameters from the assessment (e.g. migration rates) and exploring scenarios which were not quantified in the assessment (e.g. future effort trends in the international fleet).

Step 5. The final selection of the HS requires effective communication between the technical staff in the project, and the broader stakeholder community. The results from step 4 need to be summarized to reflect the variability in management performance resulting from each harvest strategy, and presented in such a way that stakeholders can compare the outcomes across harvest strategies. This is easier if there are clearly defined management objectives and performance measures defined in step 1, however, it is usually the case that many performance measures are highly correlated, and a number of simple trade-offs are generally evident, e.g.:

- Higher average catches are usually associated with lower biomass, lower CPUE and higher levels of over-fishing risk,
- For the same level of over-fishing risk, larger inter-annual variability in catches is usually associated with higher average catches,
- There may be substantial short-term and long-term trade-offs, particularly if the initial population is already depleted (i.e. such that rebuilding would increase productivity).

Step 6 is the actual implementation of the HS. In practice, it is never expected that the HS would be expected to operate forever on auto-pilot. Regular supervision is required to ensure that nothing exceptional happens that was beyond the anticipated range of the simulation testing, and for which the HS would not be expected to cope appropriately (e.g. recruitment regime shift, operational changes in the fishery that erode the information content of the data). Periodic review (e.g. every 3-5 years) is also required to ensure that the HS meets management expectations.

The original work of the HSWG on formulation of the ETBF HS (Davies et al. 2008) did not include evaluation using the full MSE procedure described above. The initial work focused on the development of a candidate HS (item 2) and provided a promising framework for further consideration. The HSWG report included some initial simulation testing for hypothetical fisheries resembling swordfish and yellowfin tuna. However, the operating models were not explicitly conditioned to the available data, and the uncertainty in the fishery and population dynamics was under-represented.

This project has contributed toward all of the steps identified above, with the main emphasis of the work being on steps 3-5. While many candidate harvest strategies were developed (step 2), they were all derived from the HSWG decision rule framework (or consisted of constant catch projections). At the time of completion of the final report, a HS for each species has been adopted by the AFMA Board and is scheduled for implementation in November 2009 as part of the new Management Plan for the ETBF.

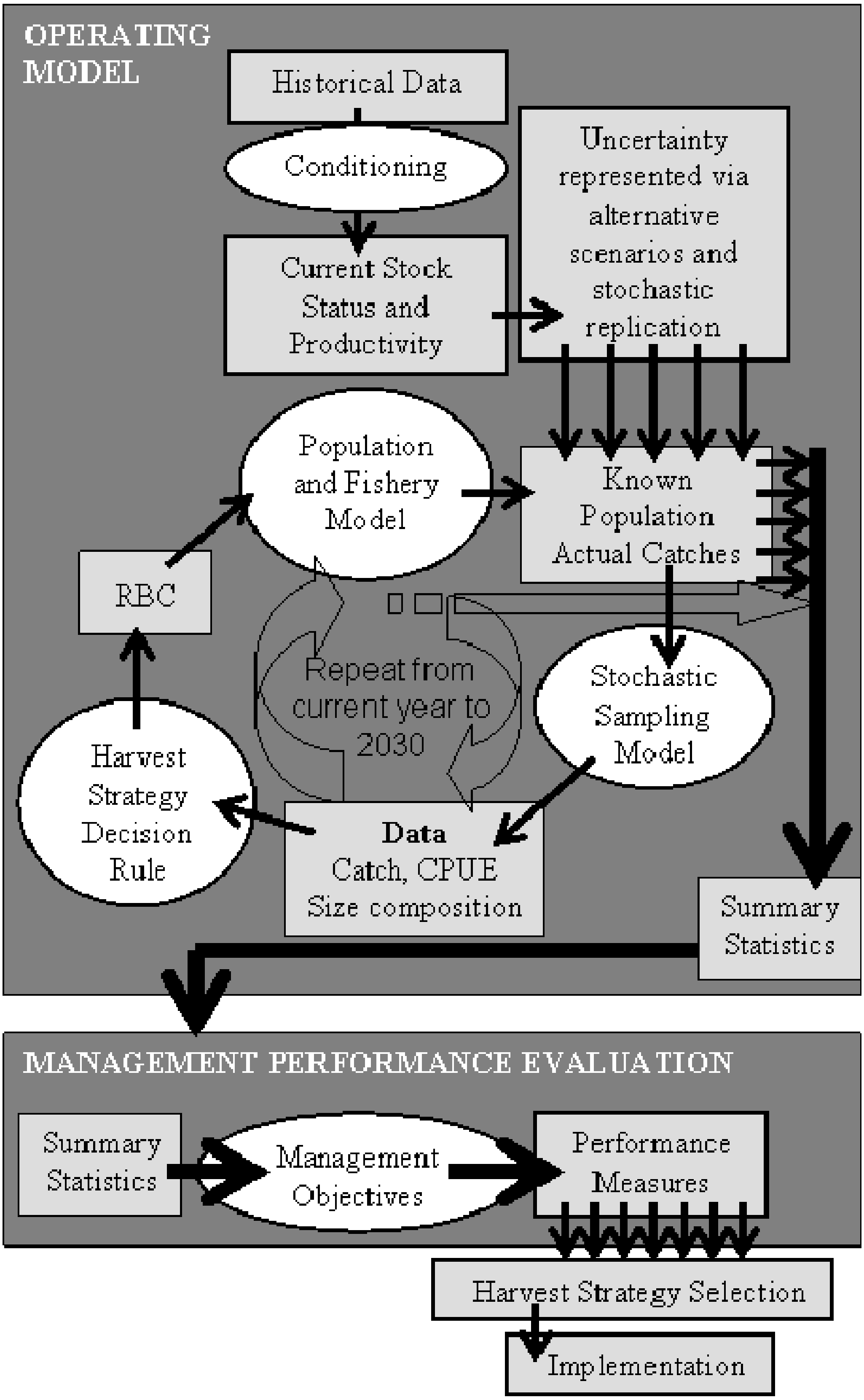


Figure 3. Flowchart of processes and sub-components in Management Strategy Evaluation as applied to the Eastern Tuna and Billfish Fishery.

Timeline of progress, consultation and project outputs

Over the duration of the project, a series of progress reports and consultations were undertaken with domestic stakeholders and international RFMO scientific bodies. These meetings and associated papers are listed below. In many cases, the results presented in the papers below differ from, and are superseded by, this final report.

August 2007 – Progress report to the WCPFC Scientific Committee

- Conceptual description of the HS evaluation project illustrating example results based on the 2006 swordfish assessment.

Kolody, D., Dowling, N., Preece, A., Davies, C. 2007. Application of a harvest strategy evaluation approach to the Australian swordfish fishery. Working paper WCPFC-SC3-ME SWG/WP-5.

June 2008 – ETBF RAG Progress update

- presentation and discussion of results conditioned to the 2008 swordfish assessment

March-April 2009 – ETBF RAG and MAC Management Objective Consultation

- RAG recommended a swordfish HS preference that was intermediate between the options presented.
- MAC endorsed the RAG recommendation and adopted the HS (though the specific results were never tabled)

Kolody, D., Preece, A., Davies, C., Hartog, J., Campbell, R., Dowling, N. 2009. Eastern Tuna and Billfish Fishery Harvest Strategy: A brief overview of management performance trade-offs and questionnaire for RAG participants Working Paper for the Eastern Tuna and Billfish Fishery RAG Mar 2009 (Updated to include 4 attachments for the ETBF MAC April 2009)

June 2009 – ETBF RAG and MAC Management Objective Consultation

- RAG indicated a preference for the swordfish HS endorsed by the previous RAG and MAC for all species
- HS project members interpreted the recommendation as a preference for HS_21 (an intermediate HS that was evaluated for swordfish, but never actually presented to the RAG/MAC).

Kolody, D., Preece, A., Davies, C., Hartog, J. 2009. Eastern Tuna and Billfish Harvest Strategy Evaluation: Preliminary Simulation Testing Results for all 5 Target Species. Working Paper for the Eastern Tuna and Billfish Fishery RAG June 2009

August 2009 – Progress report to the WCPFC Scientific Committee

- project description for international audience including all species results, and outlining the importance of the relationship between the domestic and international management measures.

Preece, A, Kolody, D., Davies, C, and Hartog, J. 2009. Management strategy evaluation for Australia's east coast tuna and billfish fishery: progress update. Working paper WCPFC-SC5-SA-SWG/WP-8.

August 2009 – ETBF MAC - RBC from adopted HS

- advice on the 2010 recommended biological catch (RBC) provided to ETBF MAC, for implementation of Management Plan and interim TAE for 16 months until quotas and ITQs become effective in 2011.

October 2009 – Technical Review of the Harvest Strategy Project

- A workshop was held on 26 Oct 2009 to review the technical elements of this FRDC project, with several independent domestic and international experts attending. The report from this workshop is included in Appendix 4.

The generic ETBF Operating Model (OM)

The ETBF target species share a number of important features, that are represented in the generic Operating Model (OM). Most elements of the operating model conform to fairly standard mathematical assumptions and equations used in single species fisheries models (as detailed in Appendix 3). The specific implementation details for each target species are described in the Results and Discussion.

Uncertainty Quantification: Reference and robustness sets

In formulating fisheries models, there are always a number of somewhat subjective decisions that have to be made, because the data are rarely (i.e. probably never) adequate to quantify all of the parameters that are required to fully specify the population dynamics (e.g. Schnute and Richards 2001). In an attempt to ensure that the Harvest Strategies are reasonably robust to the uncertainty inherent in the ETBF fishery system, simulation testing involved a range of alternative scenarios that were judged to be plausibly consistent with the current understanding of the system. Simulation results were aggregated into sets of scenarios, and decisions about whether or not to include or exclude different scenarios represented a large part of the uncertainty quantification process.

Model uncertainty can be separated into structural and statistical uncertainty for inclusion in the fisheries MSE process. In our experience, it has usually been the case that model uncertainty is greater than the statistical uncertainty estimated conditional on a specific model which is assumed to be correct. Model uncertainty often includes substantive structural differences that render alternative models incomparable in a statistical sense. Statistical uncertainty usually refers to the parameter estimation uncertainty associated with an individual model formulation, which can in principle be quantified with various mathematical techniques (e.g. Bayesian posteriors, inverse Hessian or bootstrap confidence intervals). Some types of uncertainty might be described as structural uncertainty (e.g. the stock recruitment relationship is often assumed to be either the Ricker or Beverton-Holt recruitment function, which might be described as unique model structures), or as statistical estimation uncertainty (e.g. the Ricker and Beverton-Holt functions represent special cases of the more generalized Deriso stock-recruitment relationship). In this report, we expanded the definition of model uncertainty to include statistical uncertainty for many parameters in which the available fisheries data are not very informative (e.g. natural mortality, stock-recruitment curve steepness, migration dynamics). In principle, these are estimable parameters, but in practice, the uncertainty estimates associated with these parameters are not credible. We use the term projection uncertainty to refer to uncertain future outcomes, that may be quantified on the basis of either historical data (e.g. recruitment process errors, CPUE observation errors) or speculative scenarios (e.g. what will the international fleet do over the next few years?).

In this document, we use the term "scenario" to represent a full specification for the operating model, including:

- Initial numbers-at-age
- Biological (e.g. natural mortality, stock recruitment relationship) and fishery parameters (e.g. selectivity)
- Stochastic process and observation errors

Most of the parameters that comprise an individual scenario are derived from the most recent WCPFC stock assessment, including fixed input assumptions (e.g. maturity schedules) and Maximum Posterior Density (MPD) estimates (the best point estimates) for key parameters and population states. For some species (swordfish, and to a lesser extent bigeye tuna) the assessment consisted of multiple models. In these cases, the different input assumptions and MPD estimates from the different assessment models were considered to be equally plausible, and worthy of equal representation in the simulation testing. In some cases, parameter values in the operating models are derived from sources other than the assessment, either because the assessment models do not provide the required quantities (e.g. future dynamics of the international fleet), or because the assessment model parameters are not considered to be very reliable (e.g. the data used to estimate migration rates are not very informative). In many cases, there is an admittedly arbitrary element to the parameters that were adopted, and we would not be surprised if some or our choices will eventually be shown to be unrealistic (e.g. recruitment variability, CPUE observation errors). It was hoped that we could err on the side of caution and demonstrate that the HS would still be robust. However, in some cases, the HS clearly is sensitive to the level of uncertainty adopted, and a strict adoption of the precautionary approach could lead to some draconian management recommendations that are not consistent with general perceptions of the ETBF fish stocks. We identify situations where this may be the case, and attempt to identify additional data and analyses that should be considered to interpret the HS results in a useful way.

The uncertainty quantification process involved defining a "reference set" and a "robustness set" of operating model scenarios, similar to the approach adopted for the development of the CCSBT Management Procedure (e.g. Kolody et al 2008a, Butterworth 2008), and the IWC (Punt and Donovan, 2007). The "reference set" is considered to be a high priority set of scenarios, all of which are highly plausible, and which are intended to span a reasonably likely set of future outcomes. The "robustness set" is a more loosely defined set of operating model scenarios, that was originally intended to define scenarios that were considered less likely than the reference set, but still plausible, and potentially very risky. It was hoped that the robustness set would be useful for identifying "pathological" behaviour that could discriminate between HSs that were otherwise equivalent. Only the reference set of results were presented to the RAG and MAC, and used as the basis for selecting the preferred HS. However, the robustness sets evolved a somewhat different emphasis in this project, and the term ultimately encompasses operating models that were both more and less challenging than the reference set. The more challenging robustness scenarios were used in a manner similar to the original intention (i.e. to check if the HS is robust under difficult conditions). The less challenging scenarios were used to provide contrast with the reference set (and more challenging robustness scenarios), to illustrate the expected gradations in HS performance over a range of conditions that we cannot currently quantify.

A large number of robustness scenarios were examined during the project, and not all results have been documented here. The robustness sets have included:

- The full set of 192 MFCL (MULTIFAN-CL) model MPD estimates for swordfish.
- Alternative productivity scenarios: + or - 25% on the numbers at age in the first year of projections, and equivalent increase or decrease to the asymptote of the stock recruitment relationship.
- Effects of different time lags in data collection for use in the HS decision rule (i.e. 6 months or 18 month delay in data availability).
- Exploration of the number of replicates required so that the distributional characteristics of the core results were not sensitive to the random number seeds.
- Alternative combinations of values for recruitment variability, including the robustness options described in Table 4.
- Alternative combinations of values for the parameters for CPUE variability, including those described in Table 5.
- Alternative scenarios for the non-ETBF future effort, including those shown in Table 6.
- Effort creep scenarios (Table 7).
- Very low levels of stochastic variability of different combinations of observation and process errors, including those in Table 8 and Table 9.
- And alternative spatial structures.

The merging of scenarios into sets implies some sort of "weighting", which reflects the idea that more likely scenarios should be given a higher weighting (or higher sampling frequency) than less likely scenarios. In the CCSBT, some scenarios were weighted on the basis of the prior beliefs of the scientists (through a process of voting by secret ballot), and sometimes they were weighted according to the likelihood values calculated in the process of model fitting (if it was believed that the data were actually informative with respect to the parameter in question). In this project, it was not practical to adopt likelihood weighting, because most of the uncertainty dimensions in the operating model scenarios were not actually derived from the assessment (e.g. migration rates, observation error characteristics and future effort in the non-ETBF region, etc. were externally imposed). Model elements were either included with equal weighting to the other elements in a particular uncertainty dimension, or they were excluded.

Population Dynamics

The age-structured and spatially disaggregated population is described by the standard discrete form of the Baranov catch equation as applied in many fisheries models (see Appendix 3). The dynamics are iterated in the following sequence:

1. Recruitment (depending on the species, this might not occur every quarter)
2. Migration

3. Natural and fishing mortality
4. Collection of fishery data (see Sampling Model below)

The model operates on a quarterly time step, partly to conform to the MULTIFAN-CL assessments, and partly because there are species-specific seasonal patterns in the ETBF catches. However, with the move to quota-based management (with an RBC setting interval of at least one year), the seasonality became less important, and no attempt was made to realistically simulate seasonal processes. Catches were removed uniformly within the first 3 quarters, with the last quarter catches adjusted to equal the RBC each year, and all outputs were based on annual statistics.

Recruitment

Recruitment is governed by a Beverton-Holt function (ignoring size-dependent fecundity) with lognormal, serially-correlated random deviates. Recruitment was annual for the temperate and sub-tropical species (albacore, swordfish, striped marlin), and quarterly for the tropical species (bigeye and yellowfin). The steepness parameter governs the degree of recruitment compensation associated with declining stock size, and was adopted from the WCPFC stock assessments (note that for some species, a range of steepness values were represented in the assessments).

Figure 4 shows the implications of different CV and auto-correlation assumptions on hypothetical recruitment time series. The justification for the different recruitment variability assumptions is provided in the species-specific sections of the *Results and Discussion*. Note that the autocorrelation introduces extended periods of above average and below average recruitment, which mimics the sort of productivity trends that are frequently estimated in pelagic assessments. While this is plausible, it is also possible to introduce these trends as an artefact of the assessment model (e.g. Kolody et al 2004).

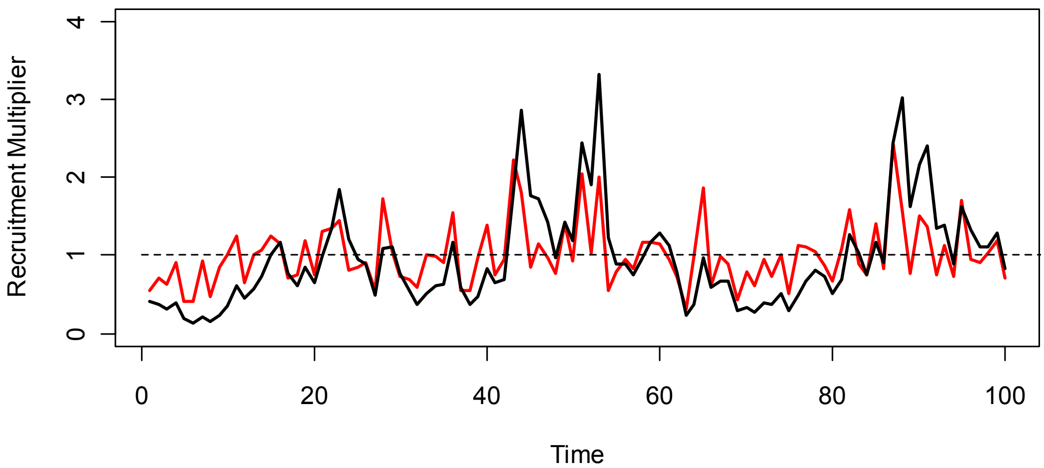


Figure 4. Example of stochastic recruitment assumptions used in the operating models (expressed as scalar multiples from the stock recruitment relationship). The red line indicates a time series with no serial correlation, SD(log(deviate)) = 0.4, auto-correlation = 0, while the black line, SD(log(deviate)) = 0.6, auto-correlation = 0.7 corresponds to the reference set of assumptions used for swordfish, striped marlin and albacore tuna). The reference set time series for bigeye and yellowfin tuna have a higher CV, but lower auto-correlation than the black line.

Spatial Structure

The OM uses a spatial structure that is divided into two distinct regions (designated the ETBF and non-ETBF) as shown schematically in Figure 5. It is assumed that the fish population has a common spawning population that is shared across the two regions (MULTIFAN-CL uses a similar assumption in the spatially disaggregated assessments), with a constant (but not necessarily equal) proportion of age 0 fish recruiting into each region (each quarter or year, depending on the species). The fish mix between the two regions at a rate that is constant among ages and over time (though the assumed mixing rate differs among operating model scenarios). Mixing is parameterized as a redistribution rate, in which the two regions tend to equilibrate toward their original recruitment distribution proportions.

The operating model spatial structure is only an approximation of the real situation, and it is easy to identify a number of potentially important situations that the model does not resolve, e.g.:

- There is some overlap between the ETBF and international fleets in the Tasman Sea (but in recent years the overlap in fishing effort distributions is not large),
- There could be independent spawning and recruitment processes in the ETBF and non-ETBF regions (this is poorly quantified and likely depends on the species),
- For some species, connectivity between the ETBF and non-ETBF populations might be strongly influenced by interannual variability (e.g. ENSO events) in which immigration and emigration processes might be more important than juvenile recruitment and mortality,
- The model is not adequate for resolving spatial management options within the ETBF.

Despite these shortcomings, the model is sufficient for describing a broad range of scenarios that are plausibly consistent with the available stock assessments. Additional species-specific information on spatial structure and connectivity is provided in the *Results and Discussion*.

While the HS is predicated on the assumption that there is a relatively discrete ETBF sub-population, it is not clear that this is true, or whether it can be adequately represented without a thorough reconditioning of the operating models. To partially consider this possibility, multiple spatial scenarios were examined for the tuna species. A distinction is made between the reference set of operating models, which more closely resemble the assessment models, and the spatially-restricted robustness scenarios. These robustness scenarios were derived by simply partitioning the existing assessment model results (i.e. splitting the numbers-at-age into proportions, rescaling the stock recruitment relationship, and assuming somewhat arbitrary equilibrium migration and population distribution parameters). These robustness scenarios would probably not be consistent with a model that was properly reconditioned with the data disaggregated at an appropriate resolution (e.g. if the assumed population is too small, there might be no way in which the CPUE and size composition data would be consistent). However, reconditioning the assessments was beyond the scope of this project, and these results are likely to only provide a qualitative indication of how the HS would perform with more localized populations.

In prioritizing the scenarios that could be represented in the timeframe of this project, there did not seem to be a compelling reason to extend the spatial complexity of the model, and doing so would also result in the need for additional speculative parameterizing of scenarios that could not be directly quantified on the basis of the currently available data and analyses. It is worth noting that different elements of this population model are highly confounded in terms of their effects on HS evaluation, and there is no need to explicitly test all combinations of options if this is recognized in advance (e.g. many of the non-ETBF population dynamics might be irrelevant if the migration rates are low). The actual approach used for the different species is described in the *Results and Discussion*.

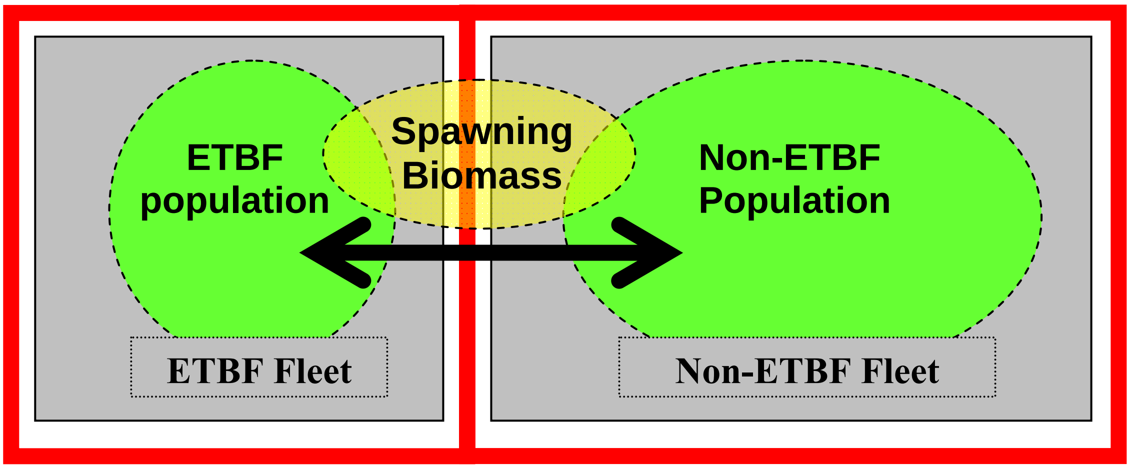


Figure 5. Conceptual spatial representation of the generic ETBF Operating Model. The ETBF and non-ETBF fleets are spatially distinct. The fish population has two components, each of which is vulnerable to only one fleet at a time, but the two mix to greater or lesser degree (depending on the scenario), and both combine for spawning and recruitment processes.

Initial Age Structure

The initial age structure (and hence depletion) of the population is adopted from the MPD estimates of the final year of the most recent assessment (including MPD estimates from multiple models in the case of swordfish and bigeye tuna). To acknowledge that the most recent recruits are poorly described by the MPD estimates, log-normal random deviates are added to the youngest 2 cohorts.

The stock assessments were between 1 and 5 years out of date. Rather than attempting to adapt all models to the same initial projection year, the simulation projections for each species were started from different years, corresponding to the final year of each assessment.

For three of the stocks (yellowfin, albacore and striped marlin), the WCPFC stock assessments only had a single "best" scenario (as recommended by the assessment analysts). As an ad hoc approach to admitting additional uncertainty in stock status and productivity, the operating model included an option to multiply the initial numbers-at-age and virgin recruitment by an arbitrary scalar (values of 0.75, 1.0 and 1.25 were used).

Other Biological Assumptions

Most of the basic biological parameters required for the population dynamics model were adopted straight out of the WCPFC assessments. These include:

- length- and mass-at-age relationships
- age-specific natural mortality vectors
- maturity schedules

Note that in the case of swordfish, and to a lesser extent bigeye, what we call the assessment actually consisted of a synthesis of several different models that included a large range of alternative plausible values for some of these parameters (e.g. the swordfish assessment included 192 models, with 8 different mortality vectors that differed in mean value and age-specific functional form).

Migration rate estimates were not adopted from the assessments, because they were either considered to be unreliable (swordfish, yellowfin and bigeye) or did not exist in the spatially aggregated assessments (albacore, striped marlin). Instead, some extremes of very low and very high mixing were tested together and assumed to be equally plausible. Several of the results below are partitioned to show the impact of the mixing rate assumptions. The implications of the different migration rates are illustrated for a hypothetical population in which there are two regions and no mortality in Figure 6.

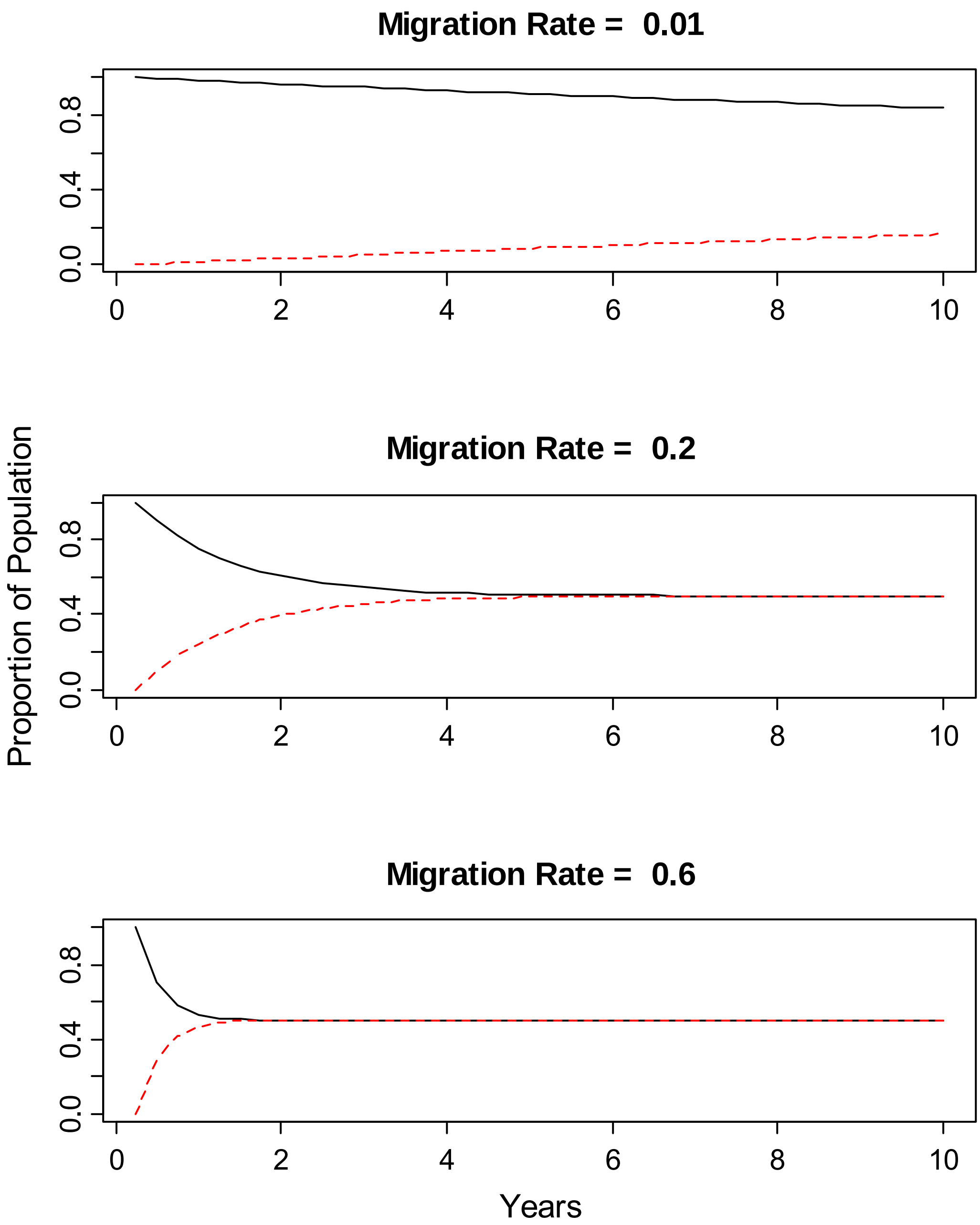


Figure 6. Illustration of the assumed mixing rates between the ETB and non-ETBF regions of the operating model. The plots assume a hypothetical situation in which the equilibrium population is equally divided between the two regions, all of the fish start in one area, and there is no mortality or recruitment.

Fishery Dynamics

The ETBF and non-ETBF fisheries operate under a separable assumption (i.e. it is assumed that age-specific selectivity is constant over time, but see observation errors below). It was assumed that the non-ETBF selectivity was equivalent to that for the largest of the longline fleets in the relevant areas from each assessment model. This could potentially lead to problems in the case of bigeye and yellowfin fisheries, where large numbers are caught in the equatorial purse seine fisheries (which have a very different selectivity). However, depending on how the purse seine effort varies among years, its effect on the longline fishery might be represented reasonably well as recruitment variability. For albacore tuna, there is also evidence for strong temporal trends in selectivity (seasonal and interannual), which the operating model does not resolve. However, in this case, there are other problems in the albacore situation that are probably more important (see *Results and Discussion*).

Three different scenarios for the effort trajectory in the non-ETBF fleet were examined for all species:

1. non-ETBF effort changes in proportion to the ETBF fleet as though both fleets were managed with the HS.

2. non-ETBF effort was held constant at the last observed value. This is not the same value from the stock assessment model, but rather is recalculated from the effort-fishing mortality relationship using the aggregated non-ETBF fleet with the assumed non-ETBF selectivity and the total non-ETBF catch.

3. non-ETBF effort changes linearly over the first 5 years of projections, and then remains constant. For all species, there was a robustness set defined in which the final effort level was 4X higher than the initial effort This might be possible in the case of swordfish, if all of the South Pacific Spanish fleet moved into the Tasman Sea, but it is not considered likely. Mostly this was defined as a robustness set to look at the qualitative implications of what might happen. In the case of bigeye, a 30% decrease in effort was adopted for the reference case, to be consistent with the agreed objectives of the WCPFC.

Additional robustness scenarios were defined in which catchability of the ETBF fleet was assumed to increase in a manner that cannot be detected (resulting in hyperstability in the CPUE-abundance relationship).

Sampling Models

Effective implementation of the feedback-based harvest strategy requires the extraction of useful information from the incoming fisheries data. In the ETBF, the fisheries data contains several potential sources of bias and variance that are poorly quantified.

The ETBF CPUE series are standardized using conventional GLM methods, but it is never certain that these methods have adequately captured all of the relevant factors related to targeting changes, efficiency improvements, and variable oceanographic dynamics that might affect catchability. In the operating model, there is a base assumption that CPUE is proportional to the fishery-selected abundance, with log-normally distributed observation errors, CPUE indices are annual, and that the errors may be serially correlated. For the species that use size-based CPUE indices (all except for albacore), the errors are implemented before the index is partitioned into size classes (i.e. all size classes are subject to the same observation error). CPUE variance estimates that are derived from GLM analyses are generally perceived to be unrealistically precise. The values assumed for CPUE variance in the operating model have been arbitrarily selected to be "reasonable, but not overly" informative.

The size composition data potentially plays an important role in the ETBF HS for most species. For some species, the proportion of the catch sampled for length composition is very high. If truly random samples are taken this would be very informative. However, there are at least two important reasons why we would not want the operating model sampling to be overly informative. First, the sampling is restricted to particular processors, which may not be representative of the whole fleet. Second and more importantly, the ETBF HS (and the assessment models) assume that selectivity is constant over time, which is probably not correct. This can lead to unrealistically reliable predictions of weakly recruited cohorts. Most of the factors that affect catchability are also likely to affect selectivity. The size composition varies by season and location, and fishing effort distributions change over time. To address some of these effects, a serially correlated, size-dependent sampling bias was added to the operating model.

The size-group definitions for each species are defined in the *Results and Discussion* section for each species. The size-group definitions are used in the calculation of CPUE by size-group and summation of proportions by size-group, which are used in the HS decision rule.

RBC Implementation Error

The operating model includes the option for implementation error, in which a random lognormal deviate was added to the RBC before the catch extraction. In most cases, the model was run with and without the implementation error, so the effects could be easily partitioned depending on how the management was implemented. Until the HS has been applied, it is difficult to speculate about plausible implementation error scenarios. We would assume that effort controls would generally contain more error than catch controls, but this might not be the case depending on carry-overs/carry-unders and discarding. We did not consider it to be very productive to attempt any complicated predictions about how the RBC implementation would eventuate.

Harvest Strategy Definitions

A large range of HSs were evaluated at different stages of the project, particularly for swordfish, as this was the original species under which the framework was developed. There are a large number of parameters required to fully define an individual HS (i.e. all thresholds in Figure 1). The parameters and the range of values explored are listed in Table 1. There was some a priori expectation that clever design might be required to suit the individual life history strategies of the ETBF species. The HSs include a number of parameters that are common to all species with a jointly defined numbering system (Table 2).

Table 1. Parameters and the range of values explored in the Harvest Strategies presented in this report. Additional values for these parameters were also explored but these have not been presented here.

Parameter	Description	Units	Values evaluated
Frequency of RBC setting	The frequency with which the RBC is reset	Years	1, 3 or 5
Maximum *RBC change constraint*	The maximum RBC change allowed	% change	unconstrained or 5%, 10%, 20%
CPUE-prime target	Target for *CPUE-Prime*	Relative to mean *CPUE–Prime* 1997-2001	1.4, 1.2, 1.0, 0.8, 0.6, 0.4
B CPUE gain factor	The gain parameter that defines how responsive the RBC change is to changes in CPUE[1]		1.0, 0.75, 0.5, 0.25, 0.1, 0.01
CPUE-Old threshold	Threshold defining if *CPUE-Old* is high or low	Relative to mean *CPUE-Old* 1997-2001	0.6, 0.8, 1.0, 1.25, 1.5
Proportion-Old threshold	Threshold defining if *Proportion-Old* is high or low	% of the catch	12%, 20%, 24%, 26%)
CPUE-Recruits threshold	Threshold defining if *CPUE-Recruits* is high	% of the catch	1.0, 1.2, 0.9
RBC reduction scalar **(δ)**	RBC reduction in lower levels (2-4) of the decision rule		0.95, 0.85
Number of years in slope calculations	Number of years in the CPUE slope calculations	Years	3, 5 or 8
Magnitude of *CPUE-prime* slope	Magnitude of slope threshold to determine if *CPUE-prime* is rising, stable or falling		5%
Magnitude of *CPUE-recruits* slope	Magnitude of slope threshold to determine if *CPUE-recruits* is falling		-10%
Size-classes	Size cut-offs for *recruits*, *prime* and *old* size-classes	cm	Fixed for each species
Timelag	Time lag between the collection of data, and its availability for use in the HS	months	6 or 18

We did not make any attempt to systematically compare all possible combinations of parameters (e.g. a balanced design comparing only 2 values for each parameter would be 2^{13} = 8192 HS definitions).

[1] Note that the gain parameter and the number of years to use in slope to target calculations, are confounded, so the two need not be considered independently.

CPUE-prime target

The *CPUE-prime target* was selected by the RAG/MAC on the basis of historically observed, economically attractive catch rates. The Australian fishery underwent a rapid expansion in the late 1990s, with very high initial catch rates, that soon dropped for most species. The target is expressed as the mean *CPUE-prime* for the years 1997/98 – 2001/02. The standardisation method and resultant annual CPUE series by size class are described by Campbell (2009; Campbell et al, 2008), and this project took these as given inputs with no expectation of further evaluation of the methods or data used. For the purposes of the harvest strategy, and all graphics in this document, the standardised CPUE series for each species has been re-normalised to have a mean of 1.0 over these 5 years.

A range of values for the *CPUE-Prime target* were explored in this project to examine alternative harvest strategies, and their performance, including 1.4, 1.2, 1.0, 0.8, 0.6, and 0.4. Level 1 of the harvest strategy decision rule uses the trend in *CPUE-prime* to adjust catches in order to return to the target CPUE level. There is nothing in the HS to ensure that the rate of TAC change is appropriately coupled to the dynamics of the fish population, so the target may not necessarily be attainable, and when it is attainable, the population will generally fluctuate around this level without stabilizing, as can be seen in the results that follow. In selecting the specific HS, it would be incorrect to assume that the target parameter provides a literal indication of how the HS is likely to perform. The simulated CPUE results provide a much better indication of expected performance.

Decision Tree Thresholds

As outlined in Davies et al (2008), the HSWG recommended SPR40 as the population state to use for defining internally consistent thresholds for size-based indices in the decision tree. The intention was to make the RBC more conservative if catch size composition proportions fall below (or exceed as appropriate) the values derived from a hypothetical population which has been fished down to an equilibrium level in which the ratio of Spawners Per Recruit (SPR) is 40% of the SPR for the virgin population. However, in this project, we did not attempt to define decision rule thresholds on the basis of the SPR40 concept for a number of reasons:

- Depending on stock recruitment considerations, this reference point can be a poor proxy for other reference points that are more commonly used, and also defined in the HSP (e.g. $B_{(t)}/B_0$ -current biomass / initial biomass).
- With the admission of uncertainty in parameters that influence SPR calculations (e.g. growth rates, maturity, natural mortality, stock recruitment curve steepness), there is no unique SPR value that can be used as a threshold (at best a compromise can be defined).
- The *CPUE-prime target* was selected by the RAG/MAC on the basis of historically observed, economically attractive catch rates, so there is no reason why adopting SPR40 size thresholds would represent a desirable or internally consistent population objective.
- The performance characteristics that were revealed across a broad range of HSs suggested that alternative size-based thresholds had very little effect on HS performance, and certainly less than the effects of other parameters (i.e. *CPUE-prime target*, *RBC change constraint*) that were not related to the size-based thresholds.

While the different HSs could have substantially different behaviour with respect to any specific stochastic realization, the statistical properties of the outcomes were often rather similar, and illustration of relatively few HSs seemed to be indicative of a broad range of results as described in the following section.

Table 2. ETBF Harvest Strategy definitions. The following definitions are used throughout the report, where *xxx* is replaced by the species abbreviation. Column 1 is the name of the Harvest strategy. Harvest Strategies labelled “CC_” are constant catch projections. The numbering system is not a code, simply a sequential numbering of different HSs. Column 4 is the gain parameter (β) that defines how responsive the RBC change is to changes in CPUE, Column 5 indicates whether stages 2-4 of the decision tree are used. The other columns are explained in the *Harvest Strategy Definitions* section above. Default values apply where no value is shown in the table.

Harvest Strategy	***Frequency* of RBC setting (years)**	**Maximum *RBC change constraint* (%)**	***CPUE-prime target***	***B* CPUE gain factor**	**Use DR tree**	***CPUE-Old* threshold**	***Proportion-Old* threshold**	***CPUE-recruits* threshold**	**RBC reduction scalar (δ)**	***Number of years in slope calculations***
Default values: HS_xxx_0	1	20%	1 = mean of observed CPUE 1997-2001	1	Y	0.6 = 0.6x mean observed CPUE 1997-2001	20%	1.0 = mean observed CPUE 1997-2001	0.95	5
CC_xxx_0	Const catch	0 t ETBF			N					
CC_xxx_00	Const catch	0 t ETBF and non-ETBF			N					
CC_xxx_1400	Const catch	1400 t			N					
CC_xxx_1800	Const catch	1800 t			N					
Purpose: 1) To span a range of aggressiveness in catch, 2) to see how slope-to-target rule alone compares with complete decision tree specification										
HS_xxx_1	1	20%	1.2	1	N	n/a	n/a	n/a	n/a	5
HS_xxx_2	1	20%	1.0	1	N	n/a	n/a	n/a	n/a	5
HS_xxx_3	1	20%	0.8	1	N	n/a	n/a	n/a	n/a	5
HS_xxx_4	1	20%	0.6	1	N					
HS_xxx_5	1	20%	0.4	1	N					
Purpose: To explore the effect of an 18month time lag i.e 18months from CPUE data used (end of season) and 1st Jan TAC setting										
HS_xxx_0_18	All variables set = HS_0, but time lag = 2 (18months) rather than 1 (6months)									

Harvest Strategy	***Frequency* of RBC setting (years)**	**Maximum *RBC change constraint* (%)**	***CPUE-prime target***	***B* CPUE gain factor**	**Use DR tree**	***CPUE-Old* threshold**	***Proportion-Old* threshold**	***CPUE-recruits* threshold**	**RBC reduction scalar (δ)**	***Number of years in slope calculations***
Purpose: Explore alternative ways to improve catch stability										
HS_xxx_14	1	Unlimited	1	1	Y	0.6	20%	1.0	0.95	5
HS_xxx_15	1	20%	1.0	1	Y	0.6	20%	1.0	0.95	3
HS_xxx_16	1	20%	1.0	1	Y	0.6	20%	1.0	0.95	8
HS_xxx_19	1	20%	1.0	1	Y	0.6	20%	1.0	0.85	5
HS_xxx_20	1	Unlimited	1.0	1	Y	0.6	20%	1.0	0.85	5
HS_xxx_21* (MAC adopted)	1	10%	1.0	1	Y	0.6	20%	1.0	0.95	5
HS_xxx_22	1	5%	1.0	1	Y					
HS_xxx_23	3	20%	1.0	1	Y					
HS_xxx_24	5	20%	1.0	1	Y					
HS_xxx_25	1	20%	1.0	0.75	Y					
HS_xxx_26	1	20%	1.0	0.5	Y					
HS_xxx_27	1			0.1	Y					
HS_xxx_28	1			0.01	Y					
Purpose: To explore a range of aggressiveness in harvest strategies with reasonable catch stability										
HS_xxx_30	1	10%	1.4		N					
HS_xxx_31	1	10%	1.2		N					
HS_xxx_32 (MAC adopted)**	1	10%	1.0		N	n/a	n/a	n/a	n/a	5
HS_xxx_33	1	10%	0.8		N					

Harvest Strategy	***Frequency* of RBC setting (years)**	**Maximum *RBC change constraint* (%)**	***CPUE-prime target***	***B* CPUE gain factor**	**Use DR tree**	***CPUE-Old* threshold**	***Proportion-Old* threshold**	***CPUE-recruits* threshold**	**RBC reduction scalar (δ)**	***Number of years in slope calculations***
HS_xxx_34	1	10%	0.6		N					
HS_xxx_35	1	10%	0.4		N					
Purpose: To try to get better performance out of the Decision tree when the TAC constraint is relaxed (and dropping gain parameter)										
HS_xxx_41	1	unlimited	1.2	0.1	Y				0.85	
HS_xxx_42	1	unlimited	1.0	0.1	Y				0.85	
HS_xxx_43	1	unlimited	0.8	0.1	Y				0.85	
HS_xxx_44	1	unlimited	0.6	0.1	Y				0.85	
HS_xxx_45	1	unlimited	0.4	0.1	Y				0.85	
HS_xxx_51	1	unlimited	1.2	0.5	Y				0.85	
HS_xxx_52	1	unlimited	1.0	0.5	Y				0.85	
HS_xxx_53	1	unlimited	0.8	0.5	Y				0.85	
HS_xxx_54	1	unlimited	0.6	0.5	Y				0.85	
HS_xxx_55	1	unlimited	0.4	0.5	Y				0.85	
Purpose: To illustrate a series of Harvest Strategies that resemble those preferred at the Mar 2009 RAG										
HS_xxx_61	1	5%	0.9	1	Y				0.95	
HS_xxx_62	1	5%	1.0	0.5	Y				0.95	
HS_xxx_63	1	5%	1.0	0.25	Y				0.95	
HS_xxx_64	1	10%	1.0	0.5	Y				0.95	
HS_xxx_65	1	10%	1.0	0.25	Y				0.95	
HS_xxx_66	1	5%	1.0	1	N				n/a	
HS_xxx_67	1	10%	1.0	0.5	N				n/a	
HS_xxx_68	1	10%	1.0	0.25	N				n/a	

Harvest Strategy	*Frequency* of RBC setting (years)	Maximum *RBC change constraint* (%)	*CPUE-prime target*	*B* CPUE gain factor	Use DR tree	*CPUE-Old* threshold	*Proportion-Old* threshold	*CPUE-recruits* threshold	RBC reduction scalar (δ)	*Number of years in slope calculations*
HS_xxx_69	1	5%	1.0	0.5	Y				0.95	3
HS_xxx_70	1	5%	1.0	0.5	N				n/a	
HS_xxx_71	1	5%	0.9	1	N				n/a	
HS_xxx_72	1	5%	0.8	1	N				n/a	
HS_xxx_73	1	10%	0.9	0.5	N				n/a	
HS_xxx_74	1	10%	0.8	0.5	N				n/a	
Purpose: Testing effects of "consistency" between threshold values										
HS_swo_80	1	10%	1.0	1.0	Y	1.0	24%	1.2	0.95	5
HS_swo_81						1.0	24%	1.0		
HS_swo_82						1.0	26%	1.2		
HS_swo_83						1.25	26%	1.2		
HS_swo_84						1.5	26%	1.2		
HS_swo_85						1.25	24%	1.0		
HS_swo_86						1.5	24%	1.0		
HS_swo_87						1.0	12%	0.9		
HS_swo_88						0.8	12%	0.9		
HS_swo_89						1.0	24%	1.2	0.85	
HS_swo_90						1.0	12%	0.9	0.85	
HS_yft_91	1	10%	1.0	1	Y	0.6	20%	1.0	0.95	3
HS_yft_92					Y				0.95	8
HS_yft_93					Y				0.85	3
HS_yft_94					Y				0.85	8

*Swordfish, striped marlin, bigeye, yellowfin **Albacore

Interpretation of MSE results

This section introduces the main types of plots that are used to summarize the outcomes from the HS simulation testing, and discusses additional general concepts that are used in the remainder of the report. Most of the discussions at the ETBF RAG focused on broad-scale generalizations and relative comparisons made on the basis of these figures. We have refrained from providing voluminous tables of numerical results, because this would imply a state of precision that does not reflect the uncertainty and subjectivity underpinning various elements of this analysis. It is possible to fill a table with results that are accurate to several significant figures, but since these numbers are underpinned by some very approximate assumptions, this would be very misleading. The main quantitative results in this report should be evident from the figures. The more important messages probably relate to the description of the methods, limitations identified through this process, caveats associated with the HSs that have already been adopted, and the prioritizations for future work, all of which are described in the text.

Description of variability

Figure 7 illustrates the time series plots that are used to convey information about an individual management performance quantity over time (usually catch, CPUE, or biomass), and shows how the summary graphics relate to a much more complicated mix of individual realizations.

Figure 8 illustrates the outcome of each individual projected realization as a single point. However, in this report, only the medians are usually shown, surrounded by a rectangle which describes the 10th and 90th percentile of the outcomes. This representation loses some of the joint uncertainty structure of the two variables, but facilitates comparison of multiple harvest strategies simultaneously.

Description of risk probabilities

The quantification of risk probabilities is a very difficult process in poorly defined systems, and inevitably includes a number of subjective decisions. In this case, we describe the MSE results in terms of the frequencies of outcomes, which sound a lot like probabilistic statements. However, they should not be interpreted in an absolute sense. We have much more confidence in the relative risk statements that arise when comparing harvest strategies (i.e. HS-A has a much higher probability of exceeding the biomass limit than HS-B). This principle of relative risk is helpful, because there is considerable ambiguity in the interpretation of the Harvest Strategy Policy (e.g. what time-frame should be used for calculating the probability of exceeding limit reference points, and how should reference points be defined when recruitment variability is sufficient to drop biomass below limit reference points even in the absence of fishing). There is no prescription for quantifying risk among fisheries (e.g. how to deal with the uncertainty associated with the somewhat arbitrary assumptions required to formulate tractable stock assessment models, or how to quantify the likely actions of international fleets). The HSP attempts to set out acceptable standards of risk for all of the Commonwealth fisheries, without being overly prescriptive:

- *"These control rules should...ensure that the stock stays above the limit biomass level at least 90% of the time (i.e. a 1 in 10 year risk that that stocks will fall* *below BLIM). The 90% probability will form a key performance criterion in evaluating prospective harvest strategies when conducting management strategy evaluation analyses. It is important to note that this is a minimum standard, and that most harvest strategies that achieve the targets on average should perform better than this standard with regard to the probability of exceeding the limits. For highly variable species that may naturally (i.e. in the absence of fishing) breach B_{LIM}, the harvest strategy for these species must be consistent with the intent of the Policy. Stocks that fall below B_{LIM} due to natural variability will still be subject to the recovery measures as stipulated in the HSP."*

In this document, we considered a number of alternative risk criteria that might be considered consistent with the intent of the HSP. For most of the target species, we do not have a lot of confidence in the estimation of biomass reference points. Spawning Biomass at Maximum Economic Yield (B_{MEY}) is difficult to quantify because of the variability inherent in economics and the international factors in the ETBF, plus all of the uncertainty in Spawning Biomass at Maximum Sustainable Yield (B_{MSY}). B_{MSY} is difficult to quantify because of the uncertainty in the stock-recruitment relationship (and other system parameters). Ignoring the problem of the spatial definition of the stock (which affects all of these reference points), initial spawning Biomass (B_0) is usually estimated more reliably than B_{MSY}, and depletion levels relative to B_0 are sensibly recommended in the HSP as proxies for B_{MSY} and B_{MEY} . However, it is also difficult to quantify B_0 for these species, because there is evidence for long-term trends in recruitment, which lead to estimates of unfished biomass that can change by a factor of 2-3 even in the absence of fishing. We defined B_0 as the average spawning biomass that was estimated to have been present in the absence of fishing over the period 1980-2004. In the MULTIFAN-CL assessments, this time series is calculated by repeating the iteration of the population dynamics that result from the MPD estimates when all of the fisheries are removed (catchability = 0). The time series was truncated in the most recent 25 year period, because the data from the early period are considered to be less reliable. In particular, biomass declines estimated for the 1950s period are questionable for many pelagic populations around the world, and it remains unclear if this is an artefact of the assessments, or a real biological phenomenon.

When this work was presented at the technical review workshop, reviewers were interested in the specific relationship between the $0.4B_0$ proxy for B_{MSY} and the estimated B_{MSY} for each species. In all cases (except possibly striped marlin, depending on the depletion definition adopted), the estimates of B_{MSY} were lower than 0.4 B_0 (sometimes considerably lower). The comparison is provided for each species in the *Results and Discussion* section. This means that the proxy value that we have adopted has an added margin of safety relative to the estimated B_{MSY} values, and this should be a factor for consideration in the HS selection process, if the options under consideration are approaching the biomass limits.

Figure 9 illustrates 3 different measures of biomass conservation risk for the swordfish fishery:

1) The first panel of Figure 9 is the most consistent with the HSP. The biomass risk represents the proportion of simulated realizations in which the biomass drops below 20% of B_0 for greater than 10% of the time (3+ years in the projection period). The literal interpretation of the HSP would suggest that any

value greater than 0 is unacceptable (i.e. in Figure 9, the only acceptable HS would be CC_swo_0 (constant catch of 0), a complete cessation of fishing). This seems to be unacceptably restrictive for a fishery that is currently judged to be in reasonably good condition relative to common (depletion-based and MSY-related) reference points.

2) The second panel of Figure 9 represents the risk as a cumulative proportion of time with biomass spent below $0.2B_0$, across all realizations. This plot seems to represent the most common intuitive interpretation of biomass risk for most people.

3) The third panel of Figure 9 is similar to the first panel, except that B_0 is defined as the biomass that would be observed if future fishing was completely stopped ($B_{CC0}(t)$, the CC_swo_0 scenario). This panel shows less risk associated with each HS when compared to the first panel because i) it takes several years for CC_swo_0 scenarios to recover to mean equilibrium B_0 levels, and ii) this index does not penalize the HS for population declines that are purely due to recruitment variability. Only the biomass risk that is caused by fishing is relevant (i.e. each stochastic realization has a unique recruitment history, which corresponds to a unique Biomass trend $B_{CC0}(t)$).

Description of trade-offs

Figure 10 and Figure 11 illustrate the general pattern of trade-offs observed among harvest strategies that have been observed in this project (and more generally):

- For a given level of catch variability, higher catches are associated with lower CPUE and higher biomass risk
- For a given level of risk, higher mean (or median) catches tend to be associated with higher variance

Since the intrinsic productivity of the stock is a biological property that is not directly influenced by management, it is unusual to find a HS in which the median performance does not closely follow the typical trade-off relationship. If an HS deviates from this general relationship, it seems to indicate large changes in abundance over time. Overfishing can cause a negative deviation from the average relationship (primarily due to recruitment overfishing). Conversely, for a highly depleted stock, aggressive rebuilding can result in a substantial positive deviation from the general relationship (i.e. relative to other HSs that maintain the population in a depleted state).

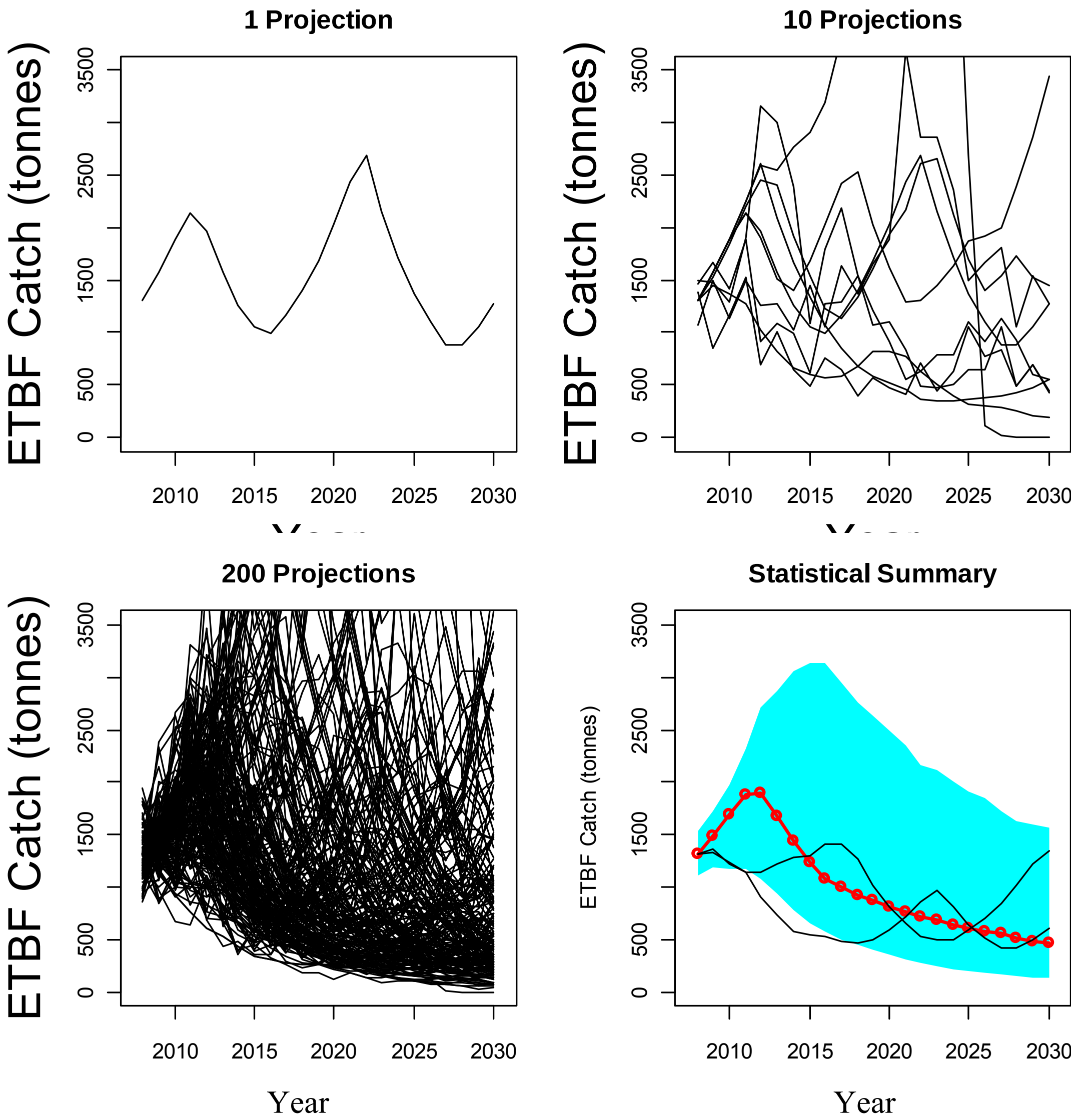


Figure 7. Estimated future swordfish catches associated with a hypothetical harvest strategy specification. The series of plots show how the statistical summary plot (bottom right, which summarizes 2240 projections) relates to individual realizations.

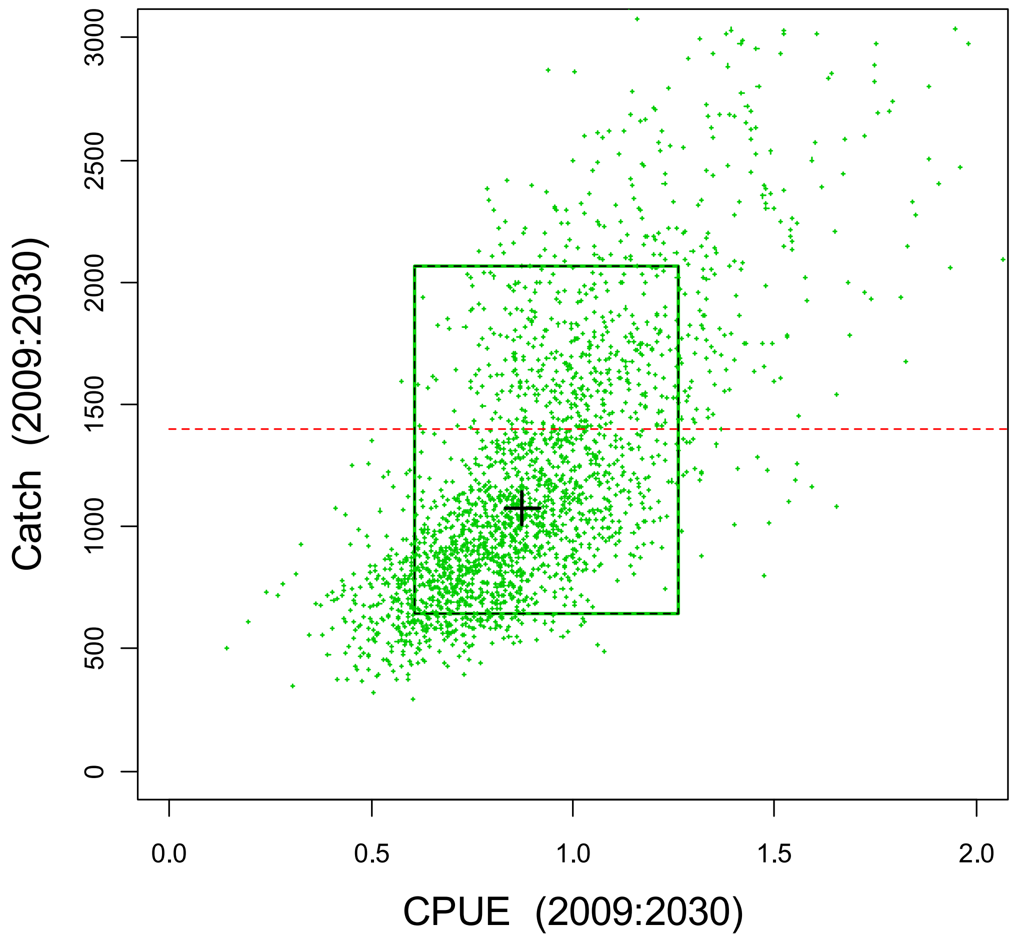


Figure 8. Relationship between average Catch and average CPUE (prime-sized) for a hypothetical harvest strategy over the period 2009-2030. The median in both quantities is indicated by the large central "+" marker, while 10th and 90th percentiles are bounded by the rectangle. Each dot represents the outcome of a single simulated projection. The dotted red reference line indicates the most recent annual catch.

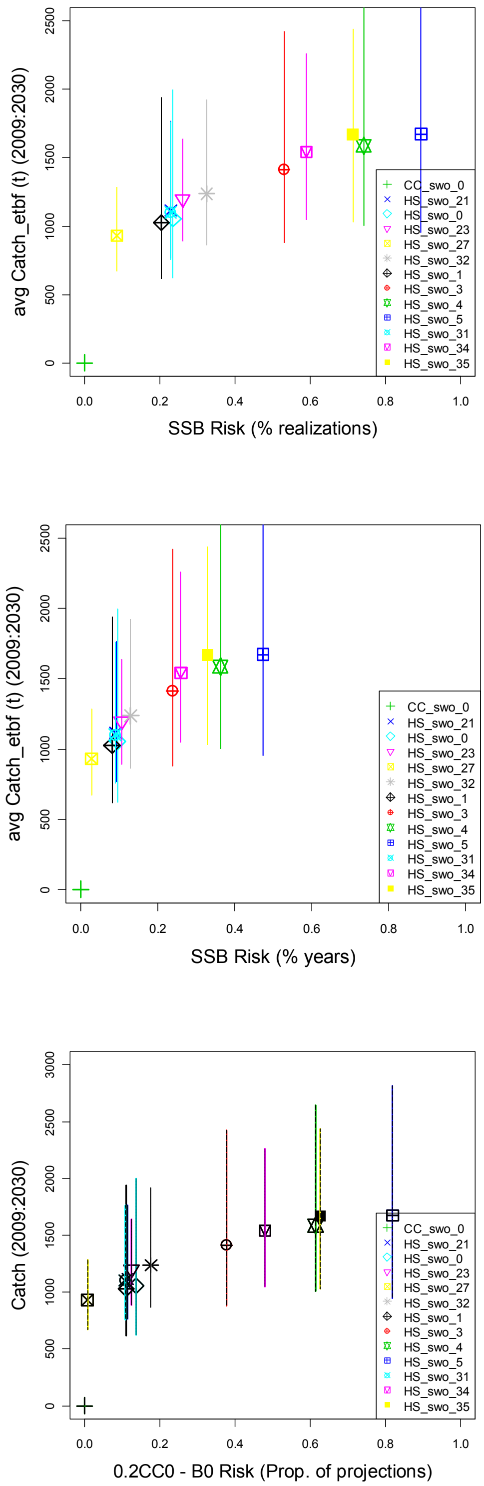


Figure 9. Comparison of alternative biomass risk indices.

Trading off Catch and CPUE (or Biomass Risk)

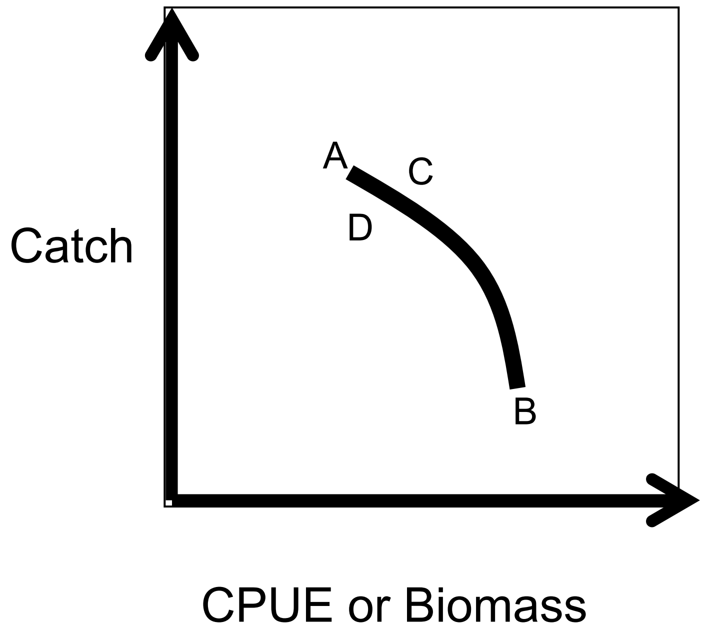


Figure 10. Conceptual illustration of a general management performance trade-off observed in fisheries MSE. The figure shows how catch and CPUE (or biomass) are usually related, in which most harvest strategies tend to fall somewhere on the black line. Letters A-D represent specific performance indices (usually medians or lower 10th percentiles are used in this document). A and B represent the most and least "aggressive" decision rules, respectively, where aggressiveness refers to the pursuit of higher catches. A and B can be considered equivalent in terms of their performance relative to the trade-off (such that additional criteria are required to distinguish which is preferable). C represents a rule that is clearly better than the general relationship, because it offers a higher catch for a given level of CPUE. D is clearly worse than average because the catch is lower for a given level of CPUE. In the ETBF MSE simulations, there were different ways to move along the line between A and B (e.g. setting a lower or higher *CPUE-prime* target makes the rule more or less aggressive, while increasing the influence of the lower levels of the decision tree will make the rule less aggressive. Movements off of the mean relationship are likely to be associated with actions that have long term consequences (e.g. C could represent the long-term benefit from the ambitious rebuilding of a depleted stock, whereas D could represent the consequences of recruitment overfishing).

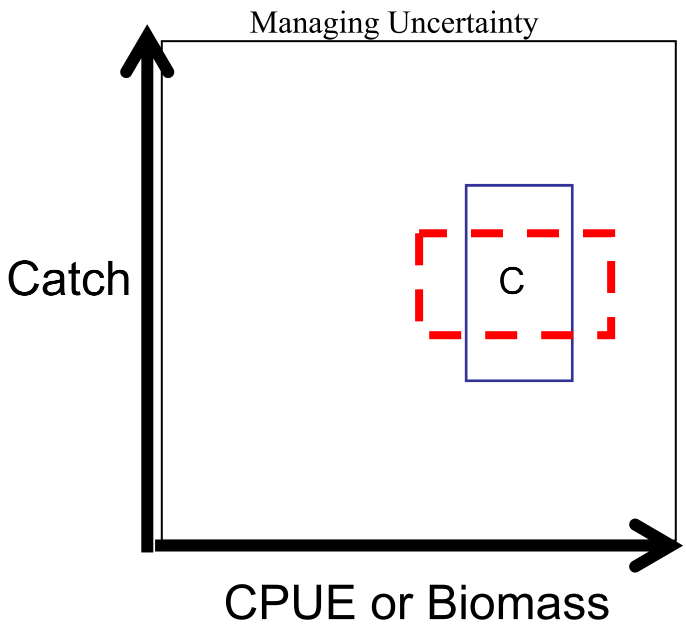


Figure 11. Conceptual illustration of how variability in catch and CPUE can be traded off once a desirable level of median catch and CPUE (or biomass) is identified. The rectangle encompasses the 10th – 90th percentiles of the simulated outcomes (but does not describe the correlation). The solid blue box represents a preference for CPUE stability, while the broken red box represents a preference for catch stability. The HSWG framework (and probably most other decision rules) has limited capacity to reduce the variance in both dimensions simultaneously. Improved data could reduce the variance in the trade-off box that is due to future observation error, but the uncertainty in productivity ensures that at least one dimension has to have variability. The horizontal axis also represents over-fishing risk (e.g. lower biomass line represents a 10% risk of biomass falling below the indicated level), such that the solid blue box is less risky than the broken red box.

Results and Discussion

This section consists of three main parts. The first section provides a general comparative overview contrasting the species-specific operating model characteristics. The second section is broken down by ETBF target species, for each of which there is a definition of the reference and robustness set of operating models, graphical summaries of a contrasting range of harvest strategy performance (including the preferred HS as adopted by the MAC), and general comments about the process and reliability of the results. Each species is presented as a stand alone section. Each stock assessment represents a voluminous stand alone document, and only core features of the assessment are repeated here. The swordfish exploration was the most thorough in terms of alternative harvest strategies, and a qualitative description of the type of performance expected with different HS variations is provided. The presentation is more restricted for the other species, consisting of the MAC-recommended HS, and a subset of alternatives that are markedly more or less aggressive. The third section provides a general summary of lessons learned about the ETBF operating models and the HS framework, and future consideration when the ETBF HS process is revisited.

Contrast in the MSE application among ETBF target species

This section provides a brief comparative overview of the characteristics of the MSE approach for the 5 ETBF target species. The specific details of the operating models and HS evaluation for each of the target species is described in the following sections.

Figure 12 provides a qualitative indication of the perceived appropriateness of the different WCPFC stock assessments for the purposes of the ETBF MSE operating models. The exact locations of the different species on this plot are debatable, but it is a convenient summary of the general perception. We consider the swordfish assessment to be the most appropriate, primarily because i) the spatial considerations in the assessment closely reflect the assumptions in the operating model (i.e. there are explicit ETBF and non-ETBF regions, with minimal regions of overlap), ii) there are good arguments for assuming that the swordfish population is reasonably discrete from other populations in the Pacific (e.g. unlike the tropical tuna species, there is no large population in the adjacent equatorial waters), and iii) there was considerable exploration of stock status uncertainty that can be directly represented in the simulation testing. In contrast, the albacore assessment is considered the least successful for MSE purposes, because i) the assessment authors describe it as preliminary, with a number of recognized problems (some were subsequently re-examined for the WCPFC-SC in 2009, but not available in time to be updated in this report), ii) the spatial representation in the model includes the whole South Pacific as a homogeneous population, and iii) there are substantial inconsistencies between the recent stock status estimates and the ETBF CPUE series (though it is unclear to what extent this latter problem is due to the assessment model or the ETBF data). The other species are intermediate between these two.

Figure 13. compares species in terms of the current stock status, and the perceived potential contribution of the ETBF to that stock status as reflected in the reference case

operating models. According to the WCPFC assessments, bigeye tuna and striped marlin are estimated to have the highest conservation risk currently. In the case of bigeye, this is the gradual and progressive result of increased targeting, and by-catch in the purse seine fisheries since the 1950s. In contrast, striped marlin seems to have been seriously depleted prior to the 1980s, such that current catches are sufficient to keep the population low, even though they are generally not targeted. Striped marlin and swordfish seem to have restricted spatial distributions, such that the ETBF is capable of exerting considerable pressure on the populations, and unilateral action by Australia could have a significant effect on the conservation status of these stocks. The reference set of operating models suggests that the ETBF has an almost undetectable effect on the yellowfin population relative to the combined effect of the international fleets. The estimated effect on the bigeye and albacore stocks is small but not trivial. Because of the uncertainty in the spatial dynamics and connectivity of the tuna populations, a series of additional robustness scenarios were defined, in which more localized populations were approximated.

Together, Figure 12 and Figure 13 provide a general summary about the priorities for adopting and refining the HSs. This is discussed further in the final section of the Results and Discussion.

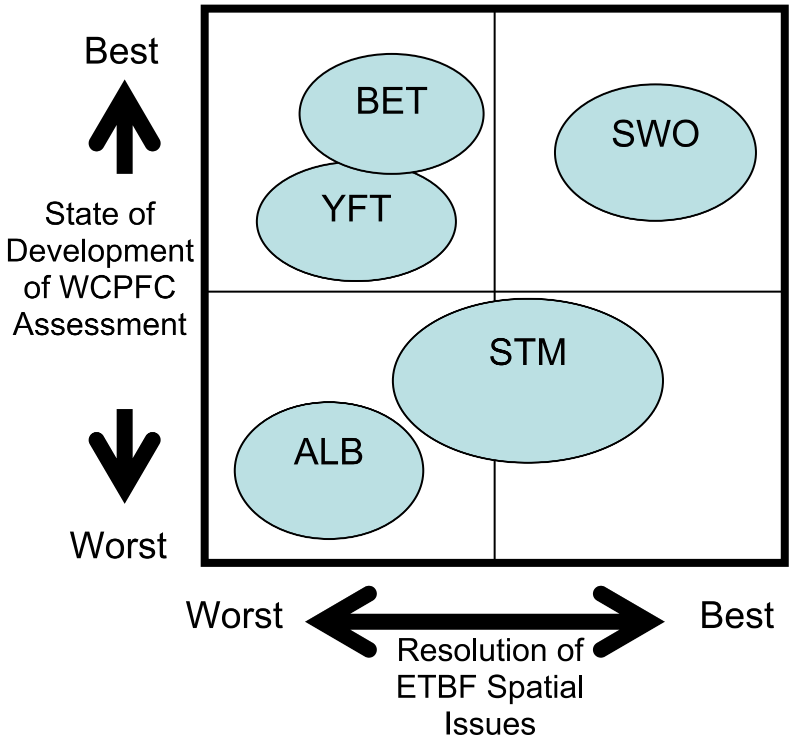


Figure 12. Qualitative comparison of stock assessment models by species as an indicator of appropriateness for use in operating models. "State of development" qualitatively includes factors like the number of years of development, unresolved conflicting signals in the models, exploration of uncertainty, and how recent the analyses are.

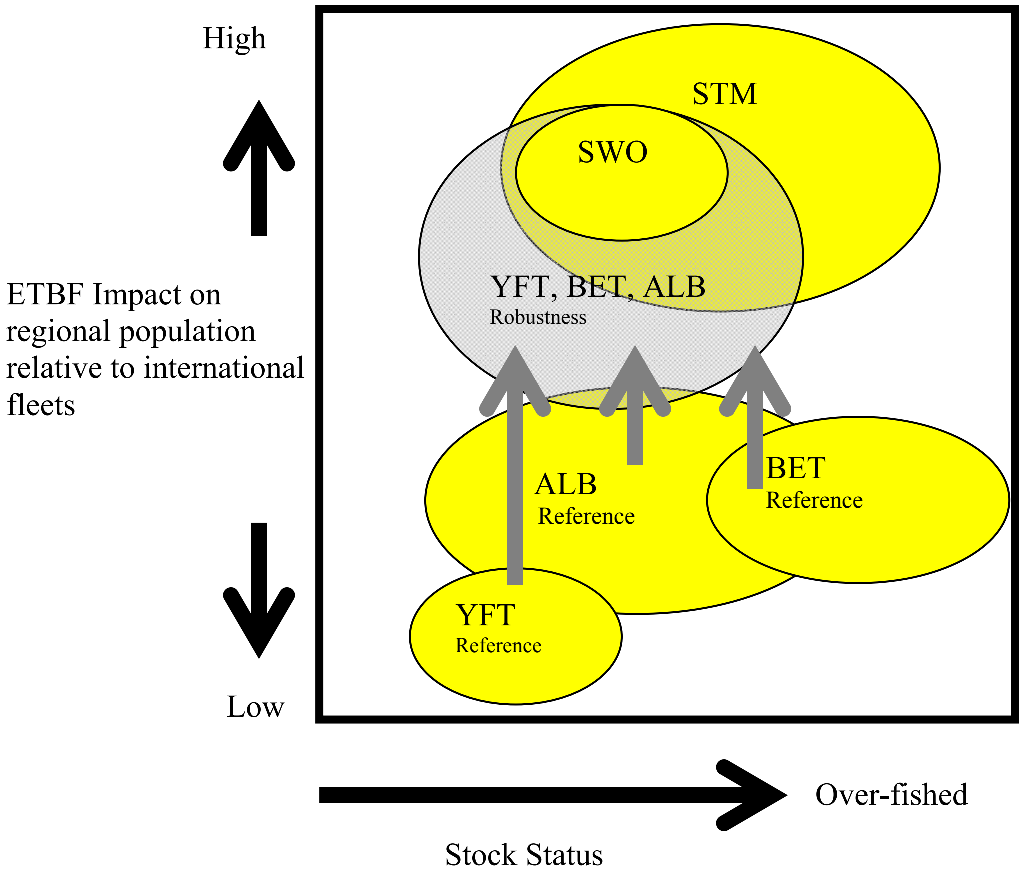


Figure 13. Qualitative comparison of the ETBF fleet impact on regional population abundance by species. Depending on how localized the population dynamics are, these species (particularly the tuna) could shift considerably along either axis.

Swordfish MSE

Swordfish Reference Set Operating Models

The most recent swordfish assessment in the ETBF region (Kolody et al. 2008b) was developed with the requirements of the harvest strategy evaluation in mind. This resulted in a reasonable spatial correspondence between the assessment model and the generic operating model. There was also a strong emphasis on the quantification of uncertainty in the assessment. The stock is estimated to be moderately to fully exploited, with current stock status relative to initial biomass estimated to be $B_{(T)}/B_{(No\ Fishing)}$ = 0.45 – 0.79 (where $B_{(T)}$ is the biomass in the final year of the assessment, and $B_{(No\ Fishing)}$ is the estimate of initial biomass in the absence of fishing (as described earlier)) .

The reference set of operating model features are described in Table 3. Key assumptions included:

- The spatial structure in the assessment consists of the two western areas shown in Figure 14, with the western most area adopted for the ETBF and the adjacent area for the non-ETBF region in the operating models. The remaining two areas in Figure 14 were explored as part of the stock assessment, but the data were poor, and the available evidence did not support the notion of a single population mixing across the western and central regions of the south Pacific. Genetic evidence strongly suggests that the mixing rate of northern and southern hemisphere swordfish populations is very low in the Western Pacific.
    - The migration linkage between the ETBF and non-ETBF regions is assumed to be an equal mix of scenarios with 1% and 20% per quarter diffusive mixing. This brackets the assumed mixing rates of 5-10% per quarter adopted in the assessment (on the basis of diffusion parameters estimated from a small number of conventional and electronic tag displacements).
    - The ETBF region is assumed to have 50% of the operating model equilibrium population and new recruitment (as in the WCPFC assessment).
- The assessment had a strong emphasis on the quantification of uncertainty. Fourteen different assessment models were used to represent alternative plausible population dynamics in the operating models. These models were selected from 192 models that were judged to be plausible, and represented the most extreme models with respect to several common reference points (e.g. maximum and minimum depletion, $B_{(2007)}/B_{MSY}$, $F_{(2007)}/F_{MSY}$, MSY, etc.). This uncertainty encompassed several elements of basic biology that were used as fixed inputs to the assessment (e.g. Figure 15 illustrates the alternative growth rate, maturity schedule, natural mortality vectors, and stock recruitment curve steepness assumptions) and the corresponding point estimates for several population parameters (e.g. numbers-at-age, fishery selectivity, virgin recruitment). All of the models were weighted equally in the simulation testing. A separate robustness test using the full 192 plausible swordfish assessment model results as inputs to the operating models was run for several harvest strategies. The performance measure results and population dynamics

behaviours were shown to be covered by the subset of 14 models. Results are not shown here.

- Unlike the other species, non-ETBF effort was assumed to change in proportion to the harvest strategy (i.e. the RBC for the non-ETBF was regulated in proportion to the ETBF RBC). This reflects the fact that New Zealand has been the other major fishery in the region in recent years, and exhibits a similar catch and effort history to the ETBF. Of course, there is no expectation that the New Zealand fleet would explicitly adopt the ETBF HS. However, it seems like a reasonable assumption that this fleet might continue to operate under similar economic conditions to the Australian fleet. Other fleets have the potential to dramatically expand their swordfish operations in the SW Pacific, but this would contravene WCPFC Conservation and Management Measure CMM2008-05. It seems more plausible that the effort of the New Zealand fleet would fluctuate with biomass in a manner similar to that simulated by the HS than for it to remain constant. However, as shown below, these two non-ETBF effort scenarios actually yield quite similar results for swordfish.
- The selectivity of the non-ETBF fleet was assumed to be the same as the ETBF fleet. In the assessment, the New Zealand fleet was estimated to have a somewhat different selectivity from the Australian and other longline fleets, but this difference was ignored. The southern bluefin tuna fleet was estimated to have a substantially different selectivity, but this minor fleet has a trivial impact on the stock.
- The recruitment variability used in the reference set operating model was higher (sd(log) = 0.6) and strongly autocorrelated (rho = 0.7) relative to what was assumed in the stock assessment (sd(log) = 0.1 and 0.4, rho = 0). The auto-correlation was introduced because most long time series of recruitment indicate autocorrelated residuals (or regime shifts), and the swordfish assessment is no exception. The autocorrelation magnitude was arbitrarily selected such that 50% of the variance of any individual deviation was due to annual stochastic events, and 50% due to historical processes (e.g. autocorrelated oceanographic processes). Additional stochastic error was also introduced to the MPD estimates of the youngest cohorts (age 0 sd(log) = 0.5, age 1 sd(log) = 0.25).
- The magnitude of the CPUE observation error variability was assumed to be relatively low (sd(log) = 0.2) and strongly autocorrelated (rho = 0.7) in the reference set operating models. This differed from the values assumed in the stock assessment (sd(log) = 0.1, rho = 0), which were recognized to be unrealistic at the time. The assessment was undertaken from the perspective that the model would probably be meaningless without a reliable relative abundance index. It was recognized that the assessment could be misleading if the CPUE was more variable than assumed, but that it would almost certainly be badly flawed if the assessment failed to fit any relative abundance index. The time series structure was introduced because the processes that affect ETBF longline catchability (e.g. both those that can and cannot be accounted for with standardization analyses) are likely to be strongly autocorrelated (e.g. targeting shifts due to changing abundance and markets, technological innovations, etc.).
- The reference set consisted of 2352 projections = (14 MPD estimates) X (2 migration rates) X (2 size composition sampling errors) X (2 implementation error assumptions) X (21 stochastic realizations per scenario).

- The depletion level corresponding to B_{MSY} (i.e. B_0/B_{MSY}) ranged from 0.14 – 0.26 (range from 14 MPD estimates) when B_0 was defined as the mean unfished biomass in the 1980-2004 period, and 0.15 – 0.27 relative to the equilibrium B_0. In all cases this is substantially lower than the 0.4 B_0 proxy value suggested in the HSP.
- Other biological and fishery assumptions correspond to those described in Kolody et al. (2008b).

Figure 16 shows the dynamics of the reference set when the fishery is stopped completely. The projections suggest that the median biomass (and lower 10^{th} percentiles) will return to unfished levels before 2030, with considerable variability around the unfished level due to the assumed recruitment variability (including the high auto-correlation). However, the 90^{th} percentile is somewhat higher than the pre-1990 levels. Assuming that HS selection is based primarily on median performance or a lower (precautionary) percentile, this inconsistency should not represent a conservation risk. It is possible that the recruitment variability is overemphasized for the swordfish stock, but this is a population characteristic that is difficult to quantify, and troublesome to manage, so this precautionary assumption was adopted (the effects of less extreme recruitment assumptions are included in the robustness set results). While we cannot know how accurate the unfished recovery trajectory is, these plots at least demonstrate that the reference set operating model is internally consistent in returning to population levels estimated prior to the rapid expansion of the fishery.

Figure 17 illustrates that there is reasonable agreement between the observed swordfish CPUE trends for the ETBF and the predicted values from the operating models. This provides some confidence that the operating model is at least consistent with the main data trends, even if it is not perfect. Figure 18 illustrates that there is an inconsistency in the size composition data. The general trends suggest that there is an important signal in the ETBF data that is being captured in the assessment (i.e. decreasing numbers of large fish), but there is a mismatch in the proportions of fish in the tails of the distributions.

The main concerns about the Reference set of swordfish operating models are as follows:

- While the emphasis on model uncertainty quantification is expected to provide a broader representation of possible future dynamics in general, reliance on MPD estimates (particularly when coupled with the constant selectivity assumption) has the potential to understate the uncertainty in year class strength, particularly for weakly recruited cohorts. In the swordfish case, this problem seems to manifest itself as a very high probability of at least one strong incoming cohort, that is consistent across all of the models. If this cohort is an artefact (e.g. due to a violation of the stationary selectivity assumption), then inferences based on short-term management outcomes might be over-optimistic.
- There is an inconsistency in the size composition data, particularly for older fish. There are a number of possible explanations for this. Foremost among them, the sex-aggregated assessment assumed that the growth curve was the mean of that estimated for males and females. The failure to explicitly account for sex dimorphism (and other sex-specific parameters) would be expected to cause problems in the size composition data.

- As with all of the ETBF species, we really have a poor idea of the implications of interpreting CPUE as a relative abundance index. There are a lot of operational data that contribute to the catch rate standardization analyses, but there has not been a concerted effort to statistically quantify the estimation errors. However, there is at least corroboration on the general trend in the ETBF series from the New Zealand fleet and the Japanese fleet (the latter taking swordfish primarily as by-catch).
- Migration within the ETBF and non-ETBF regions remains poorly quantified.
- As with all of these species, large changes in the effort distribution of the non-ETBF fleet could undermine the results.

Swordfish Robustness Set Operating Models

A series of alternative operating models were examined in developing the reference set. Most of the robustness sets were defined to illustrate the effects of an alternative assumption to those used in the reference set operating models (Table 4 - Table 6), while others were defined primarily to explore the behaviour of the HSWG decision rule framework under special circumstances (Table 7 - Table 9).

Table 4 describes recruitment variability for two scenarios. The more extreme case is adopted in the reference set, while the less extreme scenario represents a minimum bound on variability, given current levels of uncertainty in catch age composition.

Table 5 describes the implications of auto-correlation in the CPUE observation errors. The implications of the autocorrelation are trivial (not shown), and presumably reflects the fact that the time series structure really does not make much difference if the CV is low.

Table 6 describes 3 different scenarios for effort in the non-ETBF fleet: i) non-ETBF catch managed in proportion to the ETBF RBC, ii) non-ETBF effort constant at the level of the last year in the assessment, and iii) non-ETBF effort rapidly increasing to 4-fold the current level. The latter scenario is not expected to be realistic but is intended to provide a qualitative illustration of a worst case scenario. The implications of the different non-ETBF effort scenarios are illustrated in relation to the alternative migration rate assumptions.

Table 7 defines a robustness set in which there is a 2% linear increase in catchability every year in the ETBF (assumed to be undetected in the effort standardization). This is only applied to the projections, and was not retrospectively invoked in the assessment. This results in an aggregate catchability increase of 42% by 2030, and hyperstability in the CPUE time series. The HSWG recognized that the CPUE indices in the decision rule were likely to be sensitive to undetected catchability trends, and included the auxiliary size-based data in the decision tree to add an additional margin of safety to the decision rule. This scenario was proposed to see if the size-based elements of the decision rule would perform as expected.

Table 8 defines a robustness set in which the stochastic variability assumptions are reduced to a level that may be near the lower bounds of what might be considered plausible, and might represent the best possible conditions to demonstrate the effectiveness of the HS. The set defined in Table 9 essentially removes the stochastic variability altogether, and examines HS performance under ideal conditions.

Table 3. Definition of the swordfish reference set operating model. Multiple options were evaluated with a fully balanced design (e.g. all of the migration rate options were evaluated with all of the implementation error options). Each harvest strategy was evaluated with 2240 iterations (i.e. product of 14 Assessment model scenarios, 20 stochastic replicates, 2 migration rates, 2 size sampling options, and 2 TAC implementation error options: 14 x 20 x 2 x 2 x 2 = 2240)

Source of Uncertainty	Option 1	Option 2	Option 3	Number of Reference Set grid elements
M Growth Maturity N(2008) Steepness Selectivity	These biological parameters were adopted from individual MULTIFAN-CL output files from the WCPFC stock assessment (and consist of either fixed input assumptions or Maximum Posterior Density estimates).			14
Stochastic replicates	20 – errors not conserved among models			20
Recruitment CV / Autocorrelation/ N(a) bias	0.6 / 0.7 / 0			1
CPUE CV/ autocorrelation/ Effort creep in ETBF	0.2 / 0.7 / 0			1
Equilibrium (and 2008) spatial distribution	0.5/0.5			1
Redistribution rates	20%/qtr	1%/qtr		2
non-ETBF effort	= HS regulation			1
CV on N(2008,a=0)	0.5			1
CV on N(2008,a=1)	0.25			1
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0	0.7 / 0.2 / 0.7		2
selectivity shifts	main effect should be described by systematic size sampling errors			
RBC implementation error sd(log))	0	0.2		2
Data Time Lag	6 months			

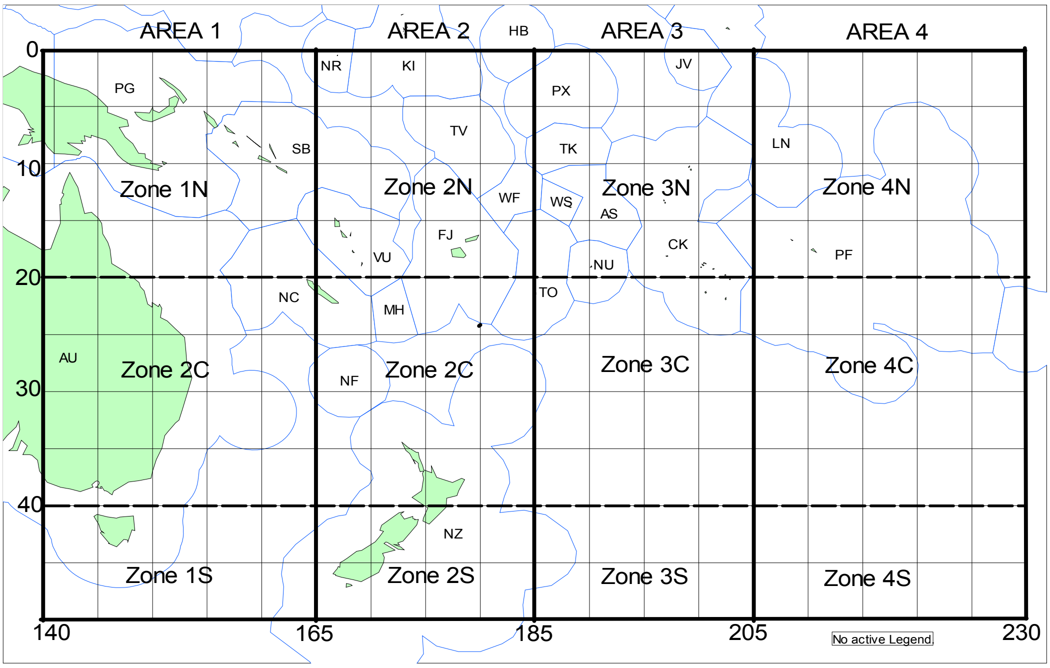


Figure 14. Swordfish assessment domain from Kolody et al. (2008b). While different spatial areas were explored, only the South-West Pacific assessment (Areas 1-2) was considered successful. In the operating model, the ETBF is defined as Area 1 and non-ETBF as Area 2.

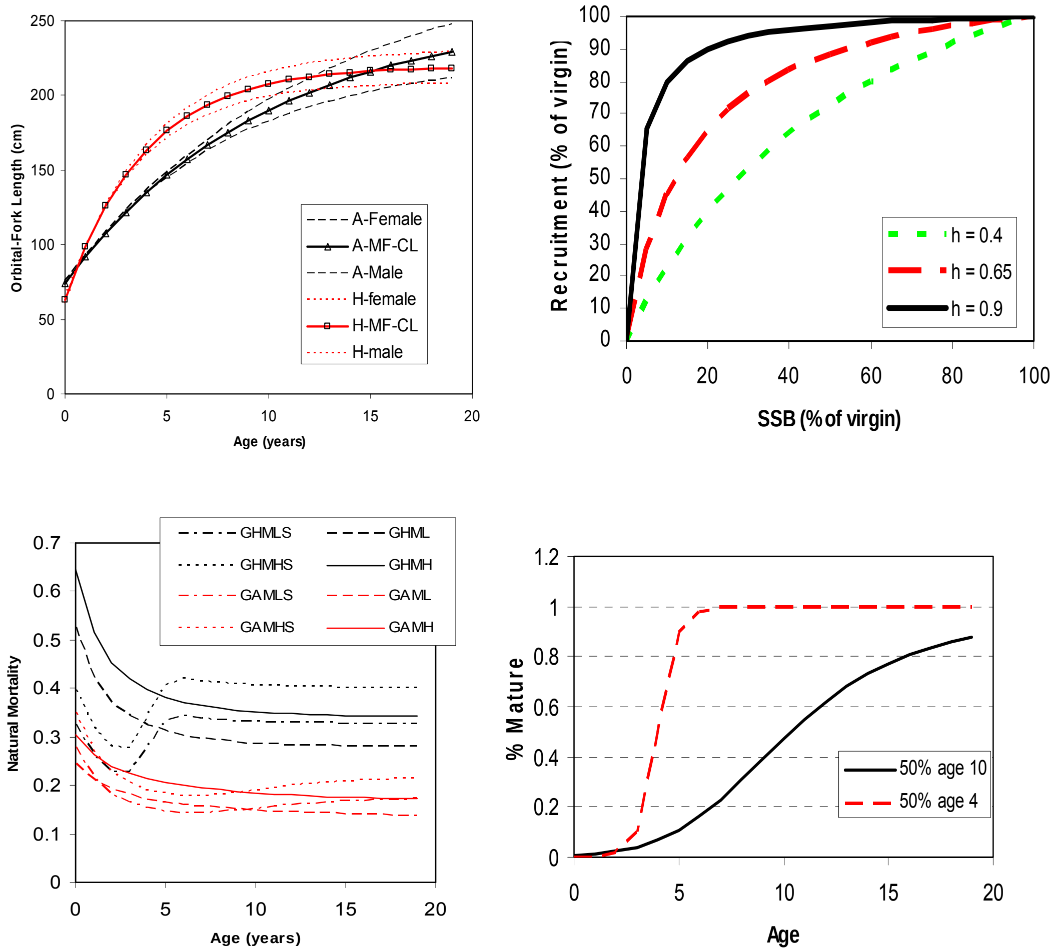


Figure 15. Illustration of some of the key uncertainties encompassed in the 192 models comprising the WCPFC swordfish assessment. Two different growth vectors were considered (A-MF-CL and H-MF-CL), in conjunction with two stock-recruitment steepness assumptions (0.65 and 0.9), eight natural mortality vectors and two maturity vectors. The details and justification for these and other assumptions are provided in Kolody et al (2008b). Not all of these assumptions are included in the 14 models that were selected for the swordfish ETBF operating model, but the most extreme combinations should be represented, as these 14 models were selected to be the most optimistic and the most pessimistic with respect to a number of key reference points (e.g. highest and lowest MSY, depletion, fishing mortality, etc.).

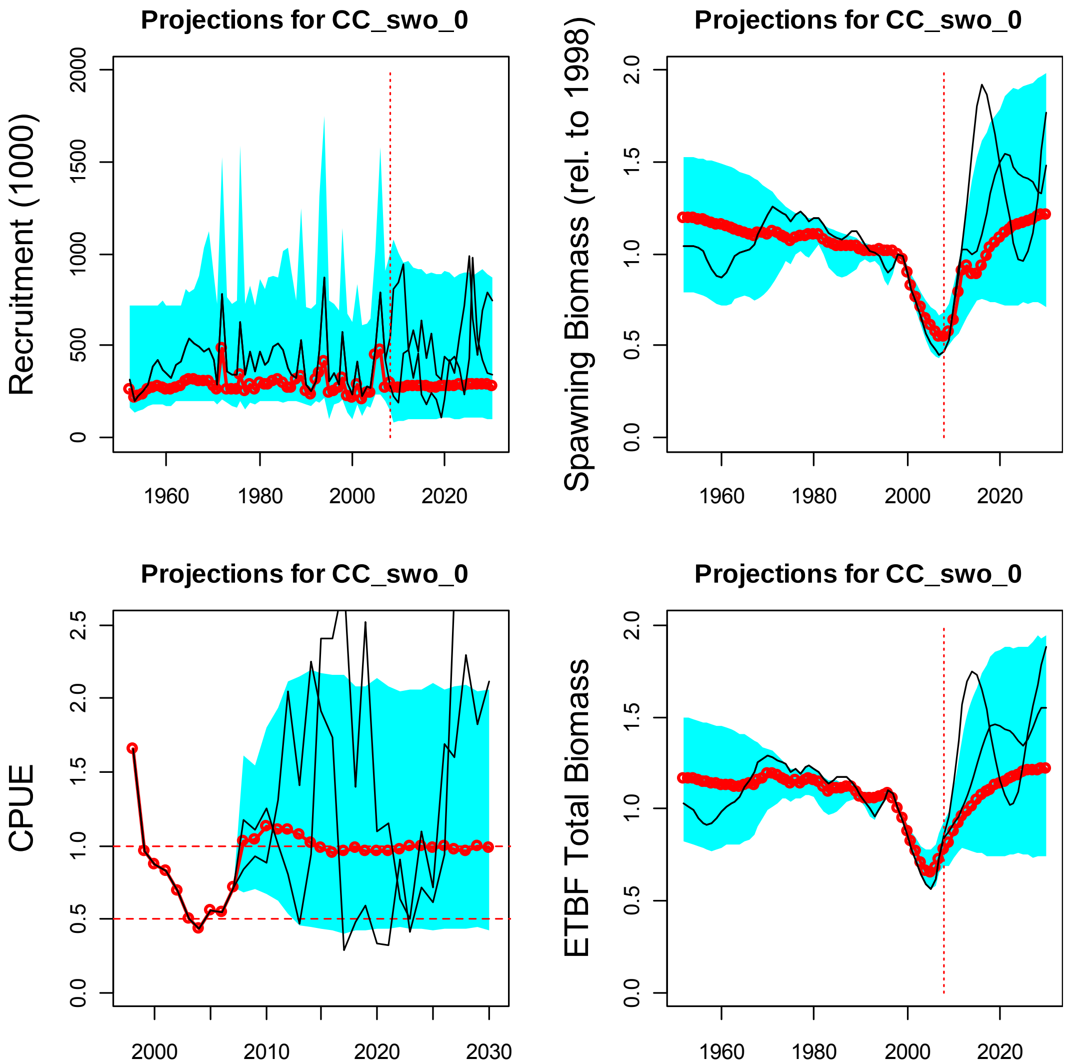


Figure 16. Swordfish operating model projections assuming that fishing ceased in the ETBF and adjacent non-ETBF fishery (Harvest Strategy (CC_swo_0). Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

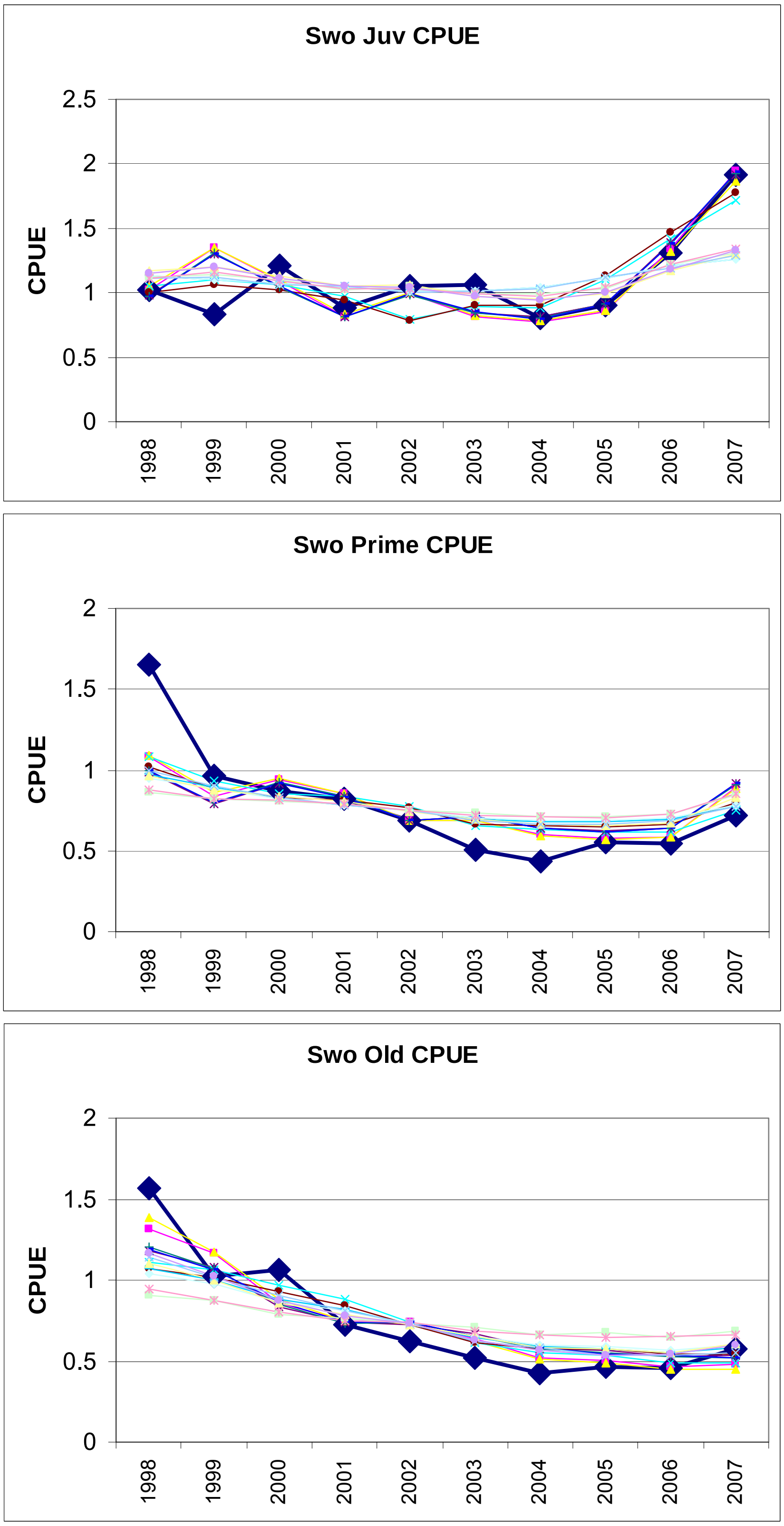


Figure 17. Swordfish comparison between predicted and observed CPUE for the Australian ETBF. Bold black lines (diamonds) are the observed standardized CPUE by juvenile, prime and old size classes; thin coloured lines are the equivalent estimates from 14 different assessment models.

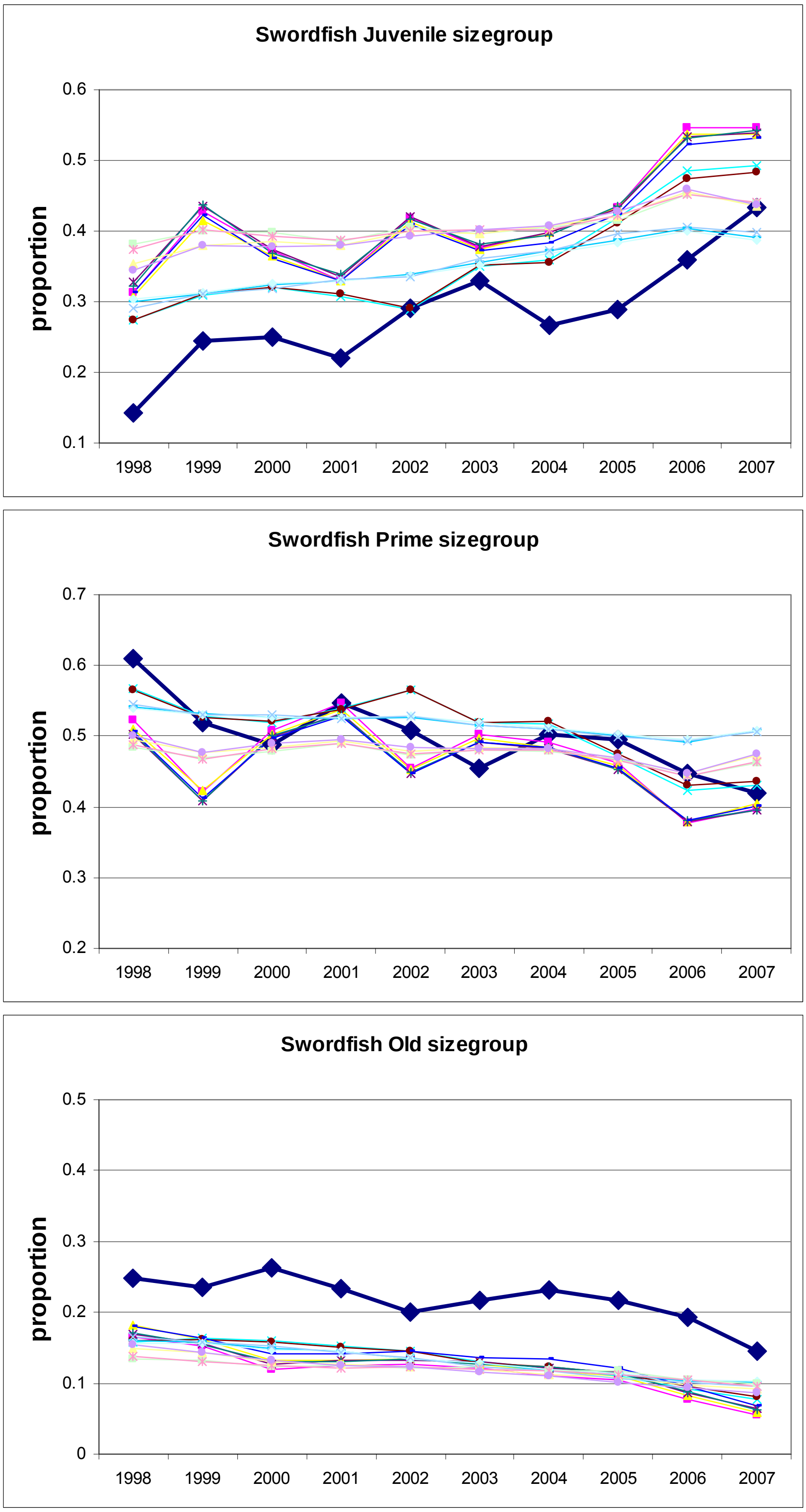


Figure 18. Swordfish comparison between predicted and observed size composition proportions for the Australian ETBF. Solid black lines (diamonds) are the observed data. Broken coloured lines are the operating model proportions (projections start in 2003).

Table 4. Robustness set – examining Recruitment variability
14*20*2*1*2*1*2*2 OMs = 4480 iterations

Dimension	option 1	option 2	option 3	Number of grid elements
	Everything in this projection set is the same as the reference set, except for the following option:			
Recruitment CV / Autocorrelation/ N(a) bias	0.6 / 0.7 / 0	0.4 / 0 / 0		2

Table 5. Robustness set – CPUE variability
14*20*1*2*2*1*2*2 OMs = 4480 iterations

Dimension	Option 1	option 2	option 3	Number of grid elements
	Everything in this projection set is the same as the reference set, except for the following option:			
CPUE CV/ autocorrelation/ Effort creep in ETBF	0.2 / 0.7 / 0	0.2 / 0 / 0		2

Table 6. Robustness set – non-ETBF effort
14*20*1*1*2*3*2*2 OMs = 6720 iterations

Dimension	Option 1	option 2	option 3	Number of grid elements
	Everything in this projection set is the same as the reference set, except for the following option:			
non-ETBF effort	= HS regulation	=linear ramp up over 5 years to 4.0*F(2006)	nonETBF Effort constant 2007 levels	3

Table 7. Robustness set – effort creep

14*20*1*2*2*1*2*2 OMs = 4480 iterations

Dimension	Option 1	option 2	option 3	Number of grid elements
	Everything in this projection set is the same as the reference set, except for the following option:			
CPUE CV/ autocorrelation/ Effort creep in ETBF	0.2 / 0.7 / 0	0.2 / 0.7 / 0.02		2

Table 8. Robustness set – low levels of error and stochastic variability

14*20*1*1*2*1*1*1 OMs = 560 iterations

Dimension	option 1	option 2	option 3	Number of grid elements
	Everything else in this projection set is the same as the reference set			
Stochastic replicates	20 – errors not conserved among models			20
Recruitment CV / Autocorrelation/ N(a) bias	0.4 / 0 / 0			1
CPUE CV/ autocorrelation/ Effort creep in ETBF	0.2 / 0. / 0			1
Equilibrium (and 2008) proportions	0.5/0.5			1
redistribution rates	20%/qtr	1%/qtr		2
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0			1
TAC implementation CV	0			1

Table 9. Robustness set – extremely low levels of stochastic variability
14*20*1*1*2*1*1*1 OMs = 560 iterations

	option 1	option 2	option 3	Number of grid elements
	Everything else in this projection set is the same as the reference set			
Stochastic replicates	20 – errors not conserved among models			20
Recruitment CV / Autocorrelation/ N(a) bias	0. / 0 / 0			1
CPUE CV/ autocorrelation/ Effort creep in ETBF	0. / 0. / 0			1
Equilibrium (and 2008) proportions	0.5/0.5			1
redistribution rates	20%/qtr	1%/qtr		2
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0			1
TAC implementation CV	0			1

Swordfish Harvest Strategy Evaluation

Reference Set

A large number of HSs were evaluated at different stages of the project, particularly for swordfish, as this was the original species under which the framework was developed. The HSs include a number of specifications that are common to all species with a jointly defined numbering system (Table 2). The species-specific size group definitions are in Table 10 (for swordfish). Most HSs were only explored in a very limited context, to see if they provided results that were different from the core set in any useful or interesting way. Only a representative subset of the full range of HSs are presented in detail here. Several additional candidate HSs are included in the Catch-CPUE and Catch-Biomass Risk trade-off plots to illustrate a broader range of options. Most of these latter HSs were judged to be of limited interest for ETBF management at this time; however, they are useful for demonstrating some of the general properties of the HSWG framework.

Figure 19, Figure 20, Figure 21 and Figure 22 illustrate the estimated ETBF catch, CPUE, spawning biomass (combined ETBF and non-ETBF), and total biomass (ETBF only) trajectories for six HSs evaluated against the reference set of operating models. These include CC_swo_0 (which illustrates what is estimated to result if the fishery was to be shut down completely), and HS_swo_21 (the HS adopted by the ETBF MAC).

CC_swo_0 (no fishing) is the only scenario in which median CPUE is maintained at the mean level observed from 1998-2002. This is not really surprising, since the stock was only lightly fished prior to that time. This suggests that the target CPUE adopted for this stock might not be economically viable because of the catch reductions required to get there. This target value is strongly influenced by the 1998 CPUE value, which was exceptionally high (for reasons that are not entirely understood, but not entirely related to very high abundance). In the adopted HS, the median CPUE is consistently below the target. Inconsistency between target and realized CPUE was typical of most harvest strategies and most species. Given that the RBC adjustment is not explicitly related to stock productivity, and the stock is initially far from any equilibrium age structure upon which the HS might be predicated, overshooting and undershooting the target CPUE would be expected (at least in the short-term). Thus it is useful to think of the actual value of the *CPUE-prime target* primarily as an adjustable parameter in the HS, that might not have a predictable relationship with the outcomes observed in the short-medium term (i.e. the timeframe that is likely to be relevant for selecting and implementing a particular HS). Some participants found this result counter-intuitive, and as a result, consultations were often presented in such a way that it was not easy to relate outcomes with input assumptions. This encouraged a focus on management performance.

At the ETBF RAG meetings, there was some confusion about the distinction between swordfish catch levels observed in the trade-off plots, and MSY as estimated in the stock assessment (which was much higher). There are two reasons why this occurs. First, the HS dynamically adjusts the catch level, with the expectation of maintaining the CPUE near a target level. The target level that was judged to be economically viable was relatively high, corresponding to a population that was considerably above

B_{MSY}, and which would on average drop to B_{MSY}, if the fishing mortality was sustained at F_{MSY}. Second, the MSY reported in the assessment was the aggregate of the domestic and international fleets.

Figure 23 illustrates the estimated relationship between Catch and CPUE for a range of Harvest Strategies, including those defined above. These figures clearly show the general features discussed in Figure 10 (i.e. median performance aligned along a continuum from more to less aggressive, with minimal deviation from this relationship). Similarly, the general features discussed in Figure 11 are evident (i.e. while it is difficult to deviate from the mean relationship, there is considerable flexibility to trade-off the catch and CPUE variability).

Figure 24 illustrates the estimated relationship between Catch and biomass risk associated with these harvest strategies. Since it is assumed that the non-ETBF effort is managed the same as the ETBF effort in these scenarios (unlike the other species), these figures do not partition the specific effect due to the ETBF fleet from those of the other fleets. The combined fishing effort among the HSs that were considered to be preferable by the ETBF RAG and MAC do demonstrate some level of conservation risk. One interpretation of the HSP might suggest that the level of risk is unacceptable. However, we emphasize that there is a lot of subjectivity in the quantification of these operating models. Figure 9 shows these same data with alternative risk measures that might look less alarming. The lower level of Figure 24 suggests that the preferred HS is near a non-linear point in the catch-risk trade-off, such that more aggressive HSs result in only moderate catch increases for large increases in risk.

Figure 25 was included to illustrate the general principle of how a feedback-based HS manages risk. Catch and biomass risk trade-off plots for three feedback-based HSs and three constant catch HSs (1000t, 1400t and 1800t) are compared. It might be argued that if one has confidence in the stock status estimates, then it should be possible to simply set a constant RBC on the basis of the stock assessment. In this case, the constant catch options of 1400t and 1800t represent a much higher risk to the spawning stock biomass than the other HSs, with many realizations resulting in a population collapse (those in which the population drops below the constant catch level)). The 1000t option represents about the same median risk as the feedback-based HSs, with a similar median catch. However, the uncertainty encompassed by the operating models indicates that the stock could be much more or less productive than the median of the distribution. The feedback-based HSs are capable of differentially exploiting the more productive scenarios, such that more than 10% of the HS_swo_0 scenarios resulted in a catch that is more than double the constant catch 1000t, with roughly the same probability of exceeding the biomass risk thresholds.

Figure 26 illustrates the variability in RBC for a range of HS's. The average annual change in the RBC is an important trade-off performance measure for industry and management who may prefer stability in RBC's.

Robustness Sets

The following section describes a series of simulation results that examine the implications of different assumptions in the operating models, and explore some of the behaviour of the HSWG decision rule framework. We have only included a subset of results toward these objectives (and most of these results are intuitively predictable). While these results shed some insight into the interaction between the HSs and operating models, they did not reveal any special insight that would assist in the selection of a swordfish HS.

The HS performance implications associated with the high and low recruitment variability assumptions (sd(log) = 0.6, rho = 0.7) and (sd(log) = 0.4, rho = 0) from Table 4, is shown in Figure 27 and Figure 28 for HS_swo_21. From these figures, it appears that the different recruitment assumptions make very little difference to the median and variance to the distribution of individual recruitment events. However, the auto-correlation effect introduces considerable variability into the corresponding biomass, catch and CPUE time series. It might be argued that the medians are not largely influenced by the recruitment auto-correlation, but even here differences are evident. Without auto-correlation, there are synchronous long time-scale oscillations in the decision rule behaviour (most obvious in the CPUE series). We chose to retain the autocorrelated recruitment assumption in the reference set of operating models, because it represents an important element of uncertainty that is often under-estimated or ignored in fisheries models (e.g. an unexpected series of low recruitments caused an important delay to the adoption of the SBT Management Procedure as described in Kolody et al. 2008a). Depending on how one chooses to quantify risk, it is recognized that the quantification of recruitment variability may have an important effect on the results.

The HS performance implications associated with the CPUE observation error assumptions (sd(log) = 0.2, rho = 0.7 and sd(log) = 0.2, rho = 0) from Table 5, is shown in Figure 29 and Figure 30 for HS_swo_21. The difference in scenario behaviour is subtle, but not trivial. The variance is similar in all of the time series shown, however, there is a temporal structure to the behaviour. The scenario without autocorrelation suggests a long periodicity oscillation that is not evident in the scenario with autocorrelation (most evident in the CPUE series). In fact, similar long periodicity oscillations are evident in the other scenarios as well, but the autocorrelated CPUE errors makes the oscillations more asynchronous, therefore smoothing the median and 10^{th} and 90^{th} percentiles. This difference could be important if a single year was used as a reference point in HS selection, but is probably not critical if a broad range of performance characteristics are used. We considered the scenario with autocorrelation to be the more important one to include in the reference set operating model.

Figure 31 - Figure 35 illustrate some of the interactions between migration rates and non-ETBF effort scenarios on the performance of the preferred HS (HS_swo_21). Figure 31 and Figure 32 illustrate the implications of the two different migration rate assumptions in the reference set. Qualitatively, the difference between the two scenarios appears trivial. Figure 33 and Figure 34 illustrate the implications of alternative non-ETBF effort scenarios. There are some important differences between the results of non-ETBF effort held constant and regulated according to the ETBF HS. This is manifested most obviously in the time series structure of the CPUE series

(though long-term average performance is probably not alarmingly different). If there are large increases in non-ETBF effort, it is not surprising that there is an adverse impact on the performance of the ETBF fishery. Figure 35 illustrates the interactions between the migration rates and non-ETBF effort assumptions. As would be expected, large increases in the non-ETBF effort have more of an impact when there is a stronger migration linkage.

HSWG incorporated the size-based indices into the decision tree with the intention of providing an additional measure of stock status that was independent of the CPUE-based relative abundance indices, and which would ideally resolve potential stock status ambiguities which could result from the use of a single index. The following figures illustrate that it was difficult to identify much benefit associated with the lower levels of the decision tree.

Figure 37 and Figure 38 illustrate the differences in HS performance that result from the effort creep scenario (Table 7). The performance of HS_swo_21 suggests that (undetected) effort creep of 2% per year would have a trivial effect over the first few years, and an increasingly strong effect over time. Median CPUE tends to be higher in the last few years, and the HS tends to recommend higher catches than if effort creep was absent. This is intuitively what would be expected (unless the effort creep was sufficient to cause a stock collapse). However, the HS tends to produce oscillating RBC recommendations which vary in amplitude and periodicity, such that the specific cycling that arises might not be intuitive.

In Figure 39, HS_swo_21 is compared with HS_swo_31, a very similar rule that has a slightly more conservative *CPUE-prime target* (1.2 instead of 1.0) and does not use the size-based elements of the HS decision tree (i.e. it only uses the *CPUE-prime target* portion of the HSWG framework). The performance of the two rules is virtually identical in all cases. This suggests that i) effort creep of 2% per year does not have much effect on the average HS behaviour over the time frame examined, and ii) the decision tree does not add very much to the HS performance over the *CPUE-prime target* rule alone. This latter point is examined further below.

There was some speculation that the uncertainty in the swordfish reference set operating model might exaggerate the real uncertainty associated with stochastic processes and observations, which could adversely impact the expected performance of the size-based indices in the decision tree. In the interest of trying to identify situations in which the decision tree has a quantifiable benefit, we tested some additional operating models, in which various sources of uncertainty were greatly reduced or eliminated. Table 8 describes a set of operating model in which a modest level of recruitment variation and CPUE observation error are retained, but potentially troublesome time series structures in recruitment, CPUE and size composition sampling were not present, and there was no RBC implementation error. Table 9 describes a set of operating models in which most of the stochastic process and observation errors were removed (no recruitment deviations, no systematic biases in the size composition sampling, no CPUE observation errors, no RBC implementation error). The performance of these 3 sets of operating models is compared in Figure 40 and Figure 41 for 6 HSs. Three of the HSs have the same *CPUE-prime target*, but differ in the values of the size-based indices and response levels used in the lower levels of the HS decision tree. The other three HSs differ in the *CPUE-prime target*, and do not use the decision tree at all.

As would be expected, reduced uncertainty in the operating models leads to reduced variability in the HS outcomes and lower risk of exceeding the biomass risk criteria. However, the catch-CPUE-biomass trade-off relationships also appear to be very consistent across medians, lower 10th and upper 90th percentiles. The HSs with the decision tree are interleaved among the HSs without the decision tree in the trade-off plots. This strongly suggests that the decision tree really does not introduce any special behaviour to the performance of the HS, and that all of the extra complexity is functionally equivalent to what can be achieved by simply adjusting the *CPUE-prime target*. The above result may seem counter-intuitive, in that one can trace individual trajectories and see that the decision tree makes sensible adjustments to some individual realizations. However, the net gain on these individual realizations seems to be offset by worse performance from other realizations. While we cannot find evidence to suggest that the decision tree adds anything to the *CPUE-prime target* level of the decision rule on its own, there also does not seem to be any adverse effect of retaining it. While this seems to be a general feature of the HS combinations that we have examined to date, we cannot conclude that the decision tree is never useful. This is discussed further in the subsequent section: *General Comments on the HSWG framework*.

Swordfish MSE Conclusions:

- We have the most confidence in the swordfish operating model because the assessment was developed with the MSE project in mind: the spatial representation partitions conveniently into ETBF and non-ETBF regions, there are good reasons for thinking that the assessment population is reasonably discrete from northern and eastern populations, and there was a concerted effort to quantify several important sources of assessment uncertainty.
- It is estimated that the ETBF potentially has a considerable impact on the SW Pacific swordfish population relative to the other fleets, and the HS adopted by the RAG/MAC seems to have a reasonable capacity to manage the uncertainty in the stock dynamics, and produce a reasonable management outcome in the short-medium term.
- However, the HS does show some performance sensitivity to population connectivity, the effects of the non-ETBF fleet, and biases in the CPUE series (under the simulation conditions, the use of size-based indices in the decision rule did not show any evidence of mitigating the effects of effort creep).

Table 10. Swordfish - specific cut-off weights for the definition of juvenile, prime and old sized fish. Includes length to processed weight parameters, and processed weight to whole weight conversion factors used (Campbell, 2008a,b, pers comm.)

Swordfish	
Upper cut-off weight for juvenile size group	30
Lower cut-off weight for Old size group	100
Processed weight to whole weight conversion factor	1.38
Length to processed weight parameters (pwt=a*len^b)	a= 0.000000762 b= 3.49

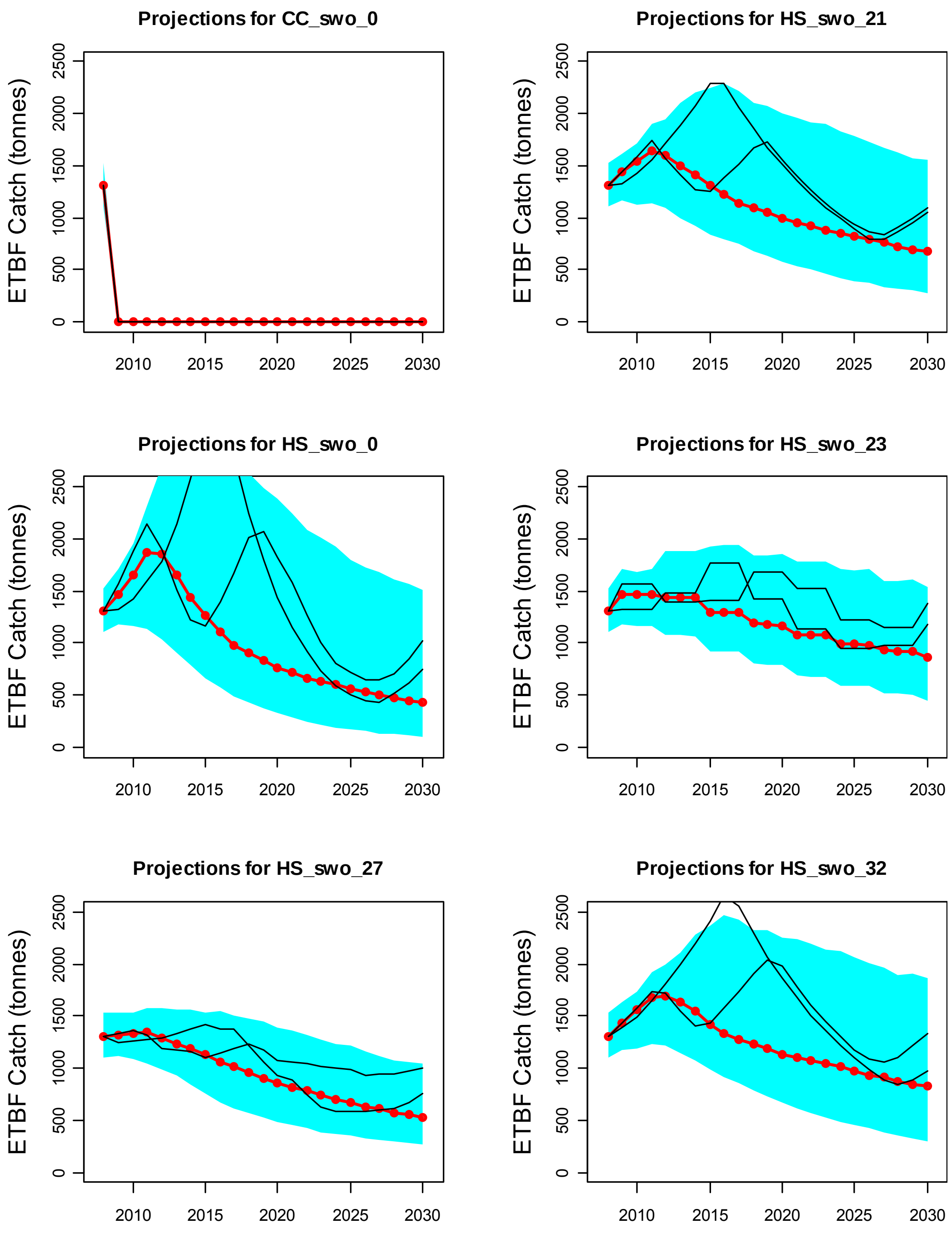


Figure 19. Swordfish estimated catch trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

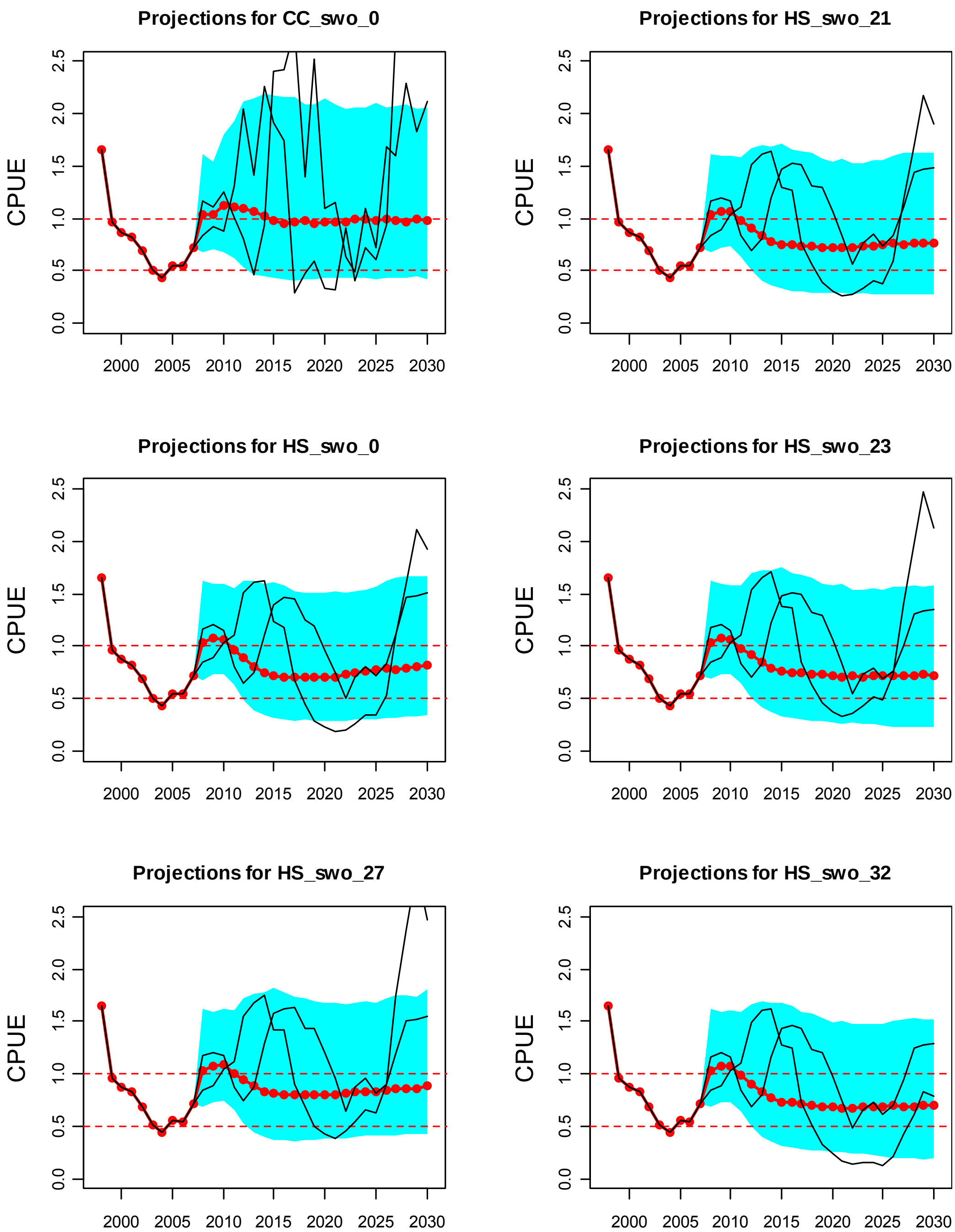


Figure 20. Swordfish estimated CPUE trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

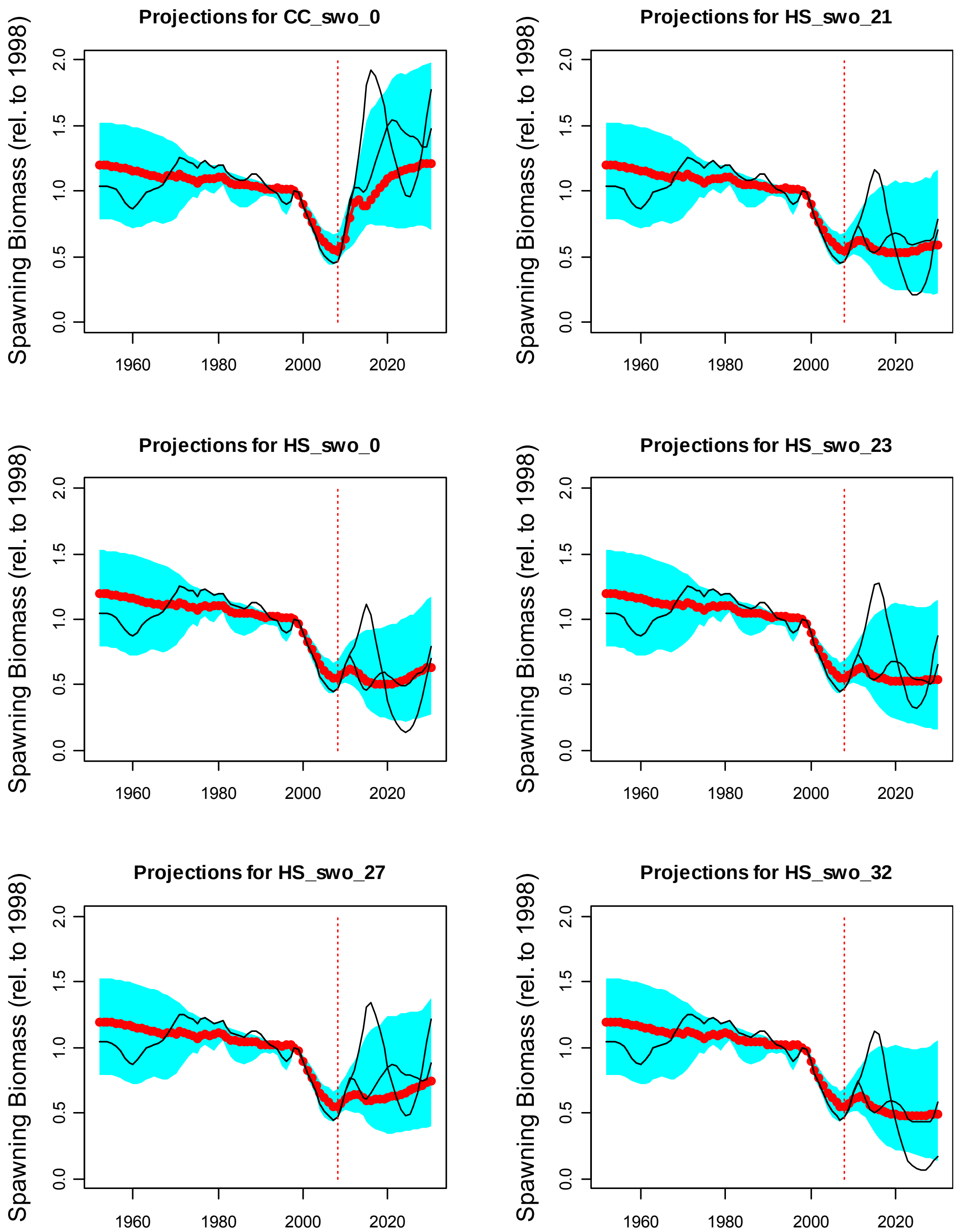


Figure 21. Swordfish estimated spawning biomass trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

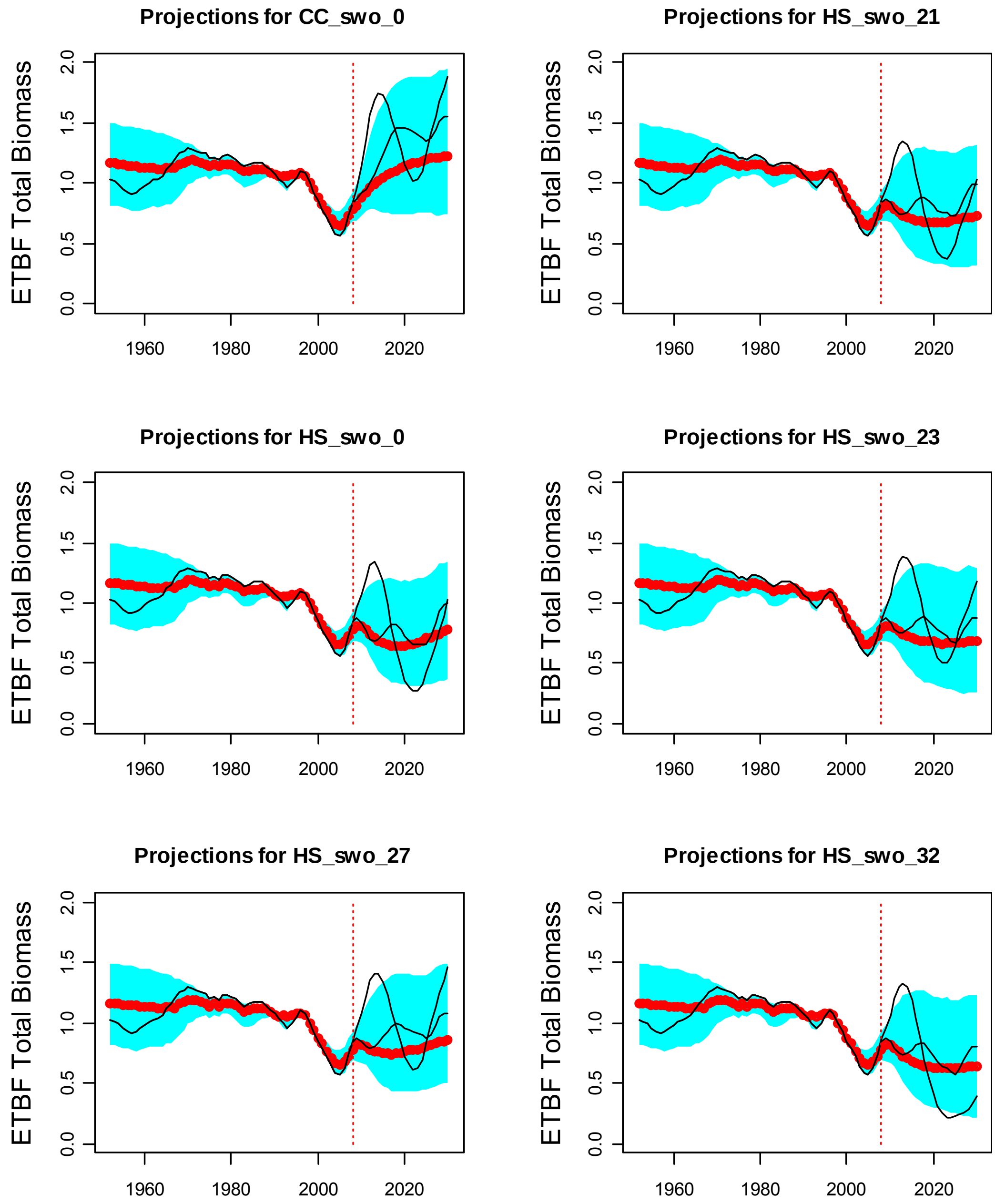
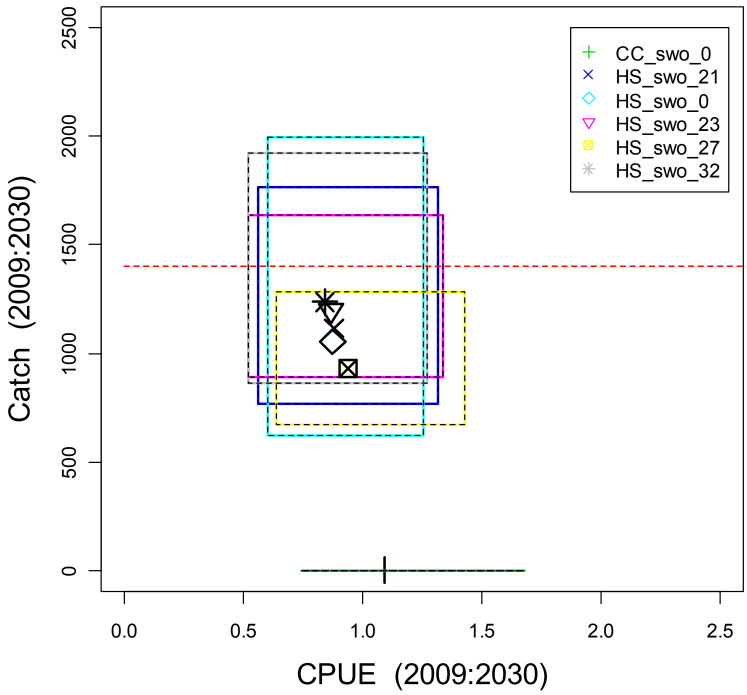


Figure 22. Swordfish total biomass trajectories (all ages; ETBF region only) for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.



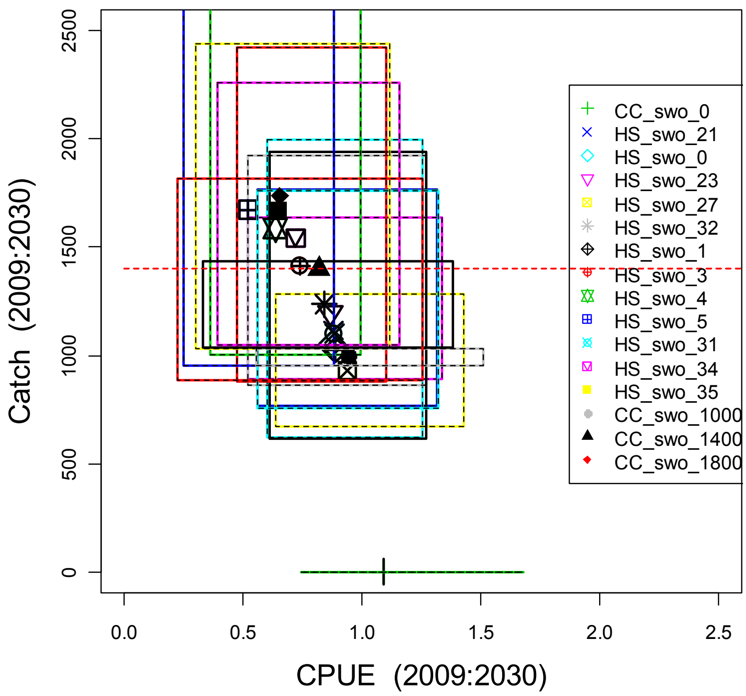


Figure 23. Swordfish trade-off plot illustrating the estimated relationship between Catch and CPUE for a range of Harvest Strategies. Symbols represent the median performance (averaged over time) for all realizations; boxes bound the 10th-90th percentile region in both dimensions. Unlike the other species, the swordfish plots are partitioned into time periods 2009-2018 and 2019-2030.

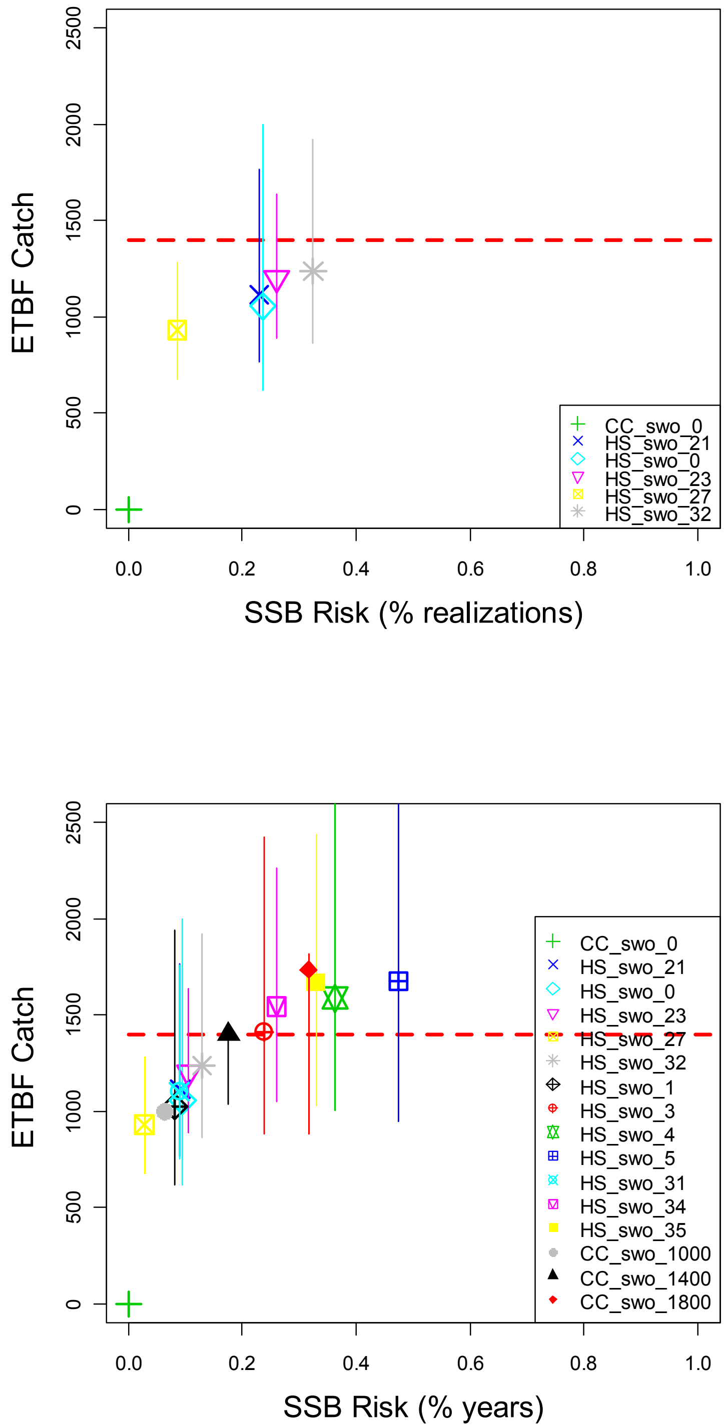


Figure 24. Swordfish trade-off plot illustrating the estimated relationship between catch and biomass risk. Risk is defined as the proportion of stochastic projections in which spawning biomass (SSB) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Horizontal reference line is 1400 t (interim catch limit).

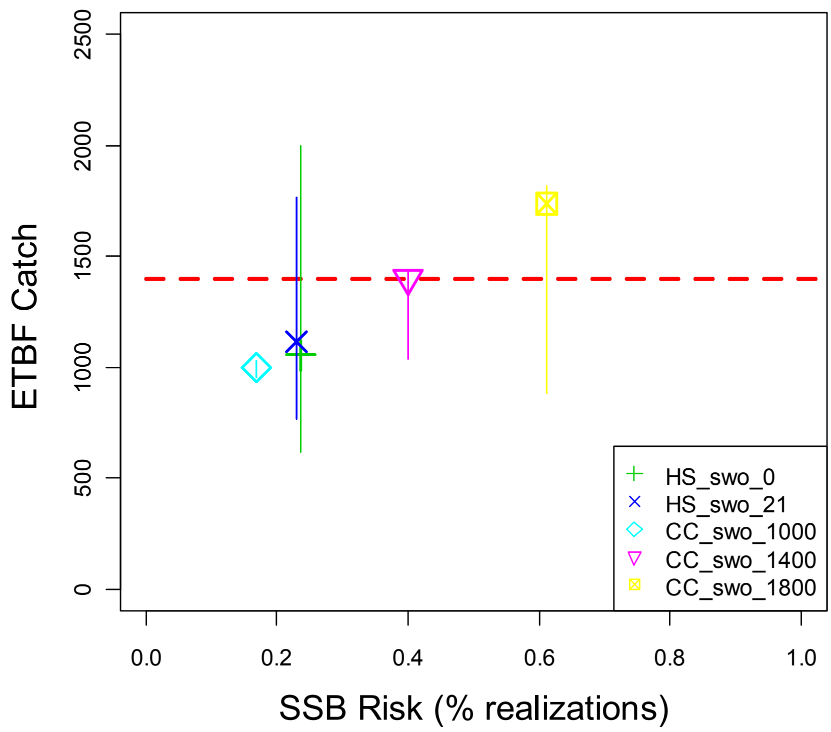


Figure 25. Swordfish catch and biomass risk trade-off plot illustrating the general advantage of a feedback-based Harvest Strategy over a constant catch strategy. Risk is defined as the proportion of stochastic projections in which spawning biomass (SSB) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Horizontal reference line is 1400 t (interim catch limit). If (for purposes of illustration) the SSB Risk level of 0.25 was considered acceptable, the Harvest Strategies are able to differentially exploit different levels of productivity and could potentially take more than double the catches realized under the constant catch scenario.

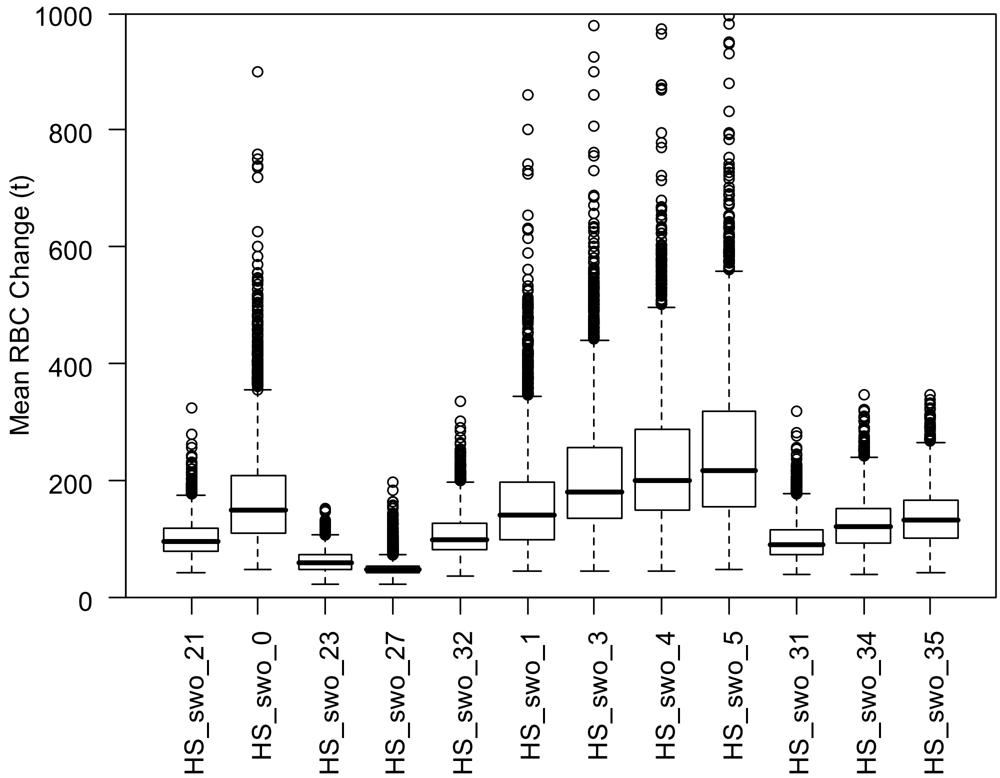


Figure 26. Reference Set swordfish RBC variability statistics for a range of Harvest Strategies. Boxplots represent the distribution of the average absolute value of the change in RBC associated with each HS (i.e. each observation within a boxplot represents the mean value from a single stochastic realization). The dark line represents the median of the distribution, the box represents the 25th-75th percentiles, whiskers represent the range or 1.5 of the interquartile distance (whichever is smaller), and circles represent outliers that exceed the whiskers.

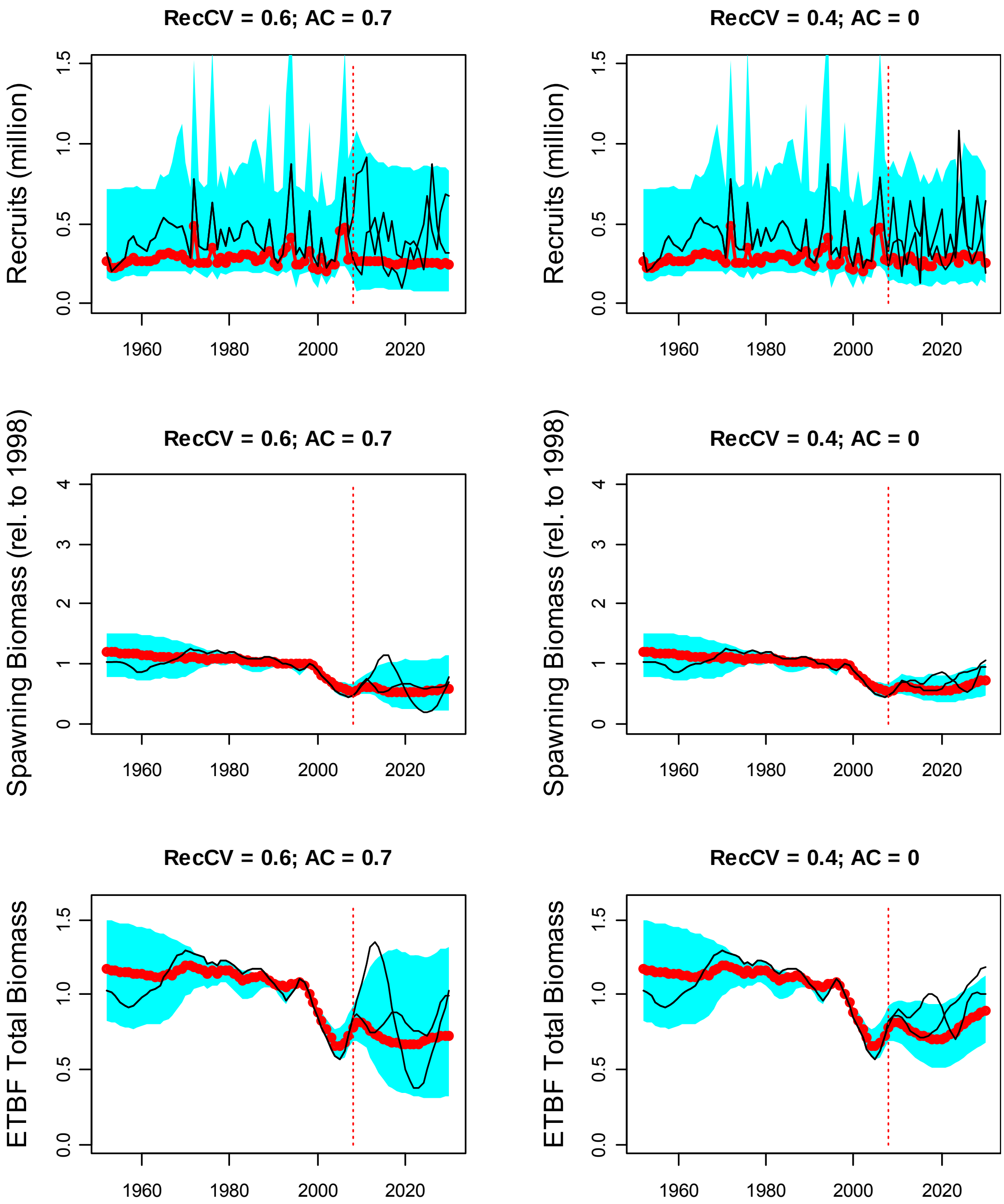


Figure 27. Implications of alternative recruitment variability assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

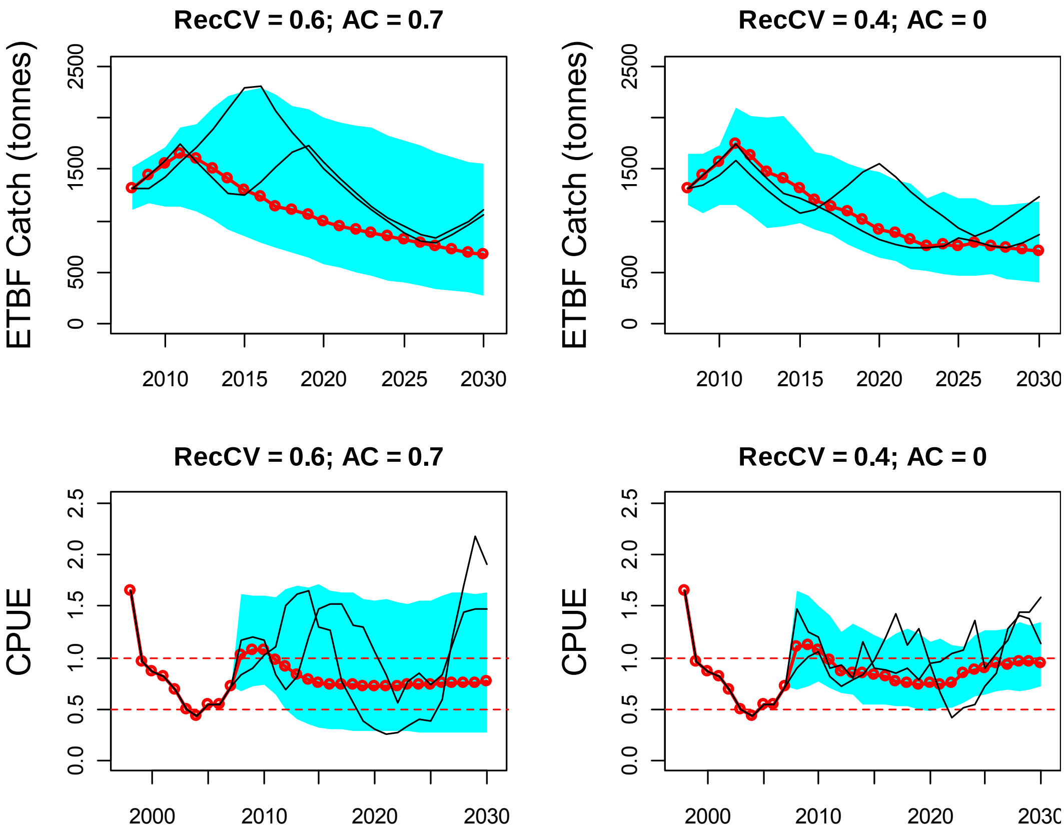


Figure 28. Implications of alternative recruitment variability assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

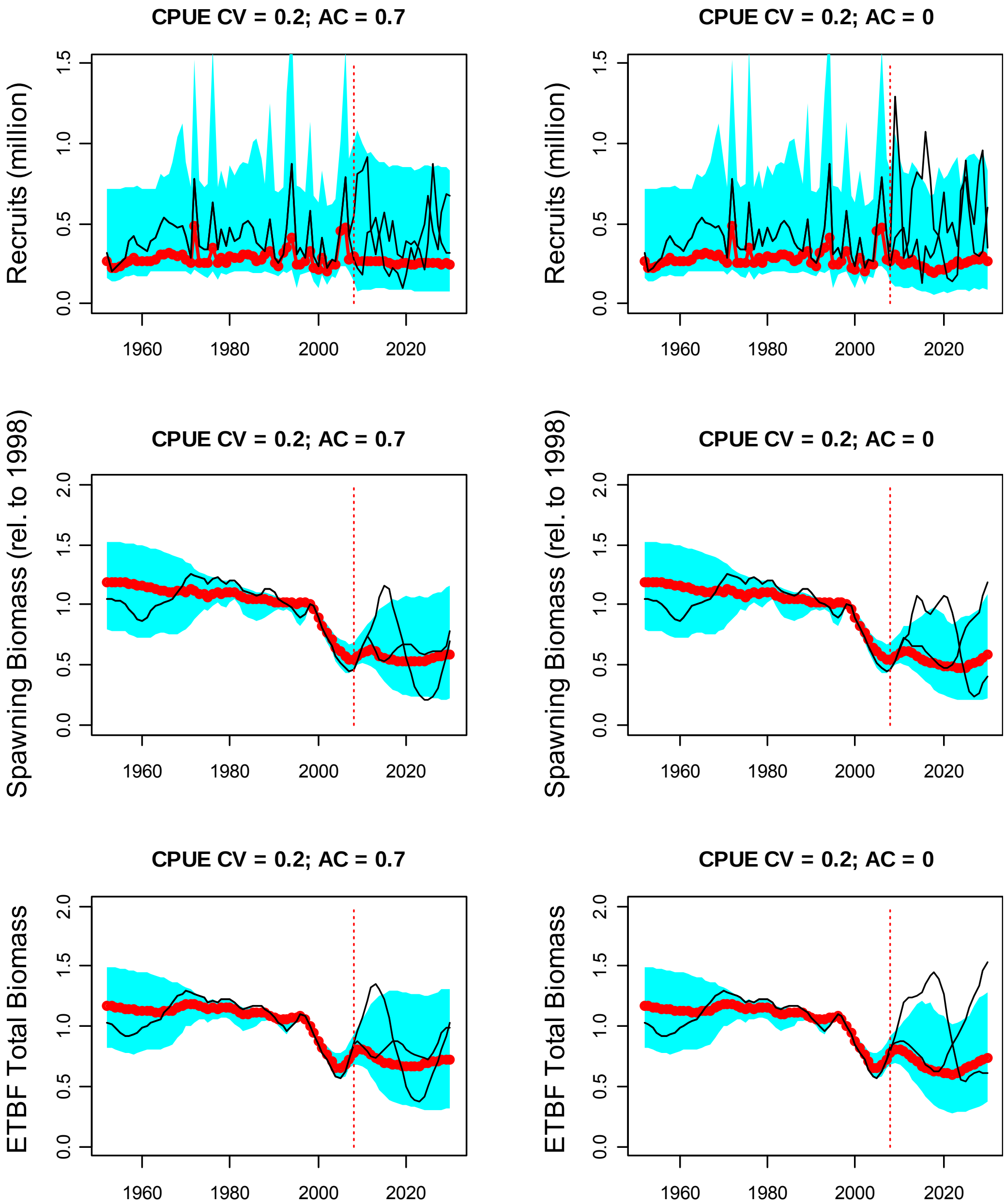


Figure 29. Implications of alternative CPUE variability assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

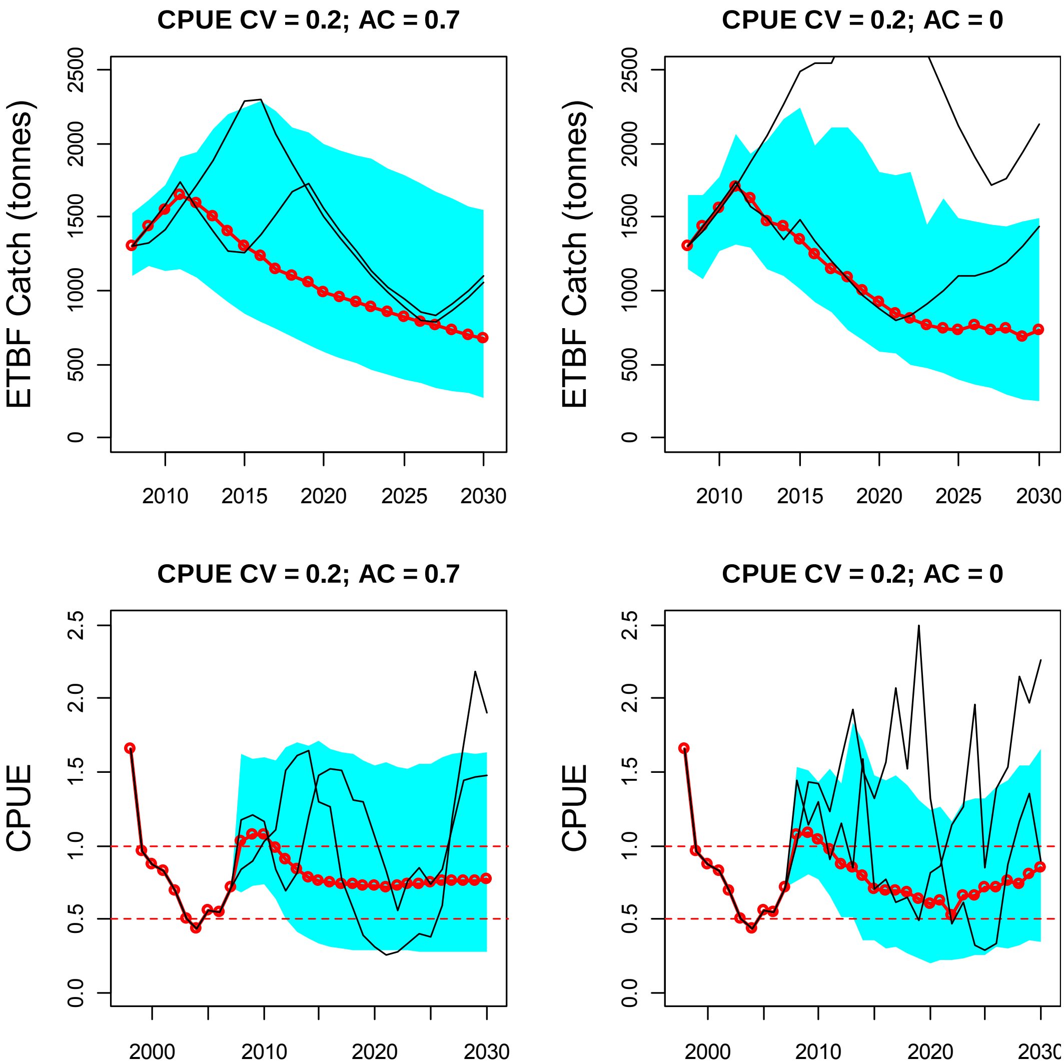


Figure 30. Implications of alternative CPUE variability assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

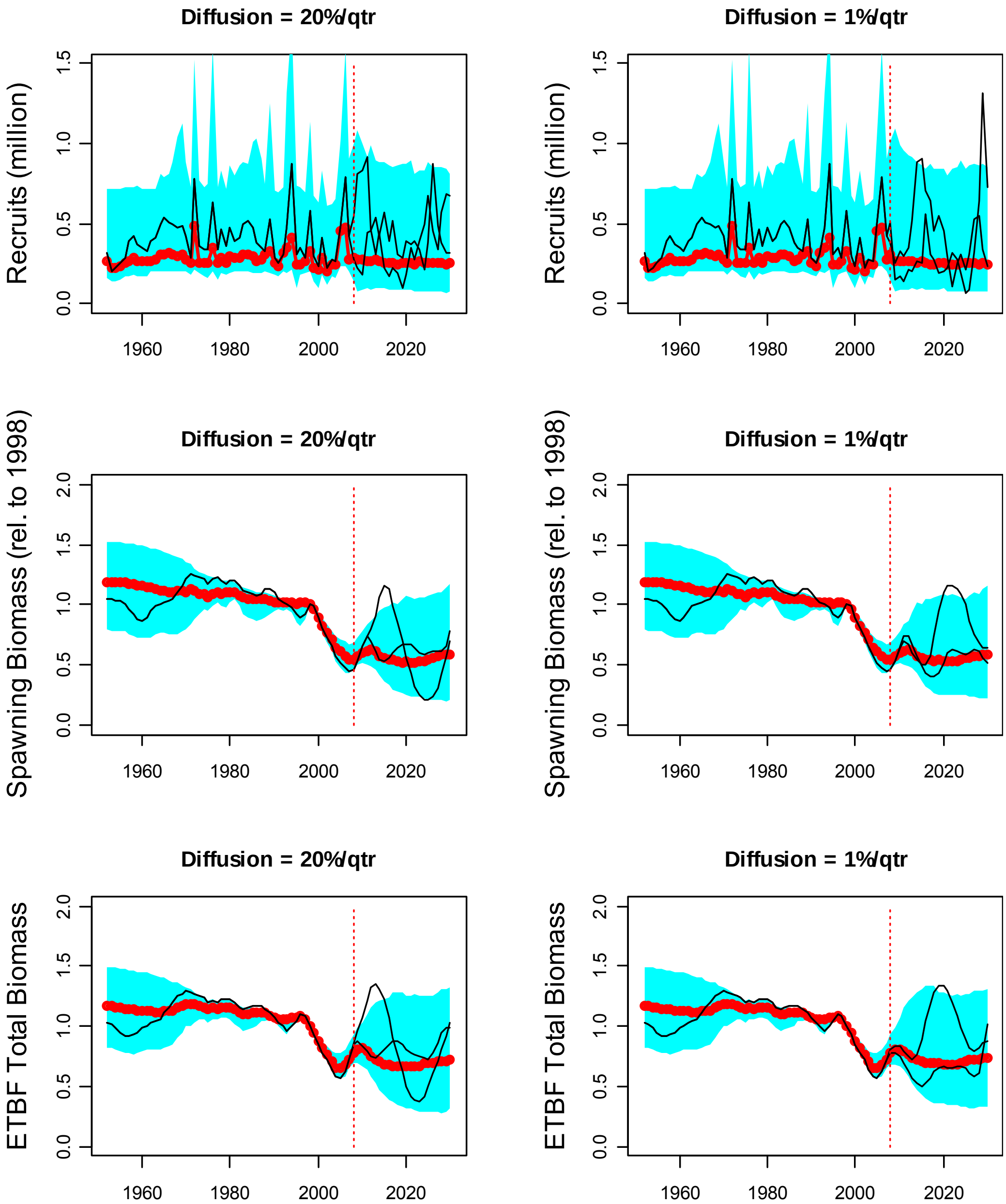


Figure 31. Implications of alternative migration rate assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

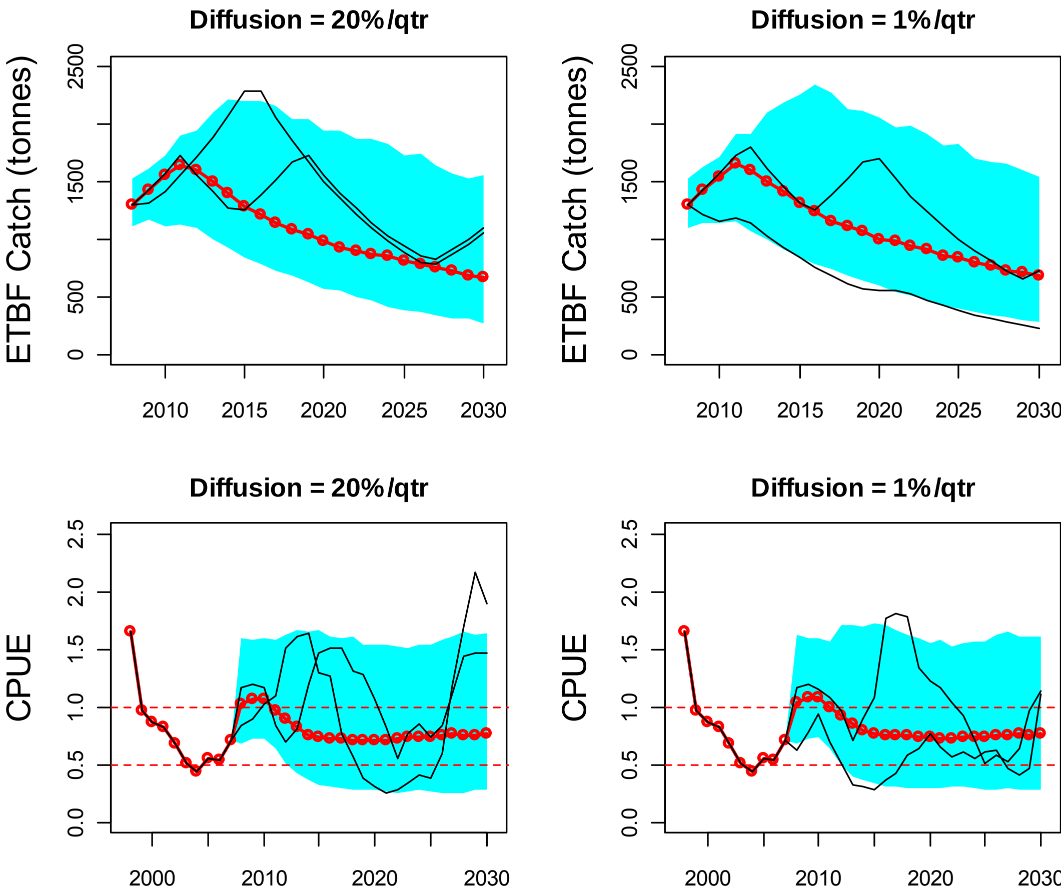


Figure 32. Implications of alternative migration rate assumptions to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

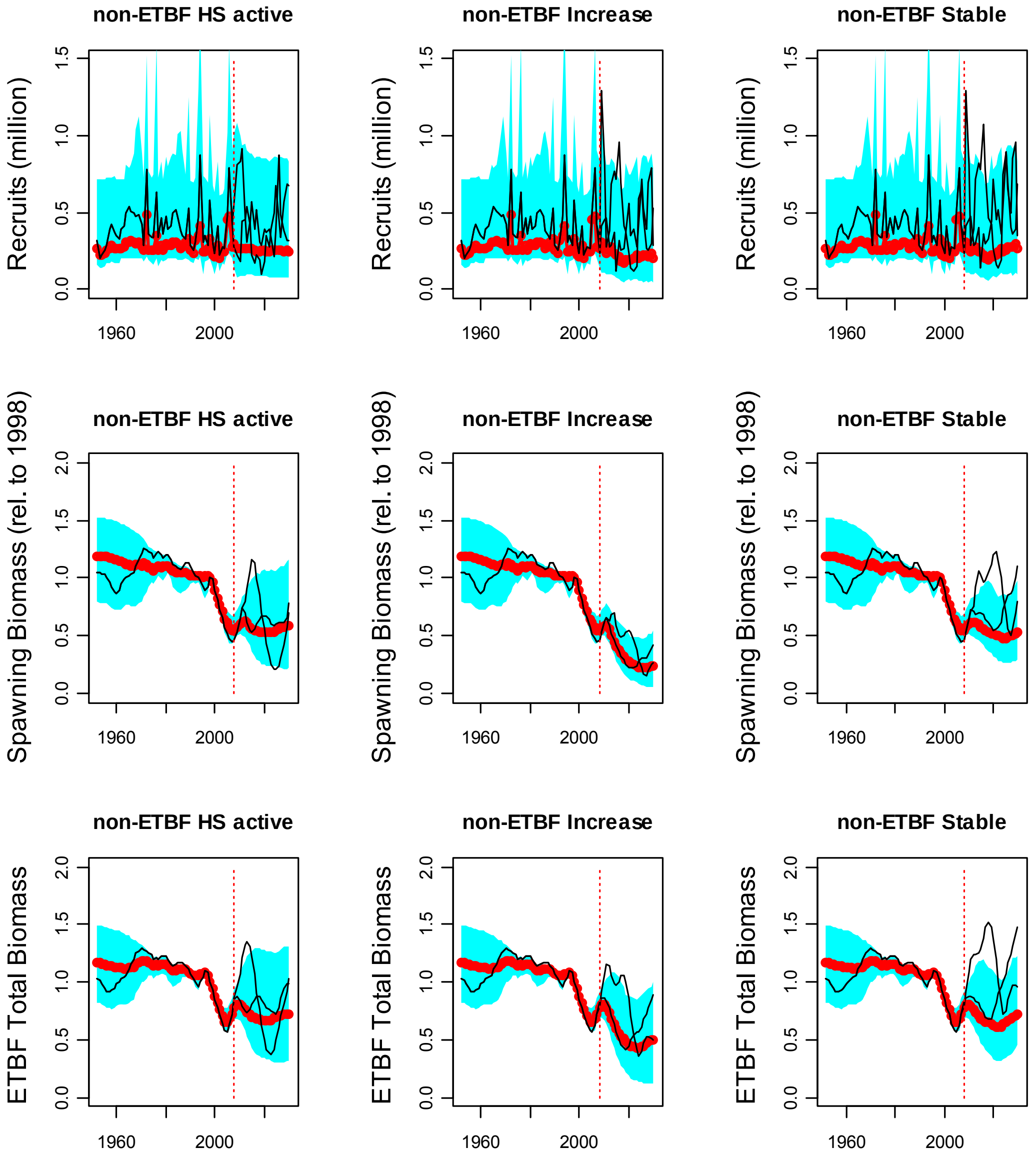


Figure 33. Implications of alternative non-ETBF effort scenarios to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

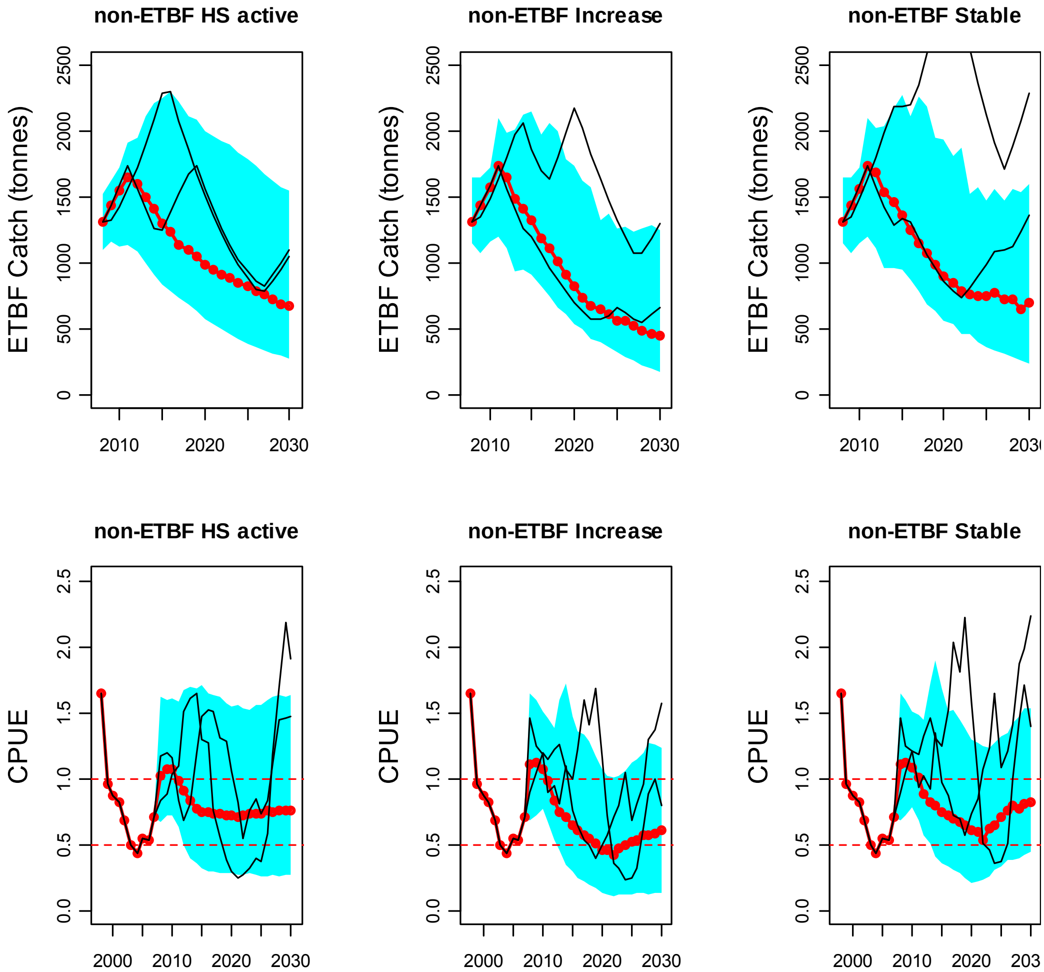


Figure 34. Implications of alternative non-ETBF effort scenarios to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

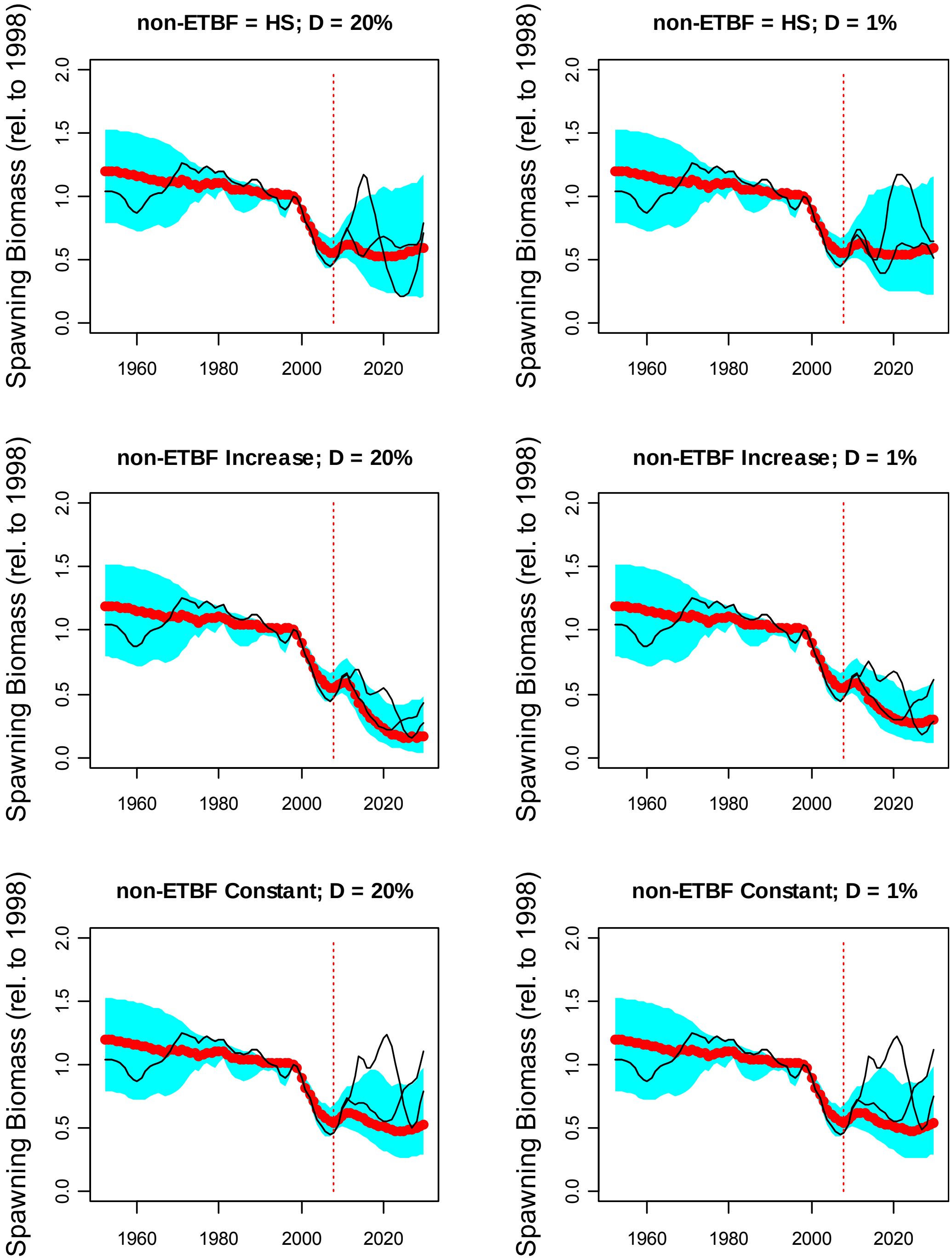


Figure 35. Implications of alternative migration rate assumptions (diffusion D =1% or 20% per quarter) combined with alternative non-ETBF effort assumptions (HS = regulated in proportion to the ETBF, Increase = 4-fold increase, Constant = 2007 level).

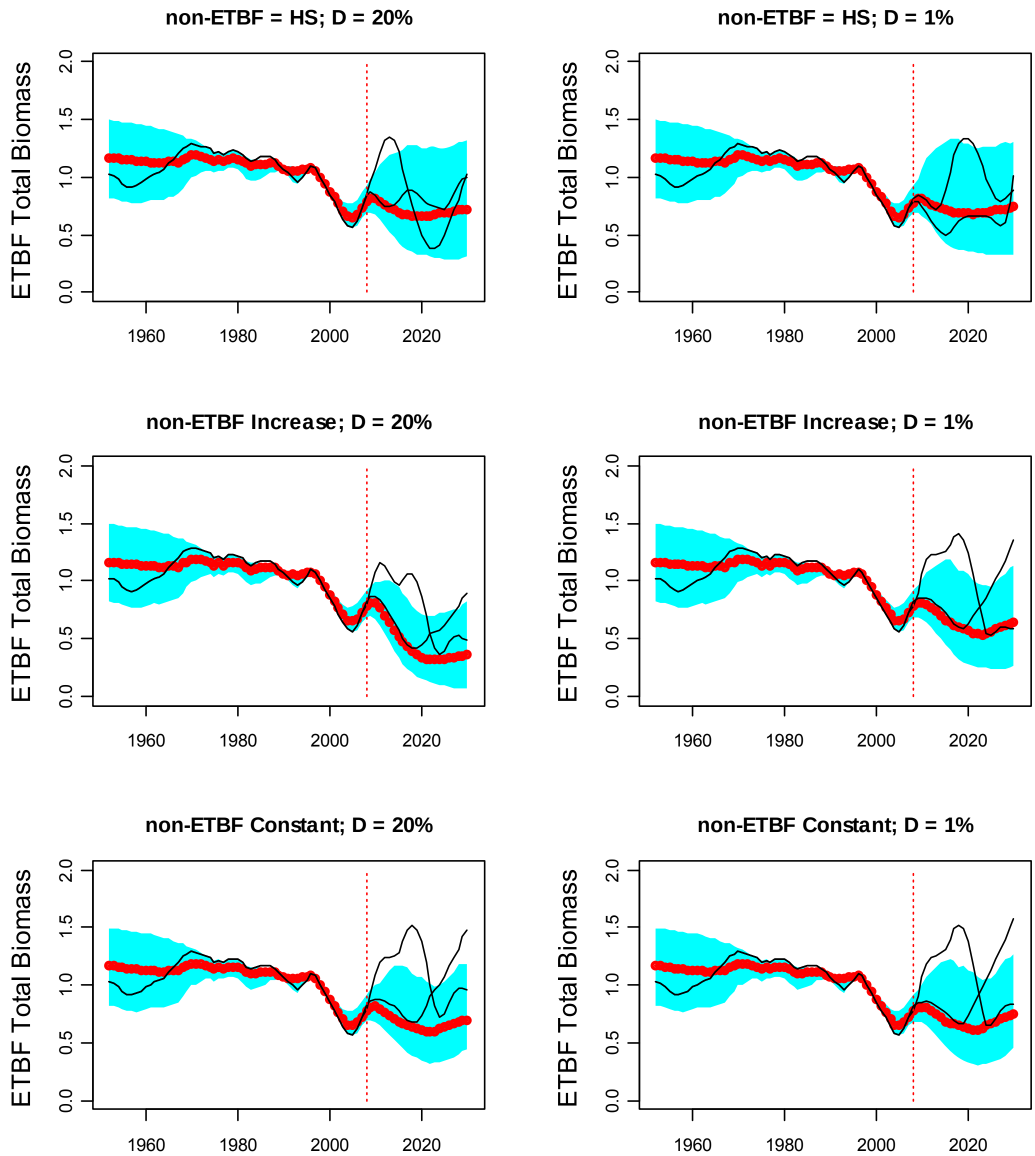


Figure 36. Total biomass (all ages; ETBF region only) implications of alternative migration rate assumptions (diffusion D =1% or 20% per quarter) combined with alternative non-ETBF effort assumptions (HS = regulated in proportion to the ETBF, Increase = 4-fold increase, Constant = 2007 level).

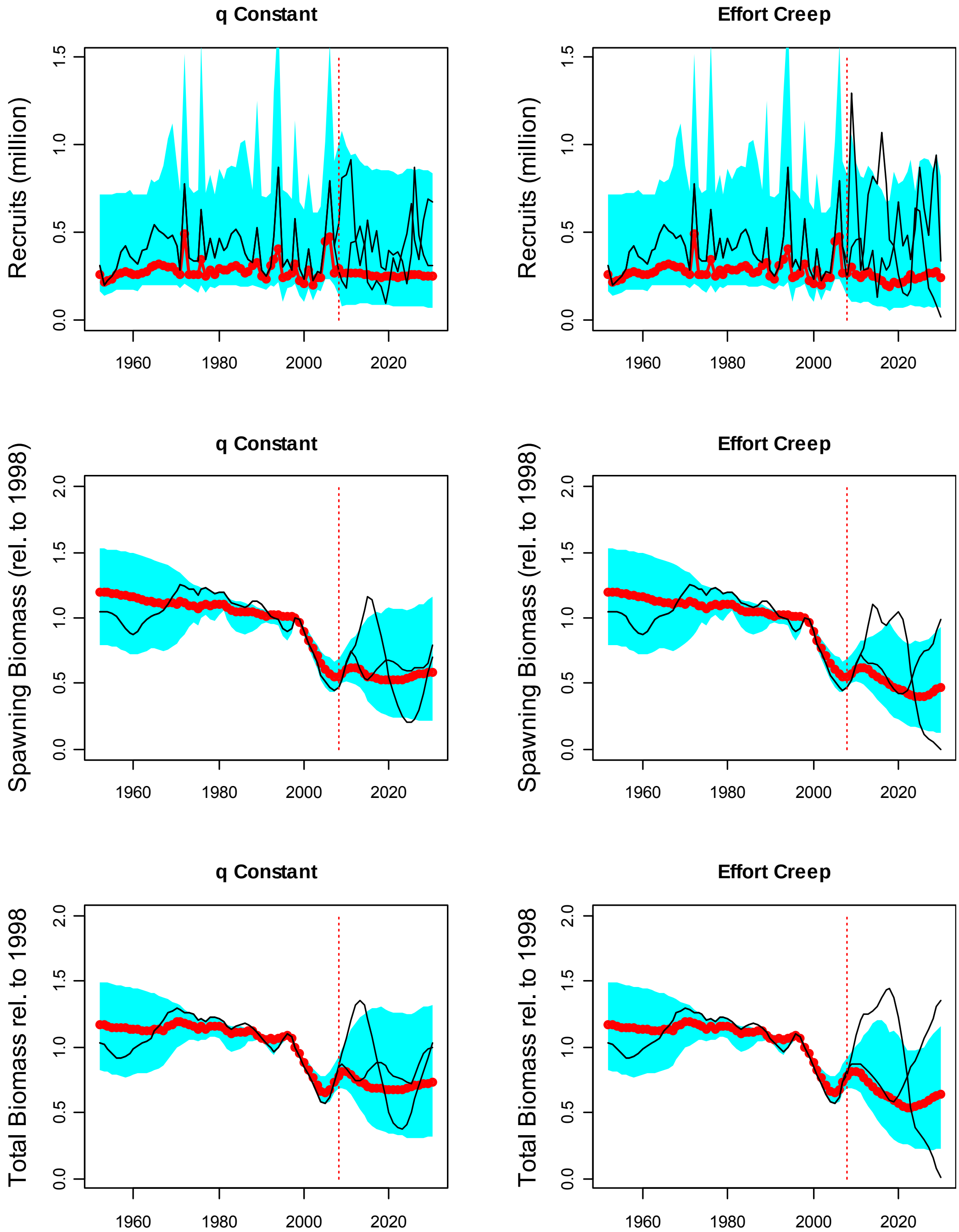


Figure 37. Implications of alternative ETBF effort scenarios to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

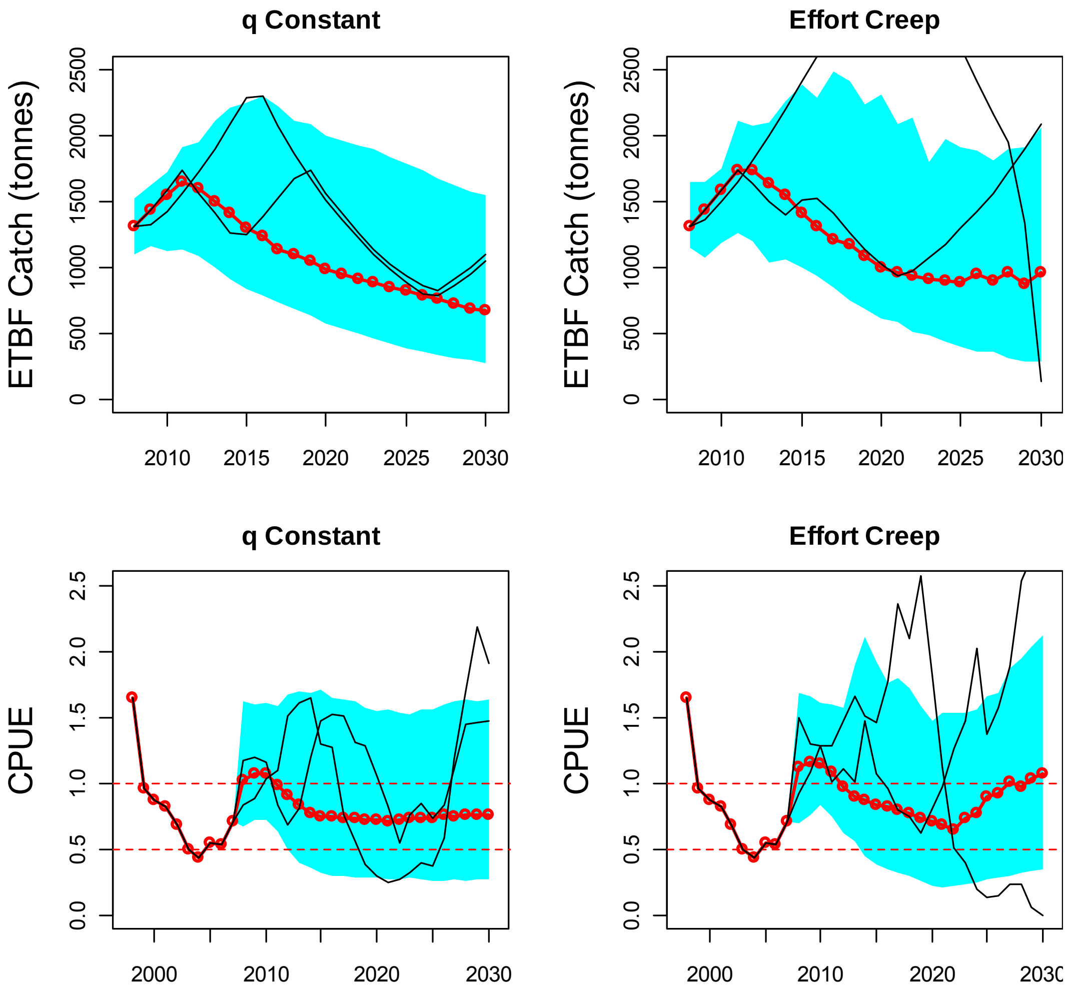


Figure 38. Implications of alternative ETBF effort scenarios to the dynamics of the swordfish operating model when HS_swo_21 was evaluated.

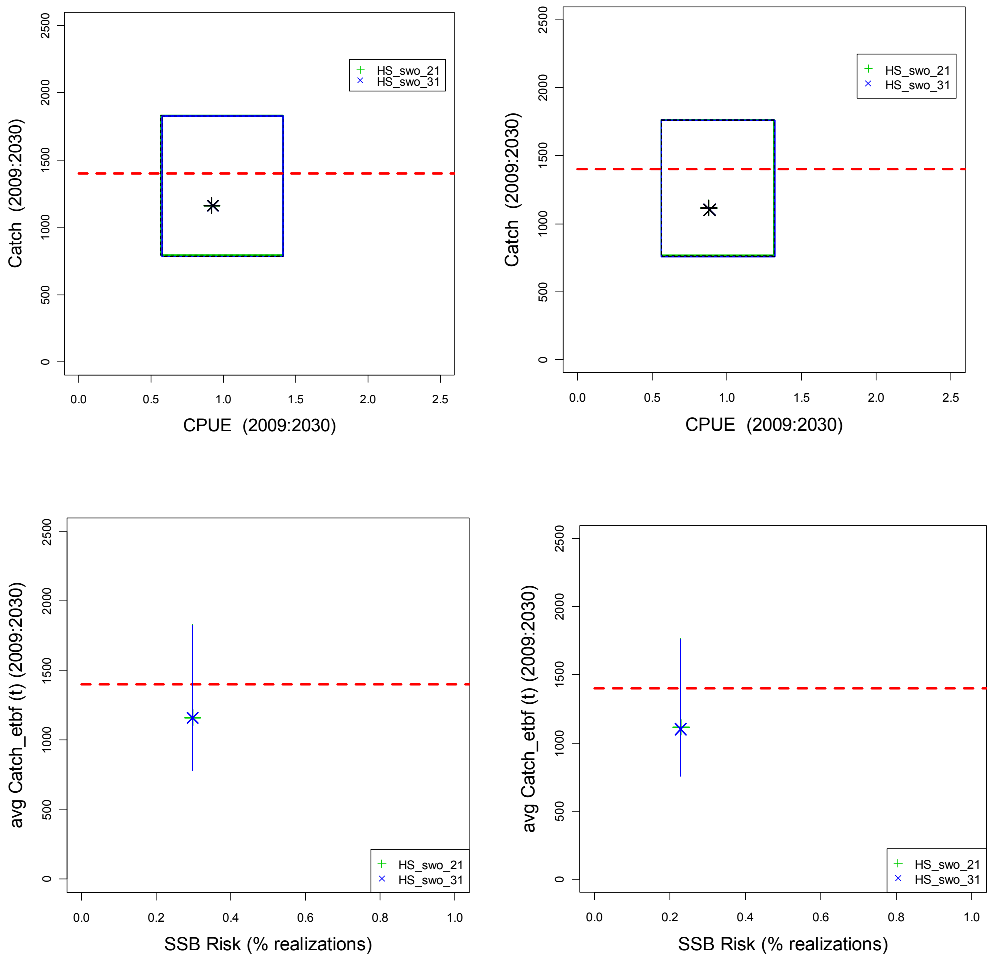


Figure 39. Comparison of two swordfish harvest strategies evaluated against the effort creep operating model scenario (left panels) and the reference set (right panels). HS_swo_21 includes all elements of the size-based indices in the HSWG decision tree, and the other includes only the *CPUE-prime target* portion of the decision rule (HS_swo_31). The performance is almost identical for both harvest strategies under both situations.

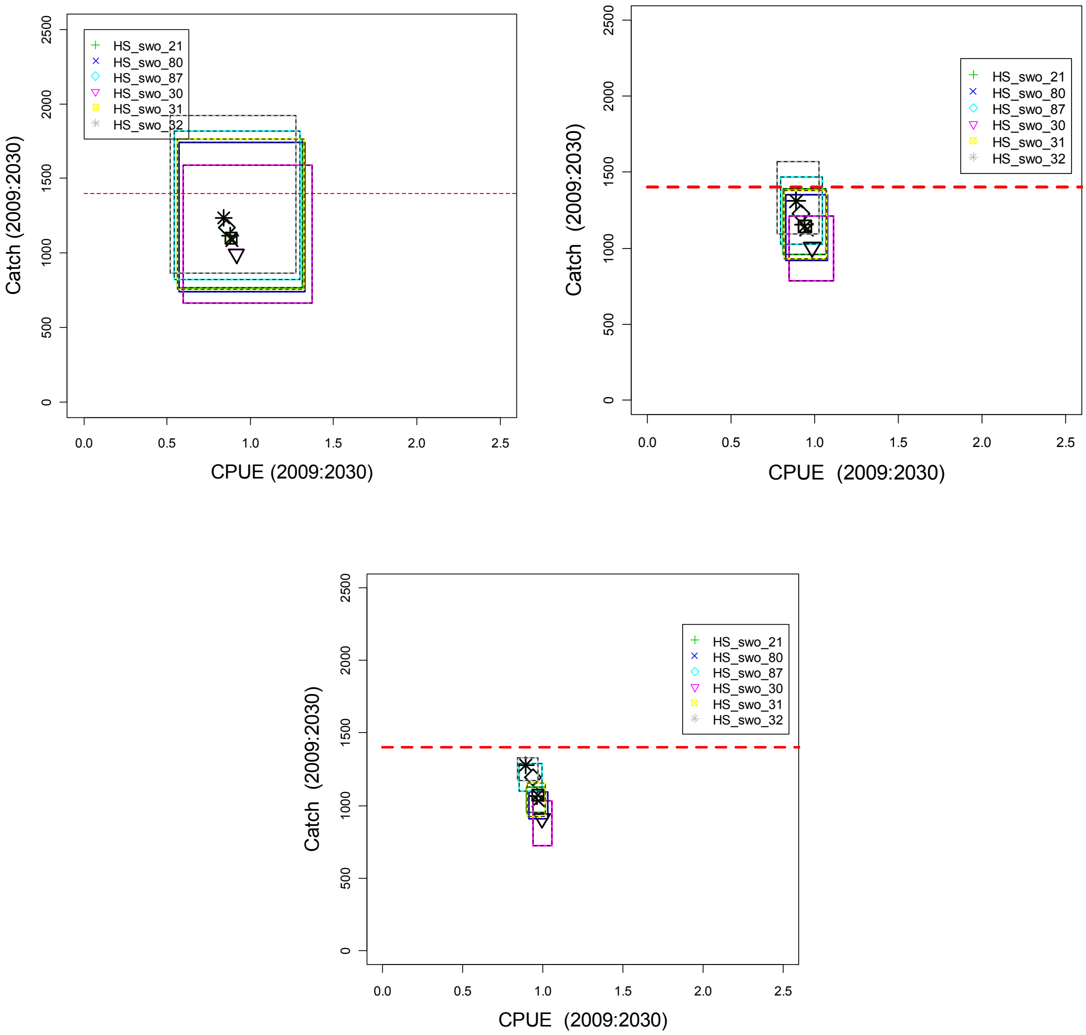


Figure 40. Comparison of 6 swordfish harvest strategies evaluated against the reference set of operating models (top), a set of models with low stochastic variation (middle) and no stochastic variation (bottom). HS_swo_21, HS_swo_80 and HS_swo_87 include different parameters for the size-based elements in the HSWG decision tree, and the others (HS_swo_30, HS_swo_31, HS_swo_32) include only the *CPUE-prime target* portion of the decision rule.

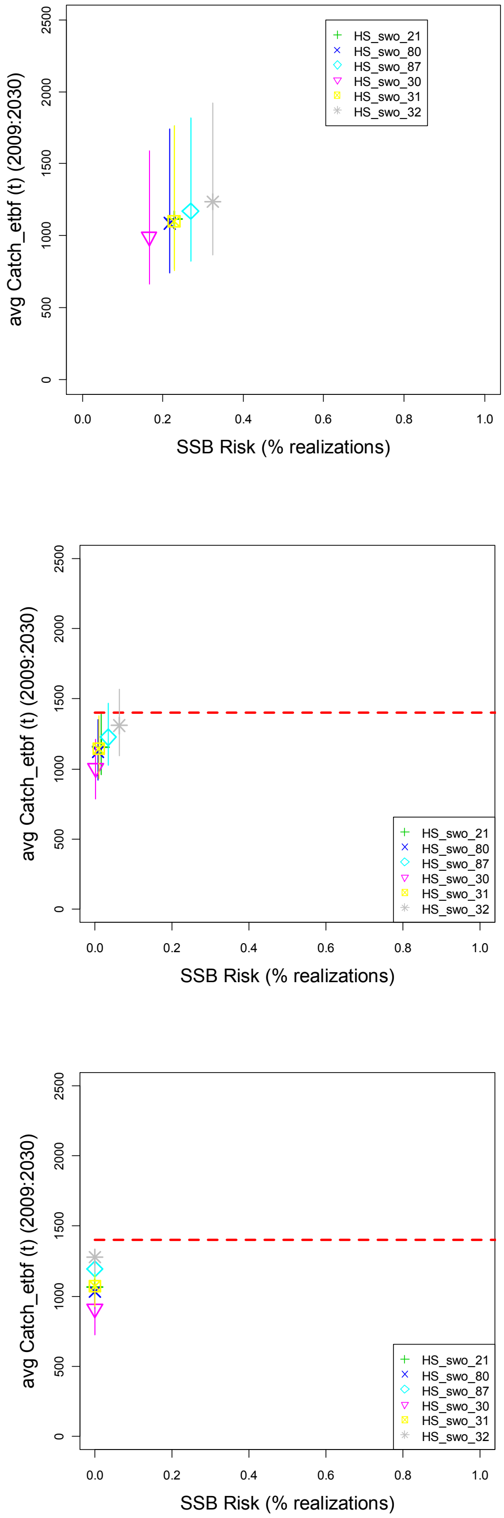


Figure 41. Comparison of 6 swordfish harvest strategies evaluated against the reference set of operating models (top), a set of models with low stochastic variation (middle) and no stochastic variation (bottom). HS_swo_21, HS_swo_80 and HS_swo_87 include different parameters for the size-based elements in the HSWG decision tree, and the others (HS_swo_30, HS_swo_31, HS_swo_32) include only the *CPUE-prime target* portion of the decision rule. The red dotted line is the 1400t interim catch limit.

Striped Marlin MSE

Striped Marlin Reference Set Operating Models

The only formal model-based stock assessment conducted for striped marlin in the ETBF region is described in Langley et al. (2006). The assessment is less than ideal for this study for several reasons, including, i) the assessment was considered preliminary when it was produced, ii) the data used are now several years out of date, and iii) there was very little quantification of the uncertainty associated with the assessment model, and some of the basic biological parameters (e.g. growth rates) were adopted from other regions. The assessment suggested that the population was heavily depleted prior to the 1970s by the international fleet, and that the relatively low catches in recent years are sufficient to prevent the population from rebuilding, even though most of the catch is not targeted. Current stock status suggests that the stock is fully exploited, $B_{(T)}/B_0 = 0.31$ ($B_{(T)}$ is the biomass in the final year of the assessment).

The reference set of operating model features is *described* in Table 11. Key reference set assumptions include:

- The MPD estimates from a single model run were recommended (Adam Langley, pers. comm.) as the primary basis for the operating models. These results included most elements of basic biology (e.g. growth rate, maturity schedule, natural mortality, stock recruitment curve steepness) and the corresponding point estimates for population parameters (e.g. numbers-at-age, fishery selectivity, virgin recruitment
- The spatial domain of the assessment is shown in Figure 42. In the assessment, the fish population was spatially aggregated, while the sub-regions shown were defined for the purpose of aggregating fisheries into units with reasonably homogenous selectivity (i.e. combined gear selectivity and availability). The spatial domain of the assessment does not resolve the migration dynamics between ETBF and non-ETBF regions. However, the largest historical catches were taken out of the ETBF region by the Japanese fleet. The assessment implies that either i) the ETBF population represents the bulk of the population, and it is considerably depleted (while non-ETBF regions may not be depleted, but represent only a small number of fish), or ii) the population is well mixed, and depleting the ETBF region effectively has reduced, and continues to limit recovery of the biomass of the whole region. Either interpretation suggests that the effect of the ETBF fleet is potentially very important.
    - 36% of the initial population of all age classes was assigned to the ETBF fishery. This partition is based purely on geographical surface area assuming a split in the assessment domain on 165°E. This proportion also corresponds to the migration redistribution proportions (i.e. the population migration will re-equilibrate to these proportions over time if not perturbed by harvesting.
    - The migration linkage between the ETBF and non-ETBF regions is assumed to be an equal mix of scenarios with 1% and 20% per quarter diffusive mixing.
- Unlike for swordfish, the non-ETBF effort was assumed to remain constant over time (at 2003 levels, the last year in the assessment model). This is justified on the basis of stable catches over the last decade, and the fact that

Australia has the only targeted fishery (albeit for only a small and seasonal component of the ETBF fleet, and ignoring recreational fleets).

- The selectivity of the non-ETBF fleet was adopted from the Japanese fleet from Area 2 (called "LL JAP2" in the assessment). This ignores all of the selectivity variability attributable to the spatial patterns in the assessment, however, this is probably not very important if the Australian fleet continues to dominate the fishery.
- The recruitment variability used in the reference set operating model was identical to swordfish (sd(log) = 0.6, autocorrelation rho = 0.7) for similar reasons. Additional stochastic error was also introduced to the MPD estimates of the youngest cohorts (age 0 sd(log) = 0.5, age 1 sd(log) = 0.25).
- The magnitude of the CPUE observation error variability was assumed to be relatively low (sd(log) = 0.2) and strongly autocorrelated (rho = 0.7), identical to swordfish.
- The reference set consisted of 800 projections = (1 MPD estimate) X (2 migration rates) X (2 size composition sampling errors) X (2 implementation error assumptions) X (100 stochastic realizations per scenario).
- The depletion level corresponding to B_{MSY} (i.e. B_0/B_{MSY}) was 0.57 when B_0 was defined as the mean unfished biomass in the 1980-2004 period, and 0.37 relative to the equilibrium B_0. The substantial difference between the two reflects the sizeable trends in estimated recruitment for this species. The equilibrium value is very similar to the 0.4 B_0 proxy value suggested in the HSP.
- Other biological and fishery assumptions correspond to those described in Langley et al. (2006).

Figure 43 illustrates that there is no obvious disagreement between the observed striped marlin CPUE trends for the ETBF and the predicted values from the operating models (but the overlap in time series is very short). Figure 44 indicates that there is a large inconsistency in the size composition data between the operating model and the assessment.

Figure 45 illustrates the dynamics estimated to occur if fishing was stopped completely. The biomass is estimated to almost triple, with biomass returning to levels seen around 1960 (but lower than the 1950s). This is reasonably consistent with the assessment.

Main concerns about the reference set of striped marlin operating models:

- Reliance on a single MPD estimate for the operating model probably results in an underestimate of the uncertainty.
- As with all of the ETBF species, the relationship between CPUE and abundance is poorly understood.
- Migration within the ETBF and non-ETBF regions is poorly understood. However, given that the largest (reported) catches have been from the ETBF region, this might be less of a concern than for the other target species.
- The assessment model is several years out of date.
- There is a large inconsistency in the size composition data between the operating model and the assessment. As with the swordfish, there are a number of possible explanations for this, including failure of the model to adequately resolve sex dimorphism (and other sex-specific parameters), ii) general

uncertainty about basic biological attributes (growth parameters are currently under investigation for the domestic fishery), iii) other unresolved issues in the assessment related to conflicting signals among different data sources and the questionable appropriateness of constant selectivity assumptions.

- As with all of these species, large changes in the effort distribution of the non-ETBF fleet could undermine the results.

Striped Marlin Robustness Set Operating Models

A number of robustness operating models were defined for striped marlin, but these results are not described in detail. We assume that most of the simulation considerations that were identified for swordfish are also relevant for striped marlin. We also concluded that there is sufficient concern about the state of development of the striped marlin assessment that we can demonstrate serious concerns about the expected performance of the adopted HS without attempting to identify more challenging circumstances.

Table 11. STM Reference Set

Dimension	Option 1	Option 2	Option 3	Number of Reference Set grid elements
M growth maturity Stock-Recruitment steepness selectivity	1 model Most population and fishery characteristics are adopted from the assessment inputs or Maximum Posterior Density (MPD) estimates			1
N(initial) and future Recruitment Bias	0 (i.e. MPD estimates are used)			1
*Stochastic replicates	100			100
Recruitment SD(log(dev)); autocorrelation	τ=0.6 ; ρ=0.7			1
CPUE obs. error SD(log(dev)); autocorrelation	τ=0.2 / ρ=0.7			1
Migration Rate	20%/qtr	1%/qtr		2
Effort in the non-ETBF fishery	Constant at 2007 levels			1
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0	0.7 / 0.2 / 0.7		2
RBC implementation error SD(log(dev))	0	0.2		2
Data Time Lag for HS Application	6 months			1

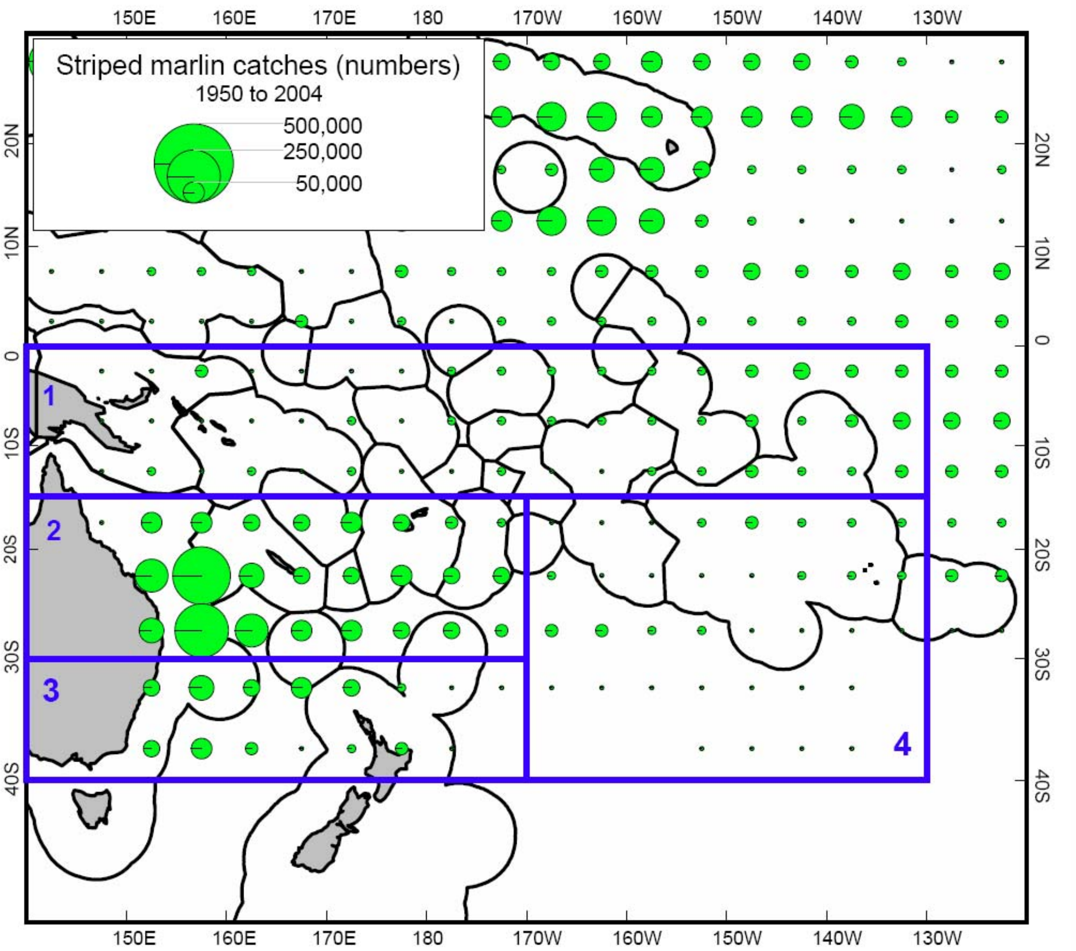


Figure 42. Striped marlin assessment domain (from Langley et al. 2006). In the stock assessment, areas are used for fishery definitions but the fish population is aggregated across areas 1-4.

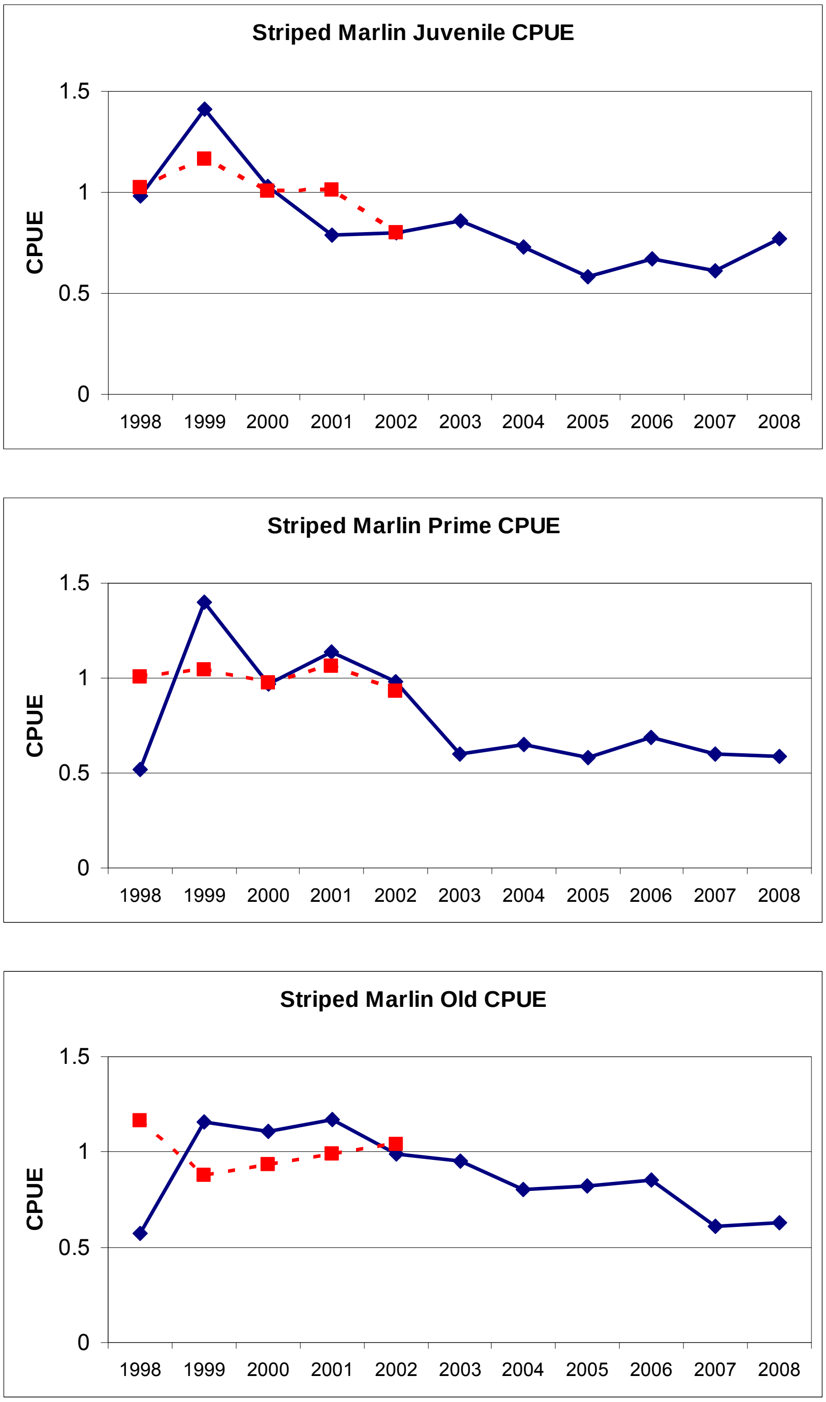


Figure 43. Striped marlin comparison between predicted and observed CPUE for the Australian ETBF. Solid black lines (diamonds) are the observed standardized CPUE by juvenile, prime and old size classes; broken red lines (squares) are the equivalent assessment model estimates (later years are not shown because they consist of stochastic projections).

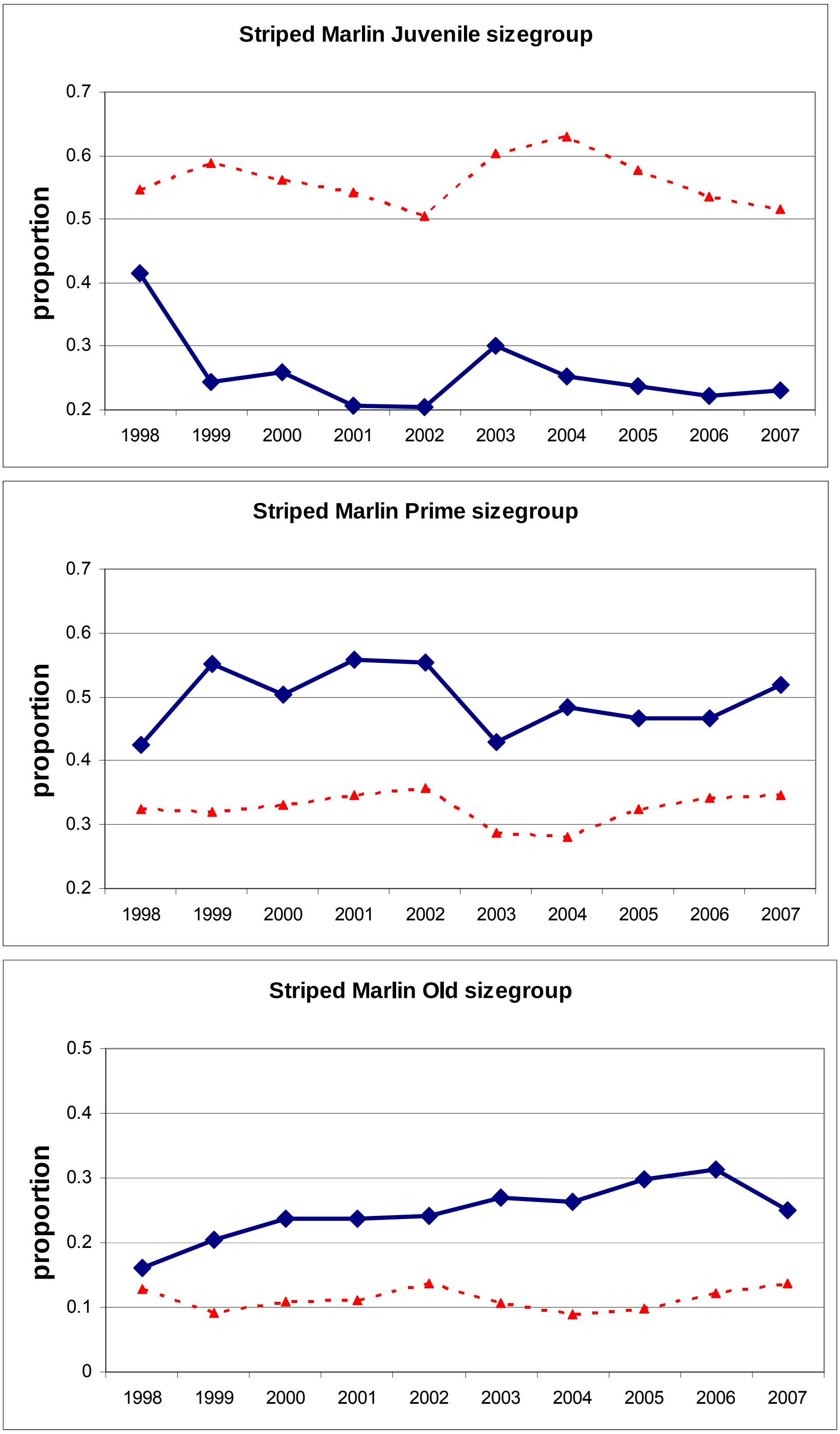


Figure 44. Striped marlin comparison between predicted and observed size composition proportions for the Australian ETBF. Solid black lines (diamonds) are the observed data. Broken coloured lines are the operating model proportions (projections start in 2003).

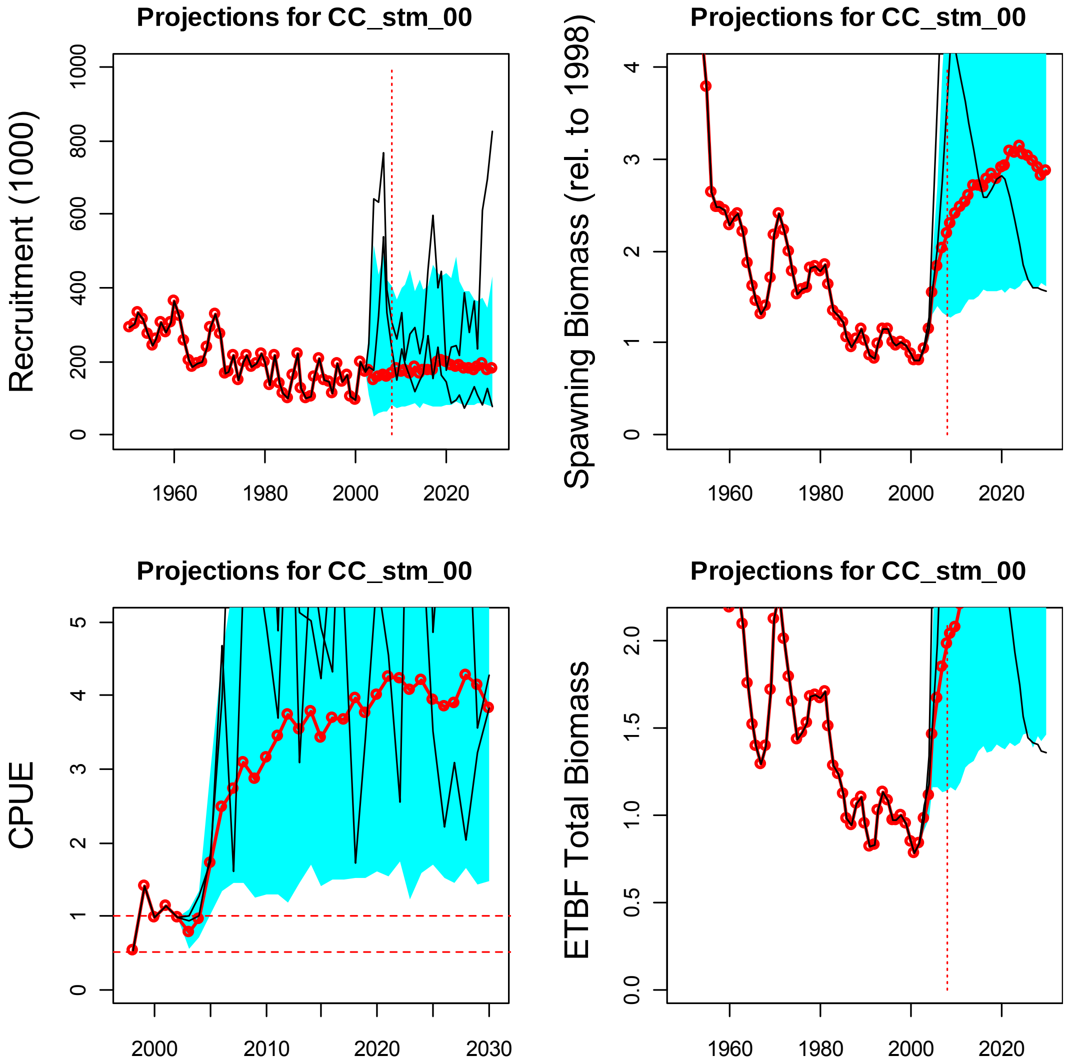


Figure 45. Striped marlin operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

Striped Marlin Harvest Strategy Evaluation

Reference Set

Fewer HSs were evaluated for striped marlin than swordfish, as it was assumed that general performance characteristics of the HSs would be similar between the two species. The generic HSs are defined in Table 2, with species-specific threshold definitions in Table 12. Only a representative subset of the full range of HSs is described in detail here.

Figure 46, Figure 47, Figure 48 and Figure 49 illustrate the estimated catch, CPUE, spawning biomass (combined ETBF and non-ETBF), and total biomass (ETBF only) trajectories for six HSs evaluated against the reference set of operating models. These include CC_stm_00 (which illustrates what is estimated to result if the fishery was to be shut down completely), and HS_stm_21 (the HS adopted by the ETBF MAC). All of the feedback-based HSs are optimistic in suggesting short-term increases in median catch and biomass over the short-medium term. The 10^{th} and 90^{th} percentiles are much more variable than in swordfish (CPUE series in particular). Since the assumed recruitment and observation errors are identical for the two species, this presumably reflects differences in life history and selectivity in the two species.

Figure 50 illustrates the estimated relationship between catch and CPUE for a range of Harvest Strategies. The operating model estimates that the ETBF fishery has a large effect on the regional population dynamics of striped marlin, such that relatively small changes in current catches are predicted to have a large effect on CPUE (relative to the other species).

Figure 51 illustrates the estimated relationship between catch and biomass risk associated with the different harvest strategies. These plots are consistent with the assessment in suggesting that the striped marlin stock is likely to be near the biomass limit reference point. As a consequence, the ETBF has the capacity to greatly increase or decrease the risk of overfishing, depending on the HS selection. CC_stm_0 indicates that the risk would be reduced substantially if the ETBF catch was stopped while the non-ETBF effort remained constant at 2003 levels. The projected impact of the current ETBF harvest on striped marlin is estimated to be higher than for any of the other target species.

Figure 52 compares the average annual RBC change between HS's for the reference set of operating models.

Robustness Set

Additional robustness testing does not seem to be a high priority for this species because the Reference Set simulation testing has already undermined our confidence in the harvest strategy adopted by the ETBF RAG and MAC. We have identified a number of concerns about the state of development of the striped marlin assessment (and hence operating model) that should be addressed as a higher priority at this time.

Striped Marlin MSE Conclusions

- The regional striped marlin stock assessment is less than ideal for MSE purposes. It is considered preliminary; it is several years out of date, with poor spatial resolution and limited uncertainty quantification. The ETBF CPUE series may be consistent with the assessment model abundance trends, but the ETBF size composition data do not agree with the model.
- The simulations suggest that the striped marlin stock is currently near the biomass limit reference point, and actions taken under the ETBF HS have the potential to substantially increase or decrease the biomass risk. The adopted HS is estimated to represent a substantial biomass risk. The risk is attributable to several international fleets, with the ETBF representing a considerable but minority proportion.
- We recommend that striped marlin should be considered one of the highest priority species for obtaining an updated stock assessment. Ideally the assessment should be devised to also address the requirements of the ETBF MSE.

Table 12. Striped Marlin specific cut-off weights for the definition of juvenile, prime and old sized fish, and length to whole weight parameters (Campbell et al, 2009; Robert Campbell, pers. Comm.).

Striped Marlin	
Upper cut-off whole weight for juvenile size group	74.2 kg
Lower cut-off whole weight for Old size group	101.8 kg
Length to whole weight parameters (wwt=a*len^b)	a= 0.00000081147 b= 3.47

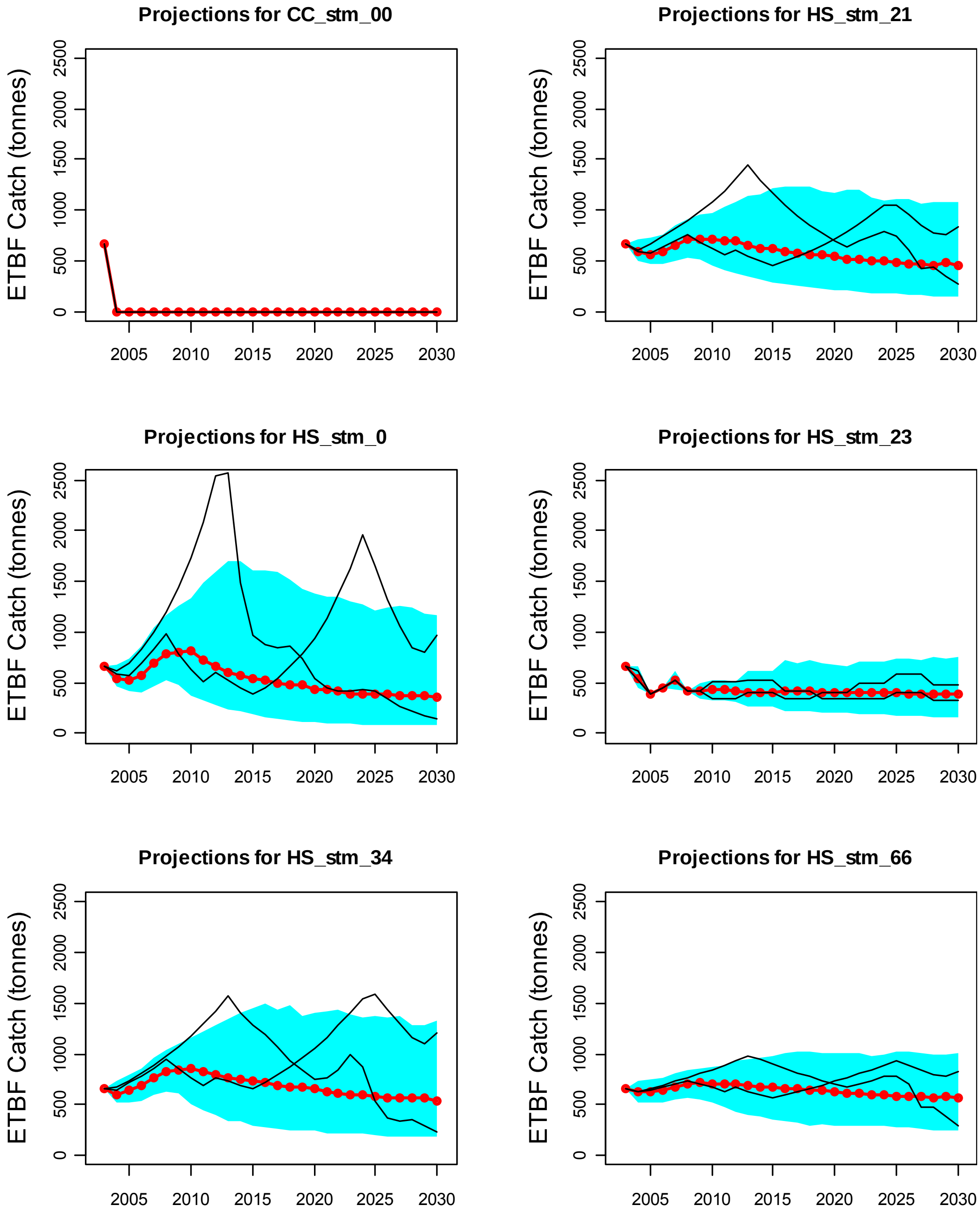


Figure 46. Striped marlin estimated catch trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

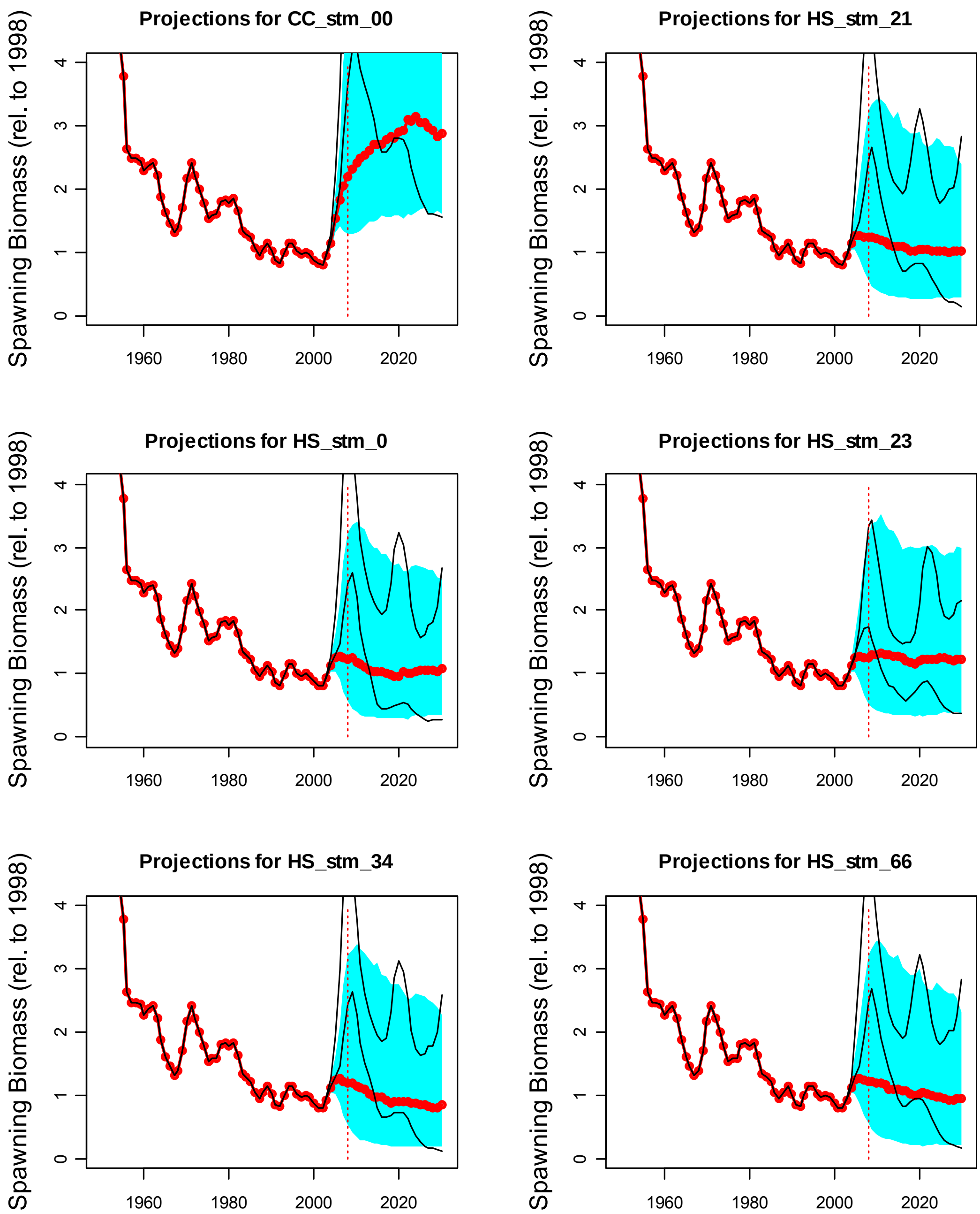


Figure 47. Striped marlin estimated spawning biomass trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

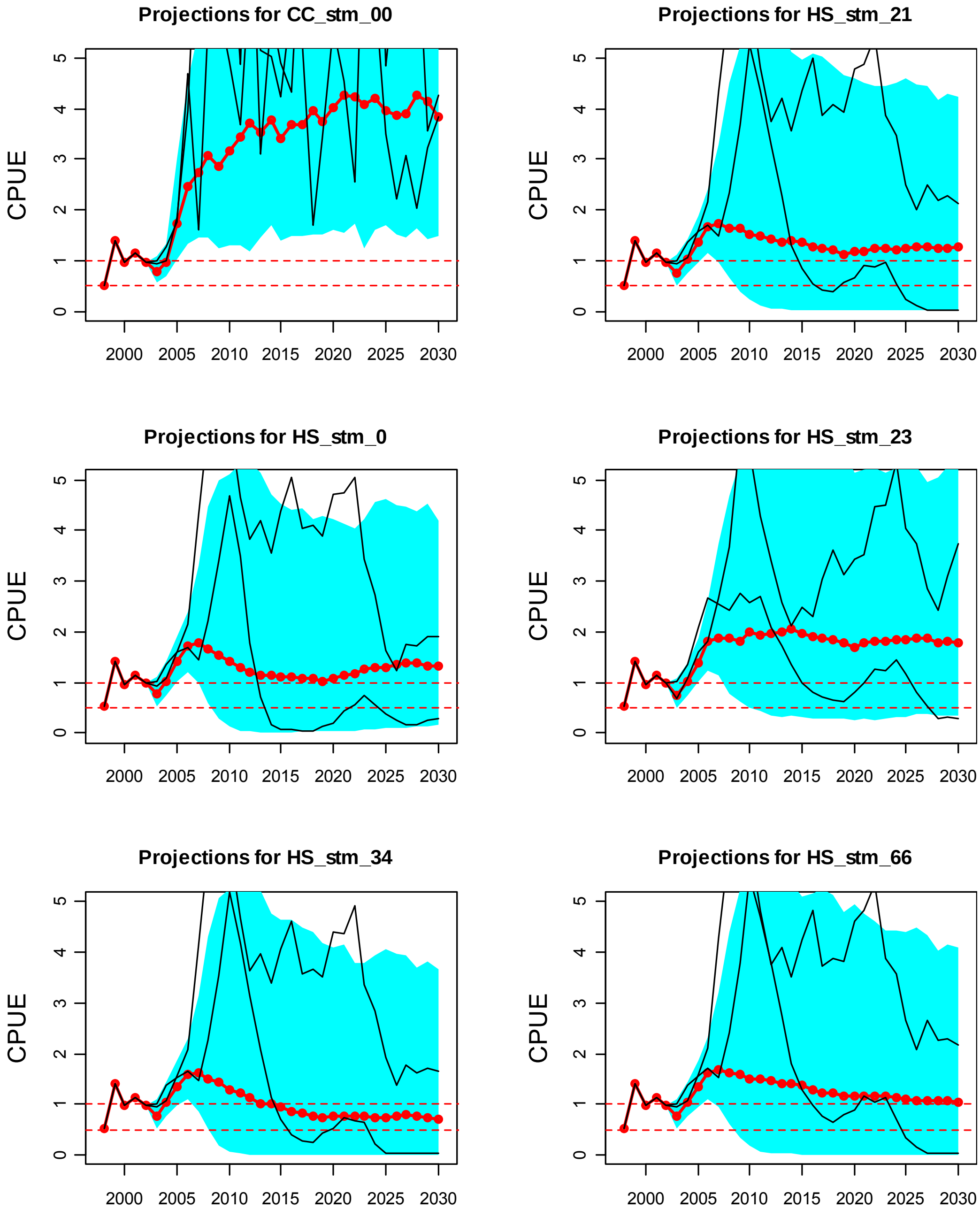


Figure 48. Striped marlin estimated CPUE trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

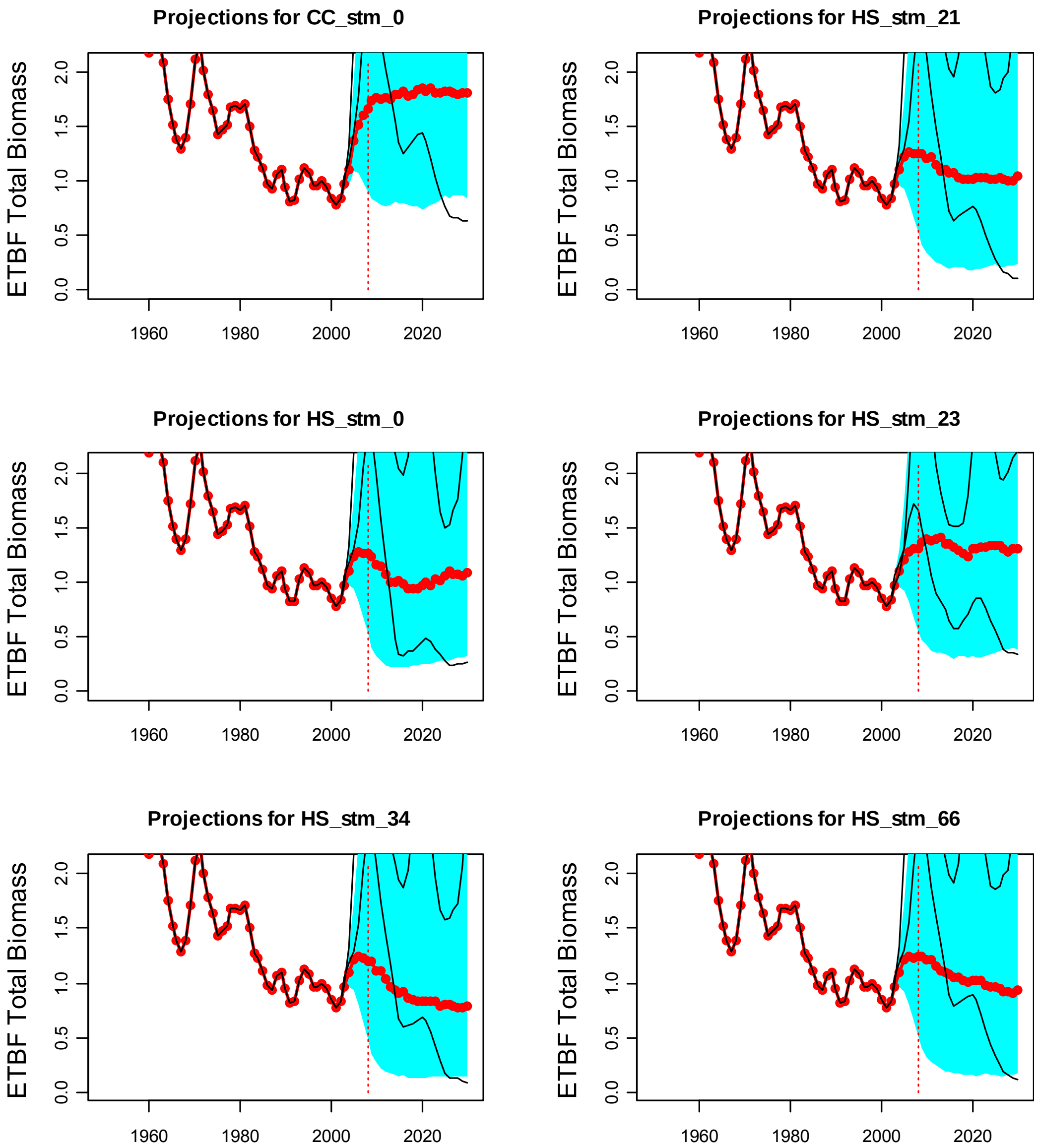
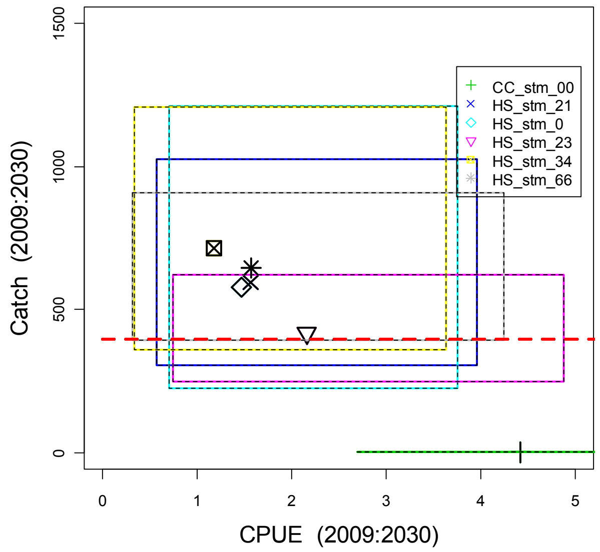


Figure 49. Striped marlin estimated total biomass (in the ETBF region) trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.



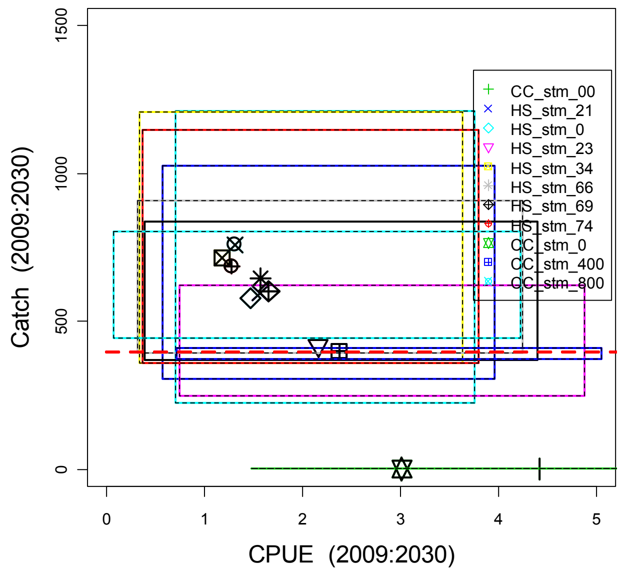
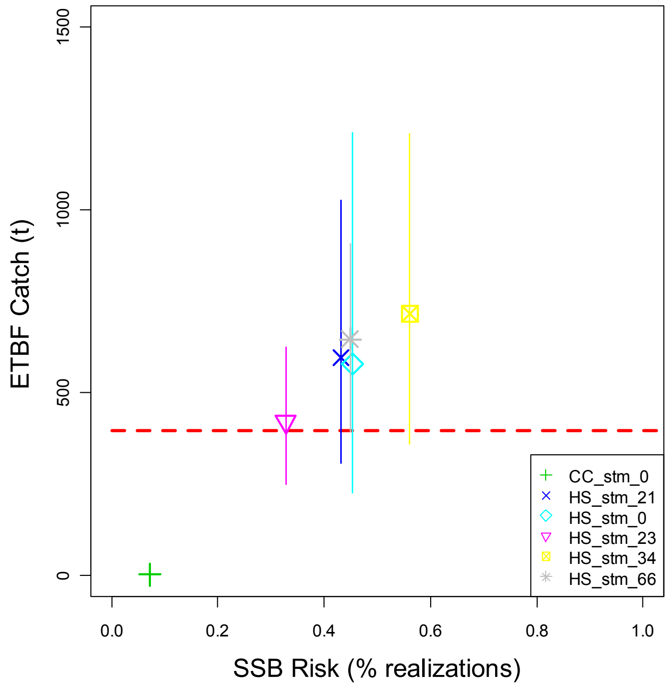


Figure 50. Striped marlin trade-off plot illustrating the estimated relationship between Catch and CPUE for a range of Harvest Strategies. Symbols represent the median performance (averaged over time) for all realizations; boxes bound the 10th-90th percentile region in both dimensions. The broken red horizontal line indicates the mean catch from 2005-2007.



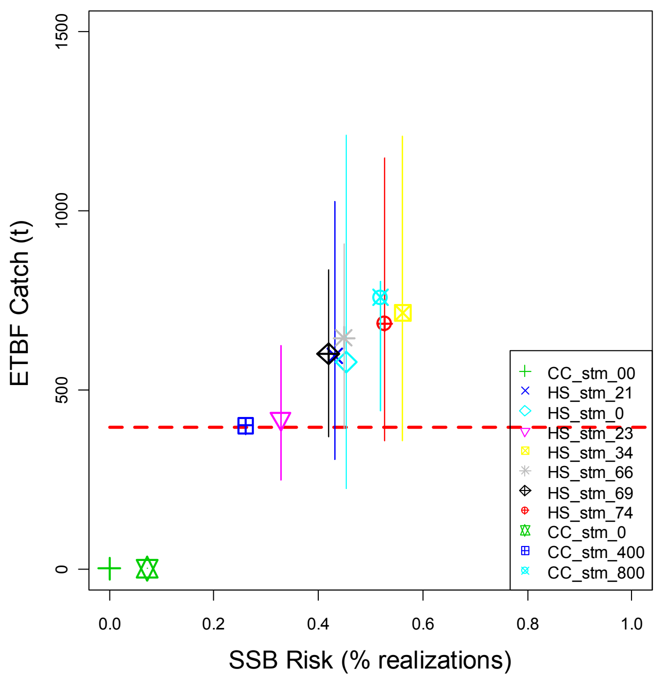


Figure 51. Striped marlin trade-off plot illustrating the estimated relationship between ETBF Catch (2009-2030) and biomass risk. Risk is defined as the proportion of stochastic projections in which spawning biomass (*SSB*) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Dotted vertical lines show how specific levels of risk might be used to remove some candidate HSs from further consideration. The broken red horizontal line indicates the mean ETBF catch from 2005-2007.

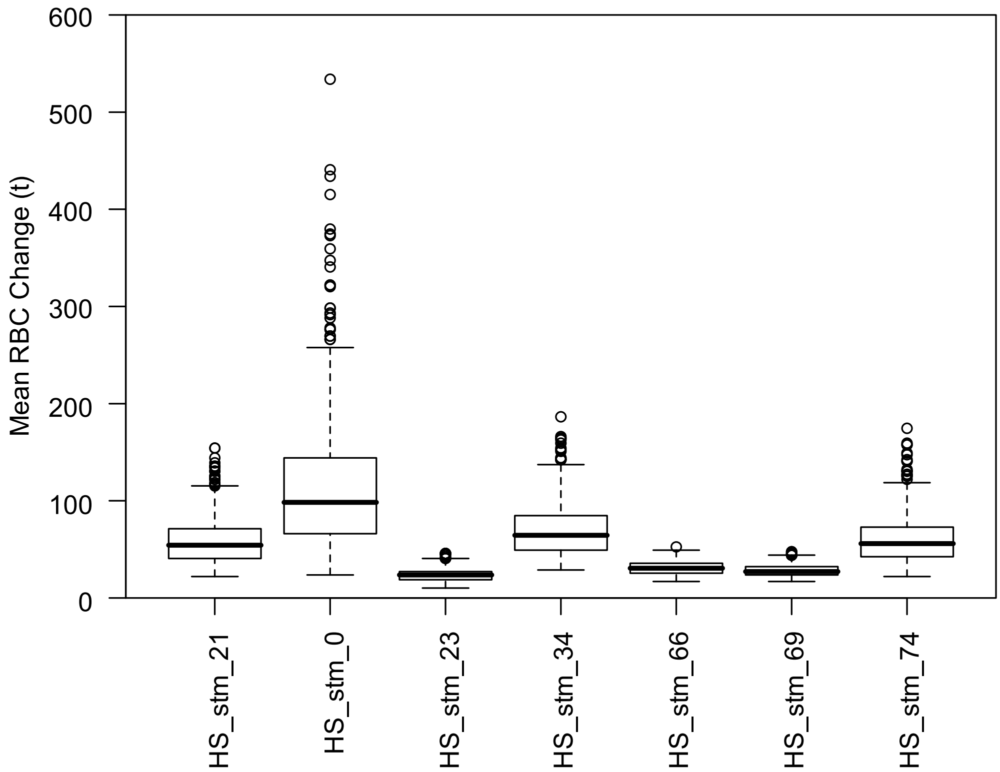


Figure 52. Reference Set striped marlin RBC variability statistics for a range of Harvest Strategies. Boxplots represent the distribution of the average absolute value of the change in RBC associated with each HS (i.e. each observation within a boxplot represents the mean value from a single stochastic realization). The dark line represents the median of the distribution, the box represents the 25th-75th percentiles, whiskers represent the range or 1.5 of the interquartile distance (whichever is smaller), and circles represent outliers that exceed the whiskers.

Bigeye Tuna MSE

Bigeye Tuna Reference Set Operating Models

The most recent bigeye stock assessment (that was available in time to be incorporated in this project) in the region is described by Langley et al. (2008). The spatial structure of the assessment covers the whole WCPO (Figure 53). The global fishery is estimated to be the most depleted of the target species ($B_{(T)}$) /$B_{(no\ fishing)}$ = 0.20 - 0.28, where $B_{(T)}$ is the biomass in last year of stock assessment, and *B(no fishing)* is the estimated initial biomass in the absence of fishing). The ETBF depletion is estimated to be somewhat less than the global population. However, given that the equatorial region accounts for the majority of the catch, and the population connectivity is poorly understood, it is not clear how well the assessment represents local processes in the ETBF fishery.

The reference set of operating model features are described in Table 13. Key assumptions included:

- MPD estimates from five different models were included to encompass some of the uncertainty in biological assumptions and stock status estimates. This set of models was judged to be plausible, with no real basis for selecting a preferred model (Adam Langley, pers. comm.).
- The south-west region (5) was assumed to correspond to the ETBF component of the stock, and the south-east region (6) to the non-ETBF component (Figure 53). The reference case assessment model illustrated in Langley et al. (2008) suggested that these two regions were reasonably discrete from each other, and the equatorial regions. However, it is also recognized that tagging studies have not covered these regions very well. It can probably be argued that region 5 is more closely related to the equatorial region than region 6, and the adoption of region 6 as the non-ETBF component in the operating model should be recognized as only one possible scenario that reflects the fact that the ETBF may be a small pool of fish that is connected to another pool of substantial size. Two additional spatial assumptions are described in the robustness sets, and represent more localized populations. These more localized scenarios were proposed as alternative possibilities, that might seem equally plausible to the reference set, but at least one of them is not for reasons described in the subsequent section. Additional spatial assumptions:
    - The migration linkage between the ETBF and non-ETBF regions is assumed to be an equal mix of scenarios with 1%, 20% and 60% per quarter diffusive mixing.
    - 51% of the recruitment is assigned to the ETBF, and represents the estimated proportion of the equilibrated population in the absence of harvesting.
    - The stock recruitment relationship is re-scaled from the aggregate WCPO assessment, such that steepness is the same, and initial recruitment (R_0) is reduced by the fraction of recruitment in areas 5 and 6 relative to the whole WCPO.
- Future non-ETBF effort is assumed to decrease by 30% from 2007 levels by 2011 (assuming implementation of the WCPFC Conservation and Management Measure for bigeye in force at the time).

- The selectivity of the ETBF fleet was adopted from the assessment estimates (named "LL AU 5" in Langley et al, 2008), while we assumed that the non-ETBF fleet was adequately represented by the major longline fleet in area 5 (named "LL ALL 5"). The validity of this selectivity assumption is closely intertwined with the spatial assumptions (i.e. selectivity is the combined effect of gear selectivity and spatial availability). If the ETBF population is closely linked to the equatorial regions, then purse seine fishery selectivity could be important. However, if purse seine activity is stable, the selectivity implications for the longline fleet might be manifested in the ETBF primarily as reduced recruitment.
- Recruitment is quarterly. The recruitment variability used in the reference set operating model was adopted from the empirical estimates in the assessment (sd(log) = 0.75, autocorrelation rho = 0.25). It is generally assumed that the recruitment estimates for the tropical tuna are better than for the billfish species because there is usually better size composition sampling, the resolution of distinct length modes are observed in the frequency distributions, and there is a general perception that other biological characteristics are more reliably quantified. However, as with the billfish species, weakly recruited cohorts are not well estimated, and additional stochastic error was introduced to the MPD estimates of the youngest cohorts (age 0 sd(log) = 0.5, age 1 sd(log) = 0.25).
- The magnitude of the CPUE observation error variability was assumed to be relatively low (sd(log) = 0.2) and strongly autocorrelated (rho = 0.7), identical to the other species.
- The reference set consisted of 3000 projections = (5 MPD estimates) X (3 migration rates) X (2 size composition sampling errors) X (2 implementation error assumptions) X (50 stochastic realizations per scenario).
- The depletion level corresponding to B_{MSY} (i.e. B_0/B_{MSY}) ranged from 0.09 – 0.23 (range of 5 MPD estimates) when B_0 was defined as the mean unfished biomass in the 1980-2004 period, and 0.11 – 0.25 relative to the equilibrium B_0. In all cases this is substantially lower than the 0.4 B_0 proxy value suggested in the HSP.
- Other biological and fishery assumptions correspond to those described in Langley et al. (2008).

Figure 54 illustrates that there is very good agreement between the observed bigeye CPUE trends for the ETBF and the predicted values from the operating models. This is particularly encouraging considering that the Australian CPUE series was not used in the stock assessment. This strongly suggests that either the population is strongly mixed across the operating model domain, or similar processes are driving the abundance in separate populations. Figure 55 illustrates that there is excellent agreement between the predicted and observed size composition in the ETBF fleet. This suggests that either i) the region 5 population is thoroughly mixed, or ii) the poorly mixed bits are subject to similar driving forces, or iii) the Australian size composition data dominates the signal in this region).

Figure 56 illustrates the dynamics estimated to occur if fishing was stopped completely. The biomass is estimated to almost triple, returning to levels seen around 1960 (but lower than the 1950s). However, the recovery is very rapid (~3 years), and presumably driven by optimistic estimates of partially recruited cohorts, that may not eventuate as predicted.

Main concerns about the reference set of bigeye tuna operating models:

- Having 5 sets of MPD estimates to include in the operating models is likely to increase confidence in the robustness of the results, but a more comprehensive set would still be preferable (particularly if related to spatial assumptions).
- Migration dynamics are poorly quantified in the assessment. The assumptions used in either the reference or robustness sets cannot be rigorously defended at this time, but should be adequate to qualitatively demonstrate how the HS framework performs under alternative situations.
- The operating models estimate that in the absence of fishing there will be a rapid recovery in the spawning biomass, which is attributable to very high recent recruitment estimates in regions 5 and 6. If these estimates are erroneous (e.g. due to selectivity variation rather than high recruitment), these results could be over-optimistic.
- As with all of these species, large changes in the effort distribution of the non-ETBF fleet could undermine the results. However, assuming that the WCPFC continues to pursue effective management measures that do not result in the unintended redistribution of effort, this might not be an immediate problem.

Bigeye Tuna Robustness Set Operating Models

We assume that most of the robustness results related to process and observation error variability in the swordfish simulations would be qualitatively similar for bigeye tuna. The main difference between the billfish and tropical tuna populations that was not examined in the swordfish testing relates to the connectivity with adjacent populations.

For the billfish, the connectivity with eastern populations is questionable, but we are reasonably confident that the assessment describes the bulk of the population in the south-west Pacific. For bigeye, the connectivity with eastern populations is also questionable, but most of the WCPO population is actually in the equatorial region. In the reference set, we assume that there is a sizable pool of fish that may or may not be closely linked to the ETBF. The merging of the region 5 and 6 populations is probably sufficient to qualitatively demonstrate the effect of having a really large pool of fish (i.e. such that the ETBF cannot have a strong impact with current effort levels). However, the ETBF HSWG framework was predicated on the assumption that it would be effective (in the sense of preventing overfishing) irrespective of whether the ETBF represented part of a large global population, or a distinct local population.

Two additional robustness scenarios were defined, in which the bigeye population was assumed to be restricted to area 5 only. In the first scenario, the ETBF population is assumed to correspond to 50% of the area 5 population (and the non-ETBF the remaining 50%). In the second scenario, the ETBF population is assumed to correspond to 25% of the area 5 population (and the non-ETBF another 25%). In the latter case, the non-ETBF catch was calculated as 50% of the total catch from region 5 minus the ETBF catch. These scenarios were not reconditioned to these spatial assumptions (i.e. ideally the data should be disaggregated according to the proposed spatial structure and the model parameter estimation should be repeated). It was assumed that partitioning the assessment estimates would produce a rough approximation of something that would qualitatively resemble a more localized population. But unintended artefacts could also be introduced (e.g. in an extreme case, there might not be enough fish in one of these restricted areas to account for the catches that were extracted).

Figure 57 and Figure 58 show the dynamics of these two robustness sets in the absence of fishing. Note that these plots are almost identical, because the combined population of the ETBF and non-ETBF is the same in both scenarios. These scenarios suggest recovery to unfished spawning biomass levels that are ~50% higher than the reference set. This emphasizes that the spatial patterns of fishing and production dynamics are not uniform across the southern hemisphere regions of the bigeye assessment domain. We would expect that patterns would also be different if equatorial populations and fisheries were considered as an alternative.

Table 13. BET Reference Set

Dimension	Option 1	Option 2	Option 3	Number of Reference Set grid elements
M growth maturity Stock-Recruitment steepness selectivity	5 models Most population and fishery characteristics are adopted from the assessment inputs or Maximum Posterior Density (MPD) estimates			5
N(initial) and future Recruitment Bias	0 (i.e. MPD estimates are used)			1
*Stochastic replicates	50			50
Recruitment SD(log(dev)); autocorrelation	τ=0.75; ρ=0.25			1
CPUE obs. error SD(log(dev)); autocorrelation	τ=0.2 / ρ=0.7			1
Migration Rate	20%/qtr	1%/qtr	60%/qtr	3
Effort in the non-ETBF fishery	Linear decrease over 5 years up to 0.7 X Effort(2007)			1
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0	0.7 / 0.2 / 0.7		2
RBC implementation error SD(log(dev))	0	0.2		2
Data Time Lag	6 months			1

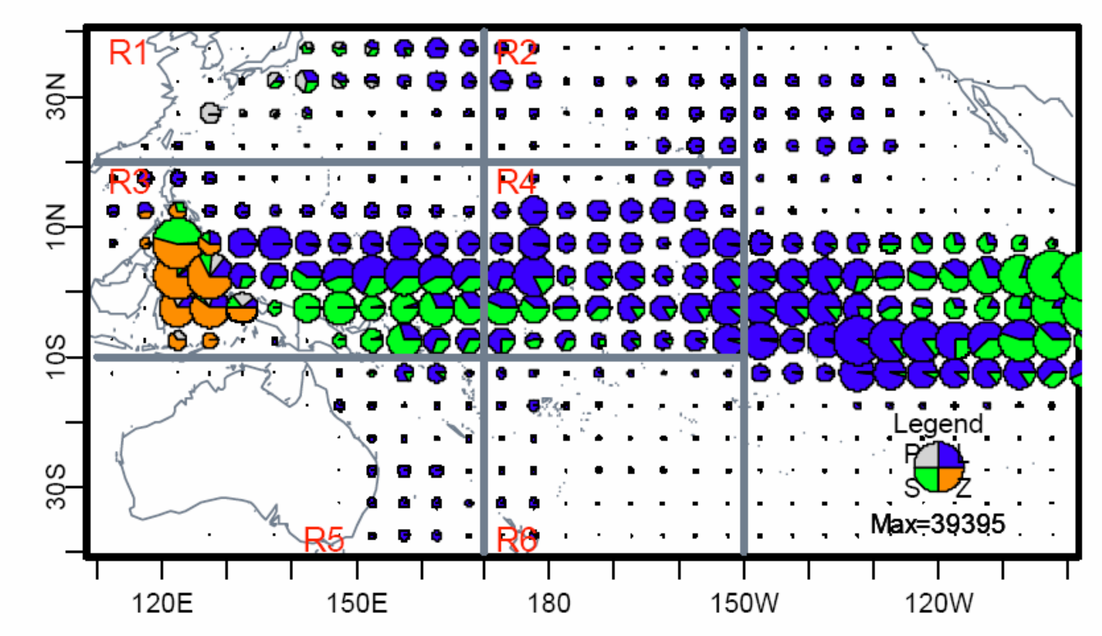


Figure 53. Bigeye tuna assessment model spatial domain from Langely et al (2008). Circles indicate the distribution of cumulative bigeye tuna catch from 1990−2006 by 5 degree squares of latitude and longitude and fishing gear; longline (blue), purse-seine (green), pole-and-line (grey) and other (dark orange). The maximum circle size represents a catch of 40,000 mt. The grey lines indicate the spatial stratification of the six-region assessment model. Area 5 is defined as the ETBF, Area 6 as the non-ETBF.

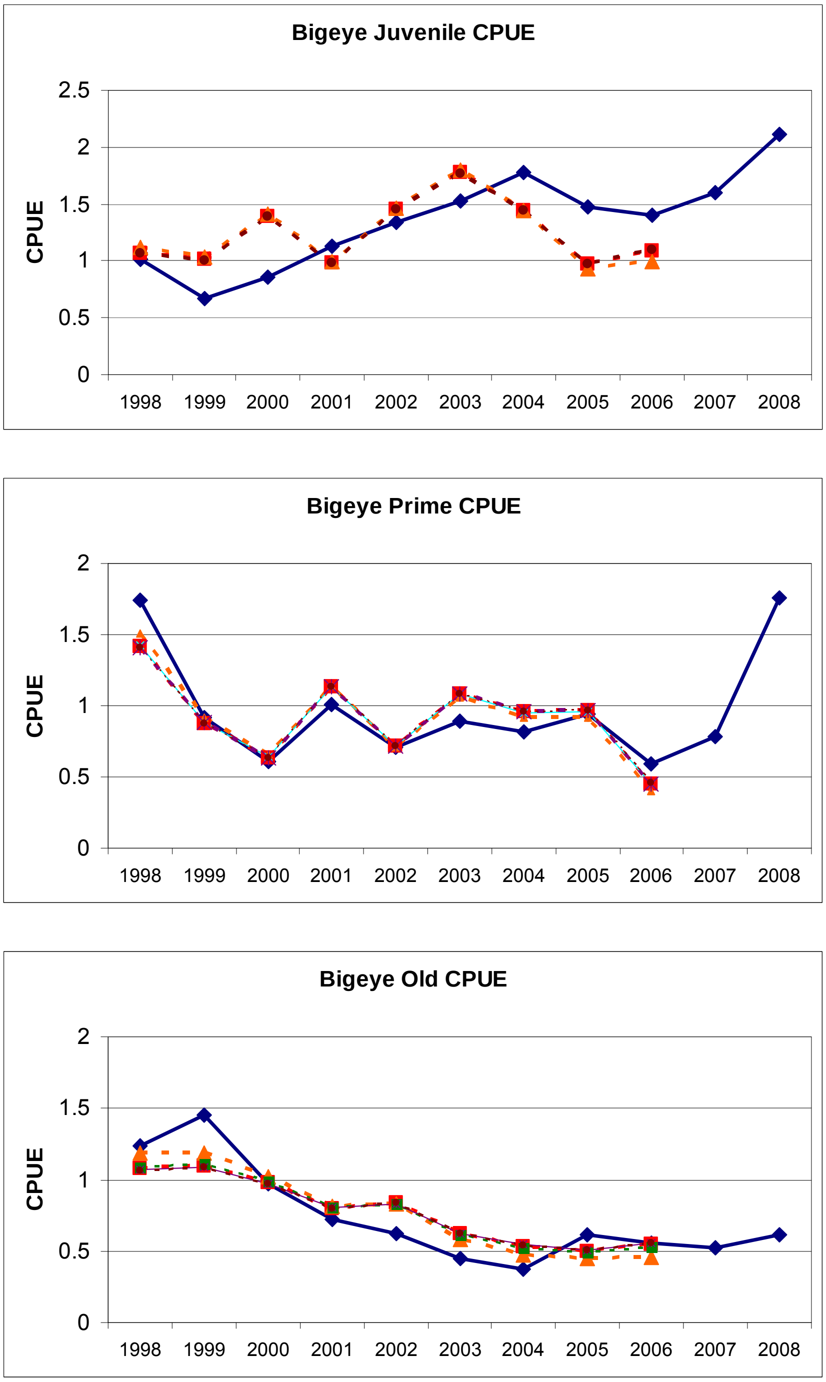


Figure 54. Bigeye tuna comparison between predicted and observed CPUE for the Australian ETBF. Solid black lines (diamonds) are the observed standardized CPUE by juvenile, prime and old size classes; broken coloured lines are the equivalent assessment model estimates from 5 different assessment models (later years are not shown because they consist of stochastic projections).

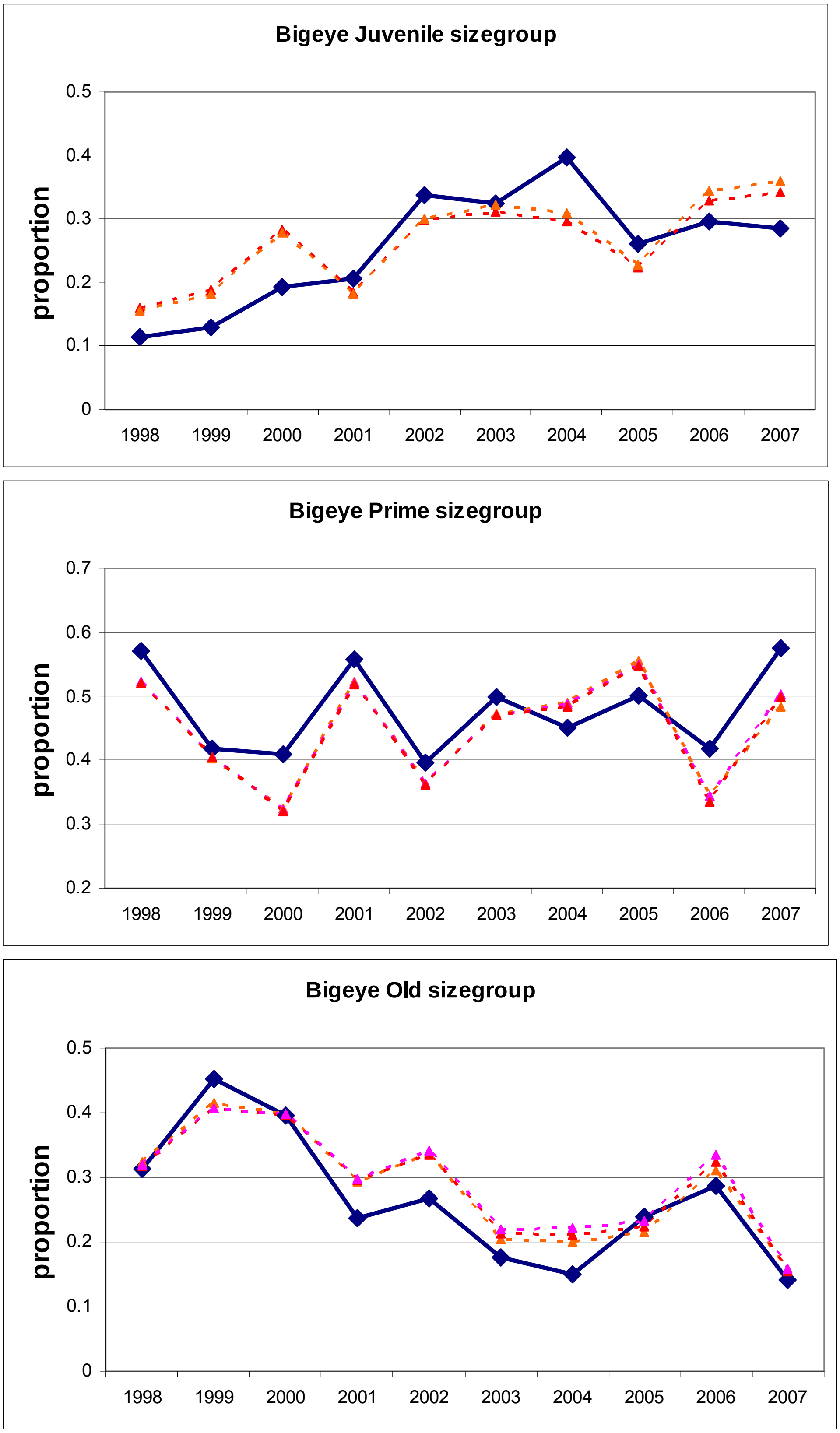


Figure 55. Bigeye tuna comparison between predicted and observed size composition proportions for the Australian ETBF. Solid black lines (diamonds) are the observed data. Broken coloured lines are the operating model proportions (projections start in 2007).

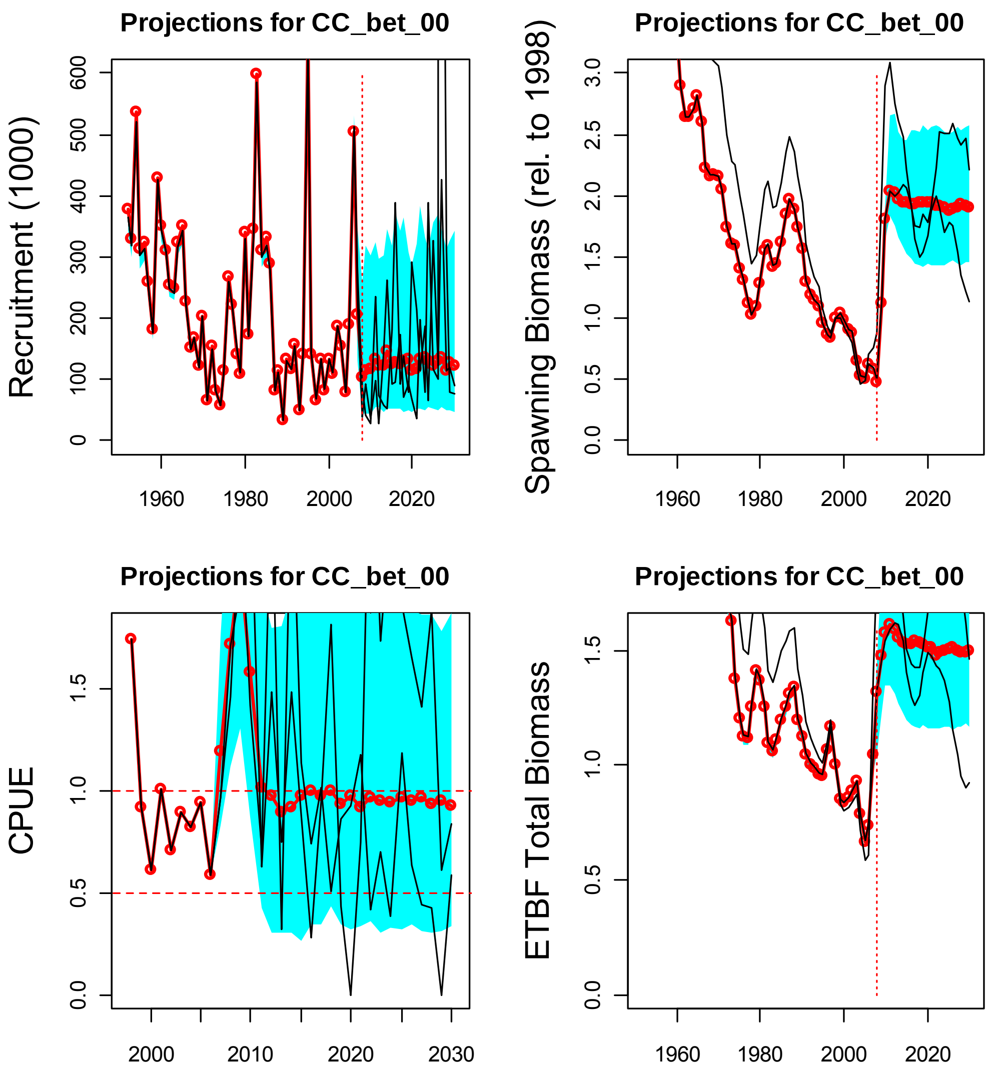


Figure 56. Bigeye tuna reference set operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

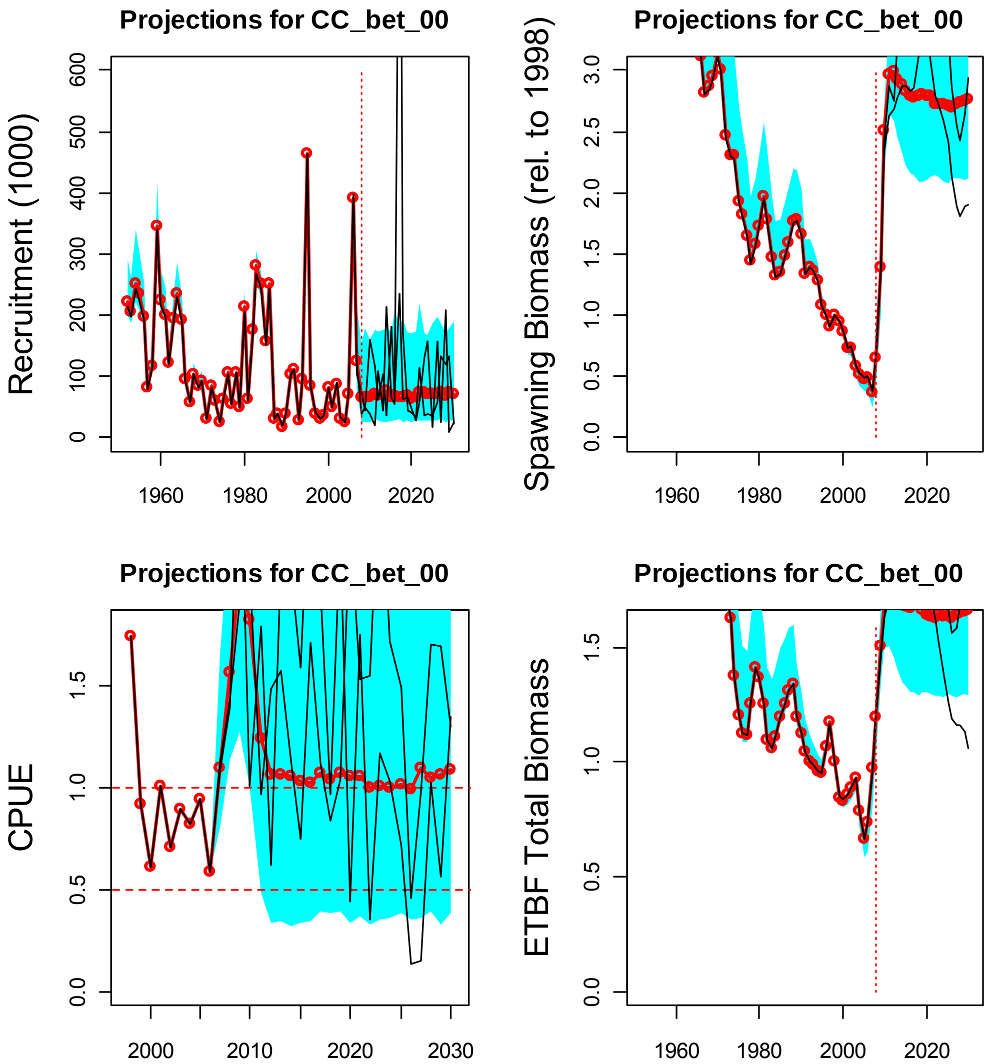


Figure 57. Bigeye tuna spatially-restricted robustness set (ETBF = 50% of region 5) operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

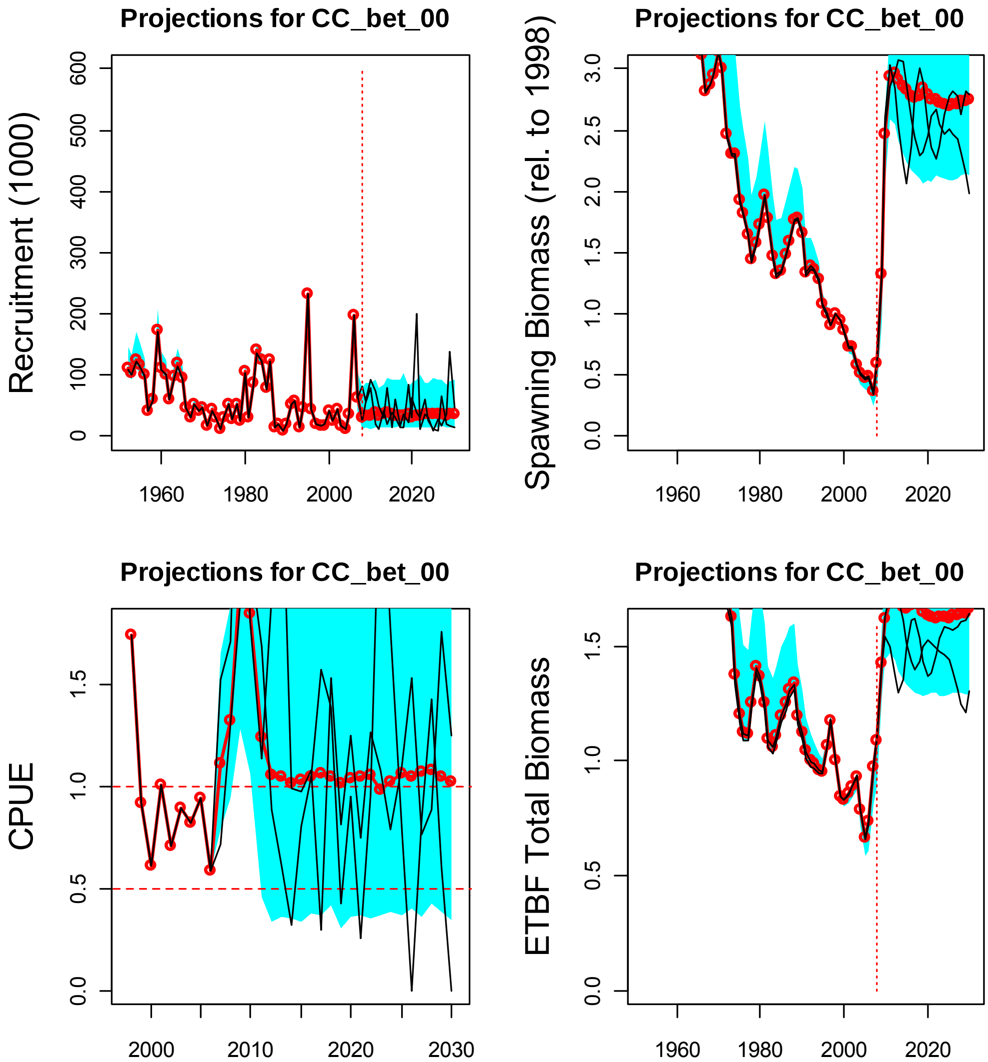


Figure 58. Bigeye tuna spatially-restricted robustness set (ETBF = 25% of region 5) operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

Bigeye Tuna Harvest Strategy Evaluation

Reference Set

Figure 59, Figure 60, Figure 61 and Figure 62 illustrate the estimated catch, CPUE, spawning biomass and total biomass trajectories for four ETBF Harvest Strategies that were selected to show a range of options. These results suggest that the various ETBF HSs can have substantially different outcomes in terms of ETBF catches, but the effects on CPUE and biomass are not substantial. In the majority of cases, the spawning biomass recovers to median levels seen in the early 2000's and CPUE returns to a level slightly below the target level. HS_34 is the exception to this general pattern.

The minimal effect of the ETBF HS is clearly evident in the catch and CPUE trade-off plot (Figure 63). Figure 64 illustrates the estimated relationship between catch and biomass risk associated with the different harvest strategies. The plot indicates that the regional spawning biomass of the bigeye stock is estimated to sometimes fall to a level lower than the limit reference point specified in the HSP. Even though the impact of the ETBF fleet itself may be small, relative to the other fleets, there is a slight increase in the biomass risk to the regional bigeye population with catches near current levels.

Overall these results are consistent with what one would expect for a small fishery, harvesting a large depleted stock in conjunction a large fishery that operates in a consistent and independent fashion. The operating model suggests that the ETBF fishery has a small effect on the regional population dynamics of bigeye (within the range of catches prescribed by the selected HSs), relative to the non-ETBF fleet. Figure 65 compares the mean annual change in RBC for a range of HS for the reference set.

Robustness set

Time series trajectories for the adopted HS (HS_bet_21) are shown in Figure 66 and Figure 67 for the two spatially-restricted robustness scenarios. If 50% of the region 5 population is allocated to the ETBF region (Figure 66), then the HS performance in terms of catch, relative biomass and CPUE, is similar to that observed in the reference set. However, if only 25% of the region 5 population is allocated to the ETBF region (Figure 67), then the HS performance is very different, with a high probability of rapid and substantial decline in *CPUE-prime*. Such a decline in CPUE would normally be expected to be accompanied by a similar decline in catch and biomass; but this is not quite what happens. There are a number of reasons for this: i) the long and sustained decline in the median CPUE shown in the percentiles of the time series does not actually occur in very many individual realizations (i.e. they tend to dip up and down over shorter time periods), and ii) when the prime-sized CPUE has declined, the fishery is still able to catch the recruits and older-sized fish (though the effort required to meet the RBC under these circumstances would probably be unrealistic).

When expressed in terms of biomass risk, the difference between the spatial scenarios is substantial (Figure 68), with both of the robustness scenarios suggesting a very high risk relative to the reference set. This suggests that, as far we can tell at the moment, the adopted HS is sensitive to the spatial connectivity assumptions. However, without reconditioning the operating model through an appropriately spatially structure stock assessment, it is not clear that the spatially restricted spatial scenarios would be consistent with the data (e.g. if the population was very small, local CPUE might have been expected to decline in a manner that is not evident in the ETBF data). Unless reconditioning is undertaken, there is not much basis for discriminating between plausible and implausible spatial assumptions.

Bigeye Tuna MSE Conclusions

- The spatial structure in the assessment cannot be easily converted to an operating model that reliably reflects the movement dynamics and spatial connectivity relevant to the ETBF. The reference set of operating models is very consistent with the ETBF data (more so than any other species), however, it does not reflect the connectivity with equatorial regions estimated from tagging studies.
- The reference set suggests that the ETBF has a small impact on the local population.
- Spatially restricted robustness sets suggest that the adopted HS would be ineffective in preventing a serious population decline if there was a very small local bigeye population. However, the validity of this simulation test is dubious and the question can probably only be properly addressed if there is a specific reconditioning of bigeye operating models using appropriately spatially structured data.

Table 14. Bigeye Tuna specific cut-off weights for the definition of juvenile, prime and old sized fish, and length to whole weight parameters (Campbell et al, 2009; Robert Campbell, pers. comm.).

Bigeye	
Upper cut-off whole weight for juvenile size group	24.4 kg
Lower cut-off whole weight for Old size group	47.6 kg
Length to whole weight parameters (wwt=a*len^b)	a= 0.000019729 b= 3.0247

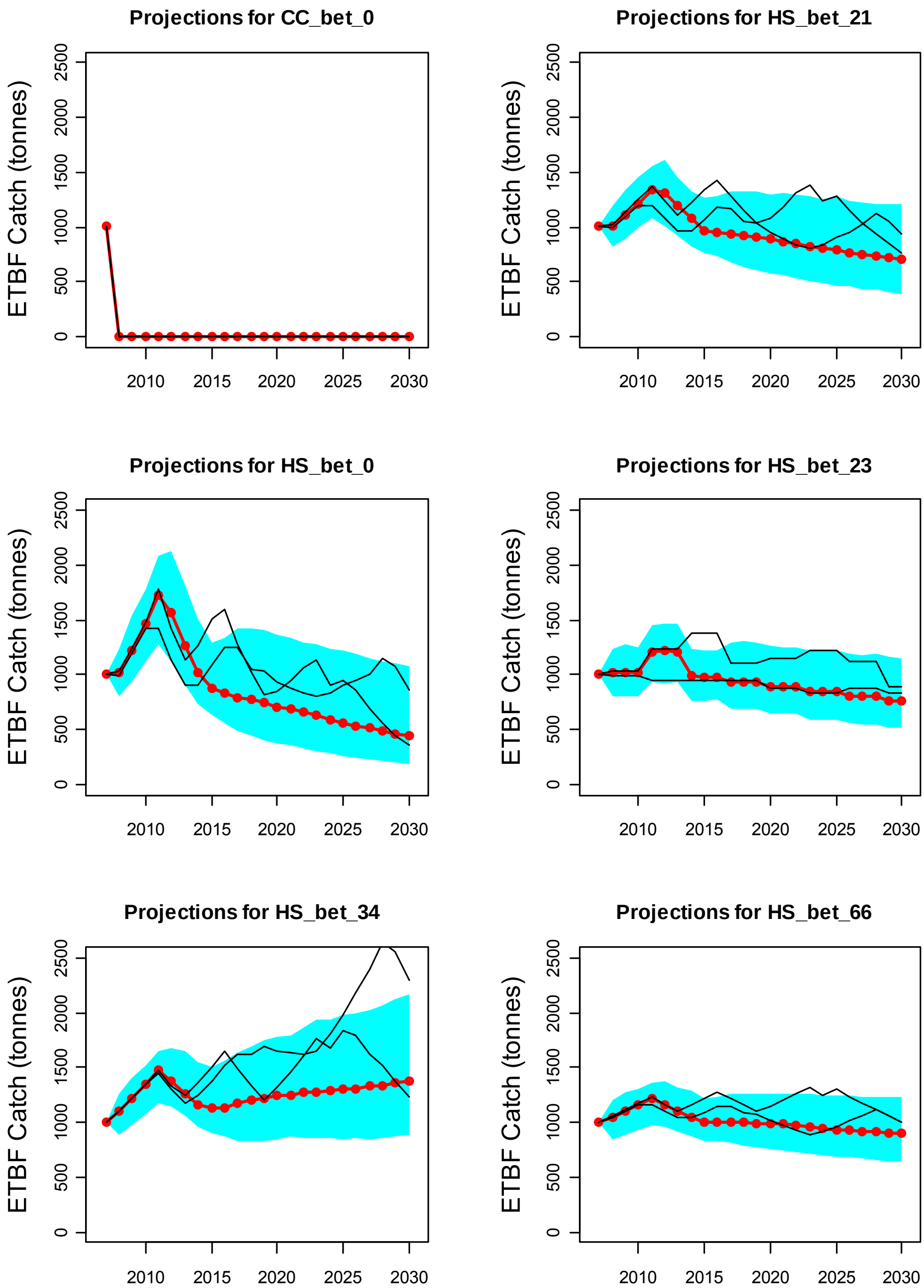


Figure 59. Bigeye tuna estimated catch trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

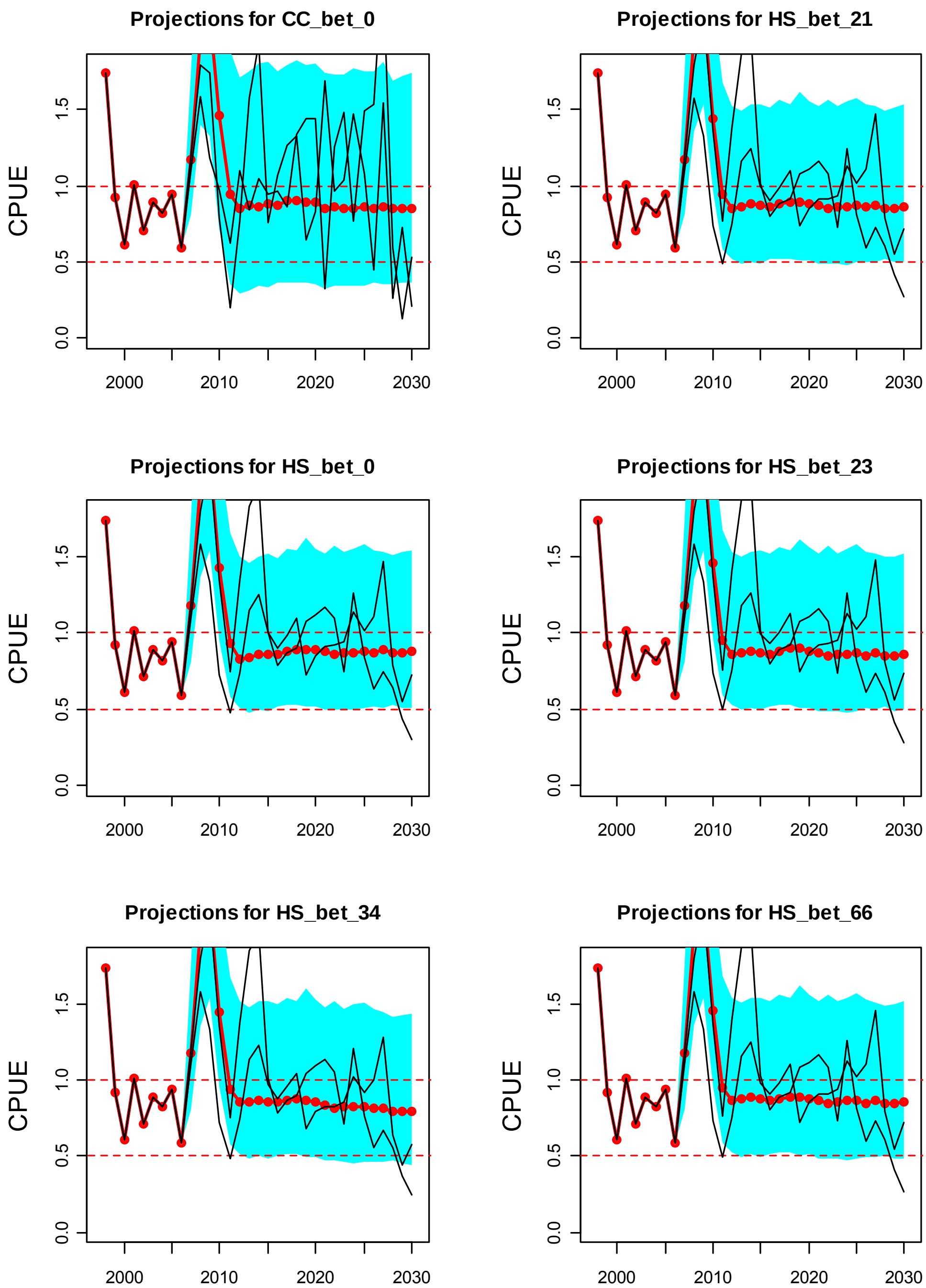


Figure 60. Bigeye tuna estimated CPUE trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

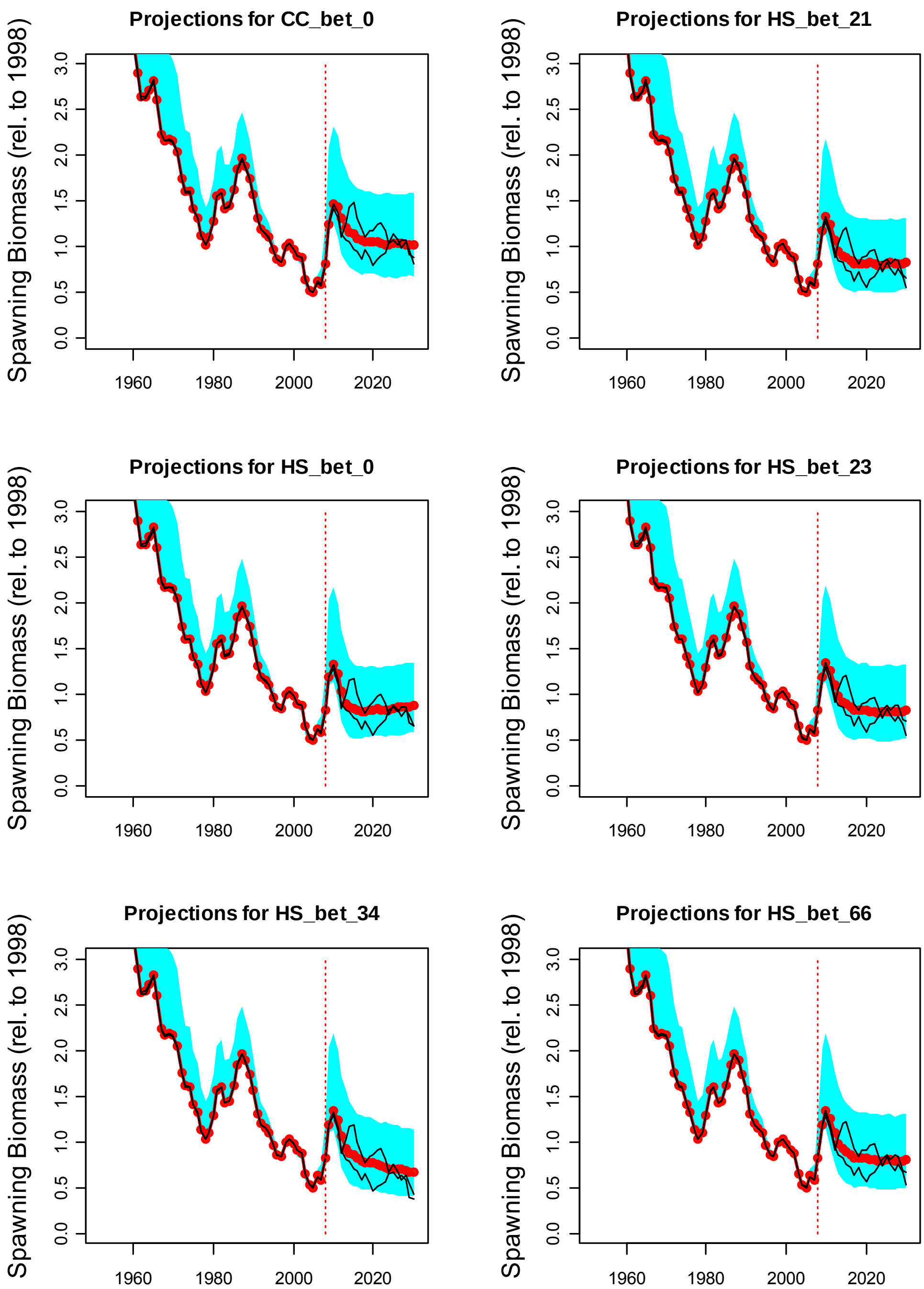


Figure 61. Bigeye tuna estimated spawning biomass (combined ETBF and non-ETBF) trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

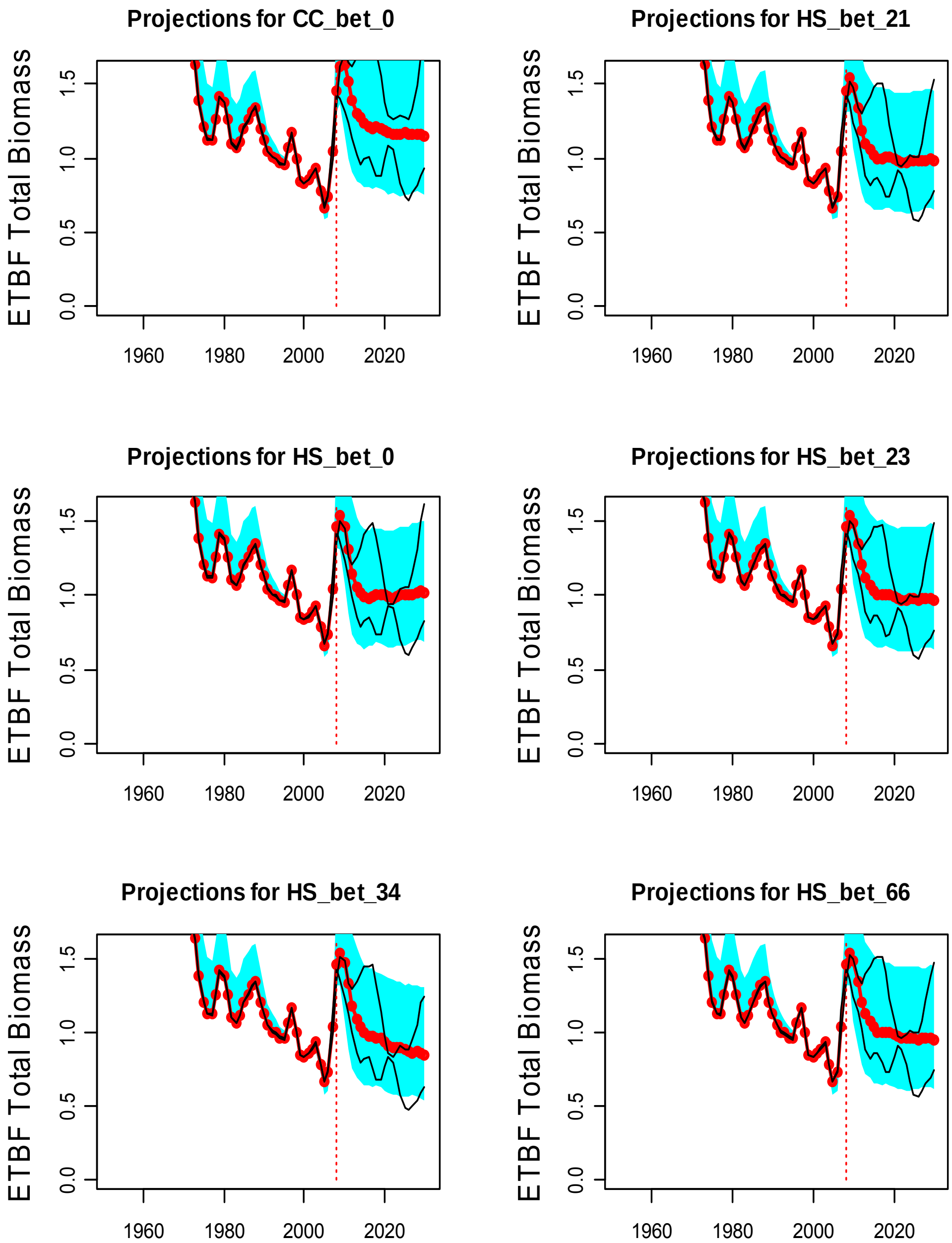


Figure 62. Bigeye tuna estimated total ETBF biomass trajectories for six ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

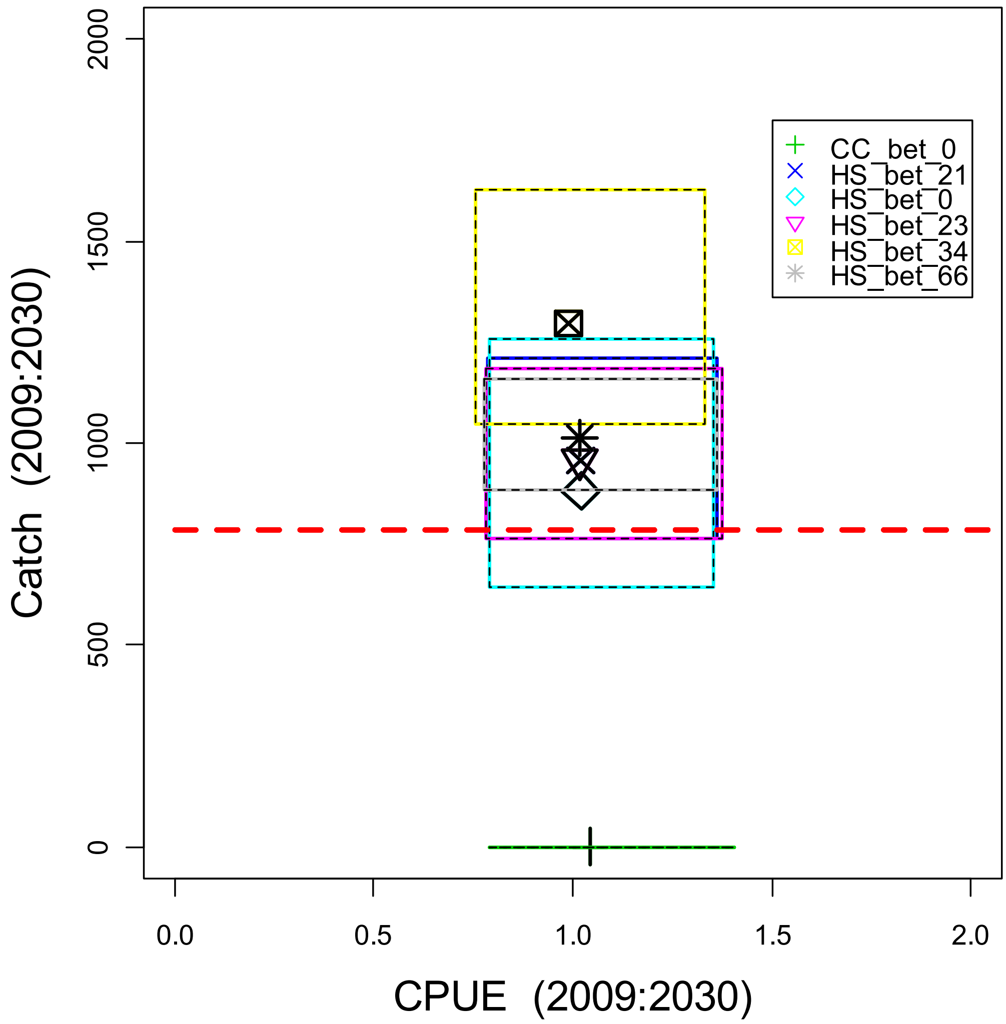


Figure 63. Bigeye tuna trade-off plot illustrating the estimated relationship between catch and CPUE for a range of Harvest Strategies. Symbols represent the median performance (averaged over time) for all realizations; boxes bound the 10th-90th percentile region in both dimensions. The broken red horizontal line indicates the 2007 catch level.

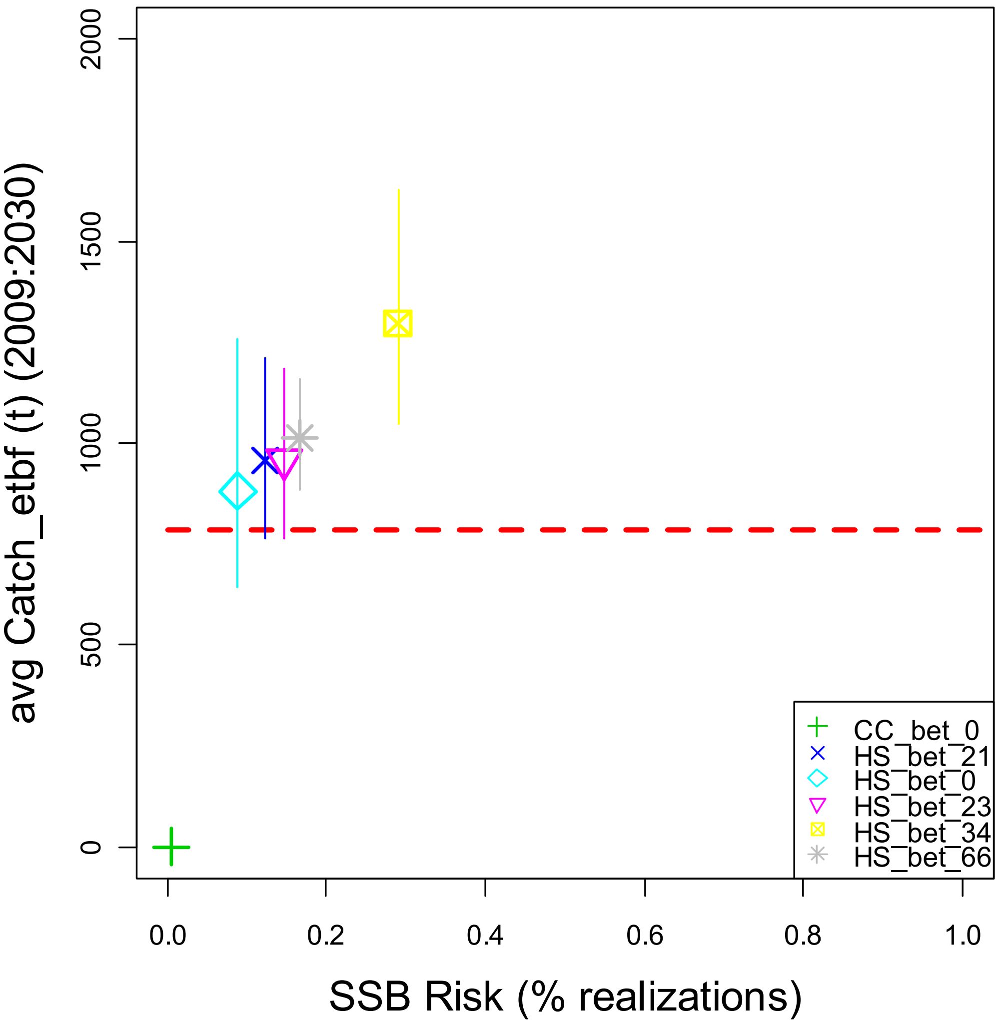


Figure 64. Bigeye tuna trade-off plot illustrating the estimated relationship between catch and biomass risk. Risk is defined as the proportion of stochastic projections in which spawning biomass (*SSB*) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Dotted vertical lines show how specific levels of risk might be used to remove some candidate HSs from further consideration. The broken red horizontal line indicates the 2007 catch level.

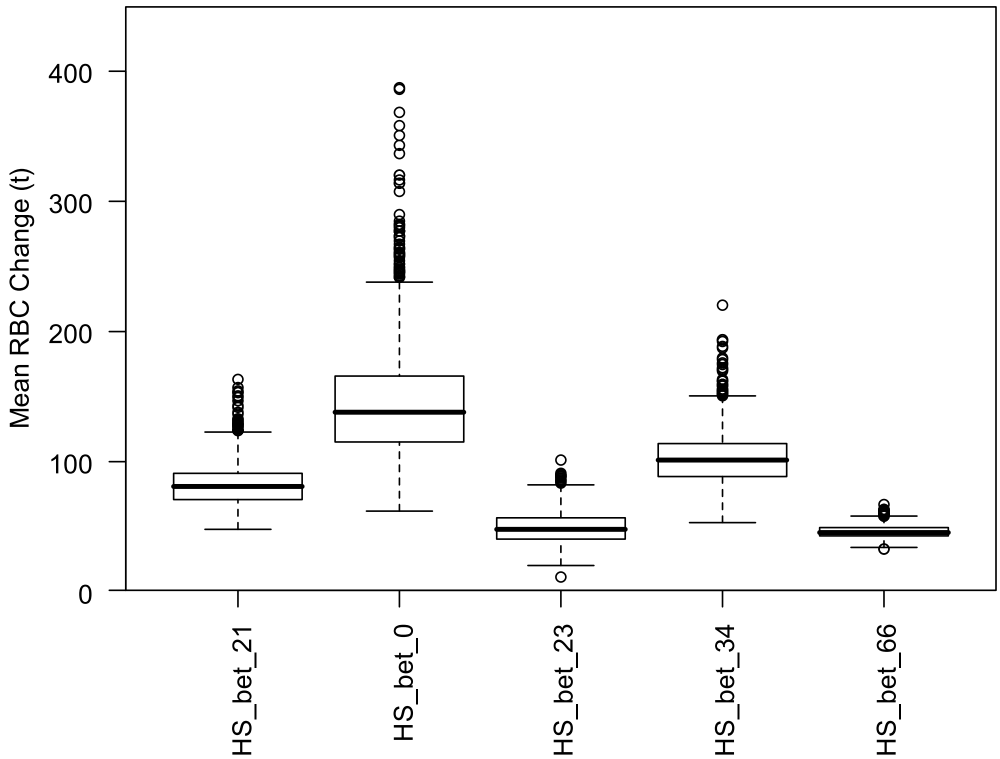


Figure 65. Reference Set bigeye tuna RBC variability statistics for a range of Harvest Strategies. Boxplots represent the distribution of the average absolute value of the change in RBC associated with each HS (i.e. each observation within a boxplot represents the mean value from a single stochastic realization). The dark line represents the median of the distribution, the box represents the 25th-75th percentiles, whiskers represent the range or 1.5 of the interquartile distance (whichever is smaller), and circles represent outliers that exceed the whiskers.

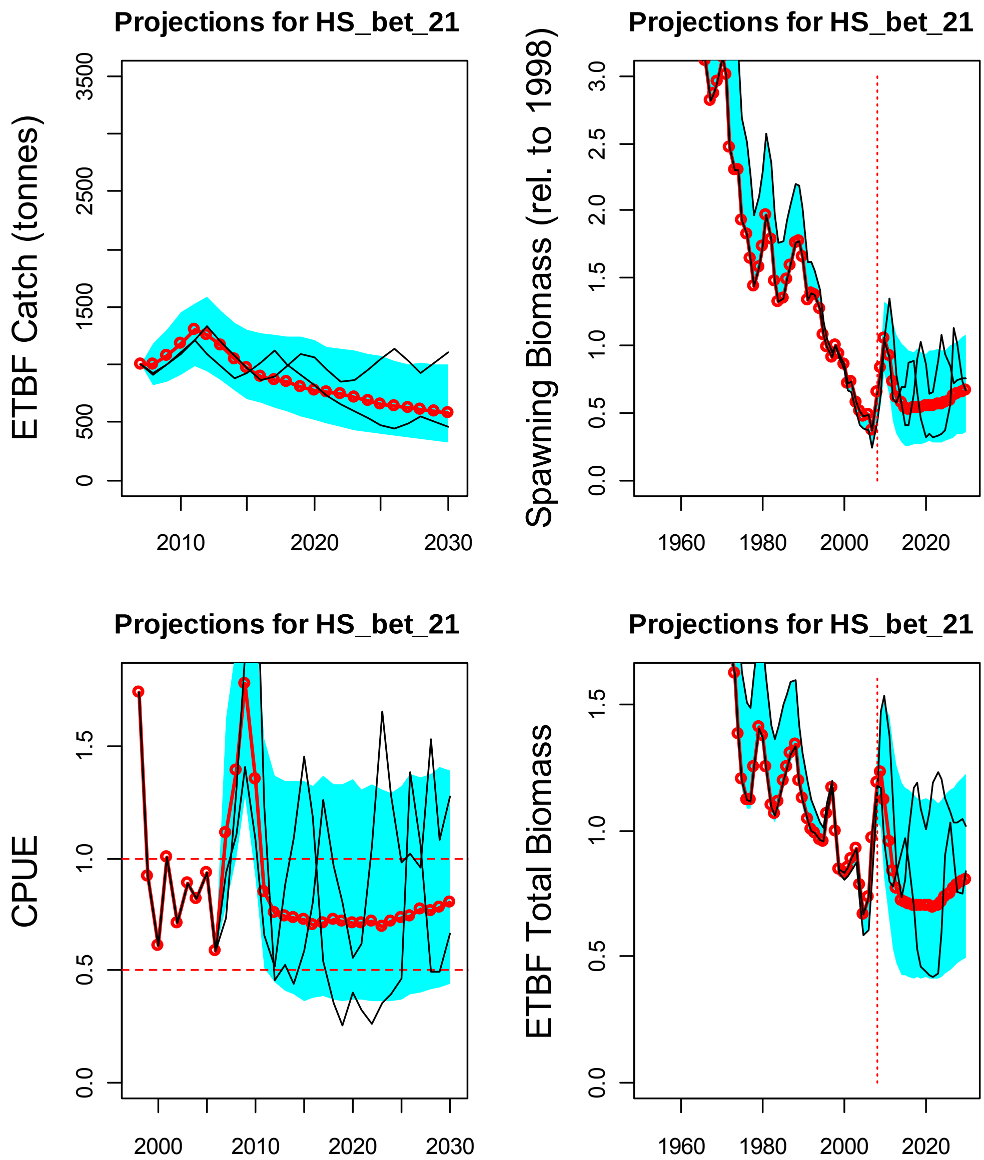


Figure 66. Time series trajectories for the adopted bigeye tuna HS (HS_bet_21) when evaluated against the restricted spatial robustness set in which 50% of the region 5 population was allocated to the ETBF fishery. Spawning biomass refers to the combined ETBF and non-ETBF, while total biomass refers to all ages in the ETBF region only.

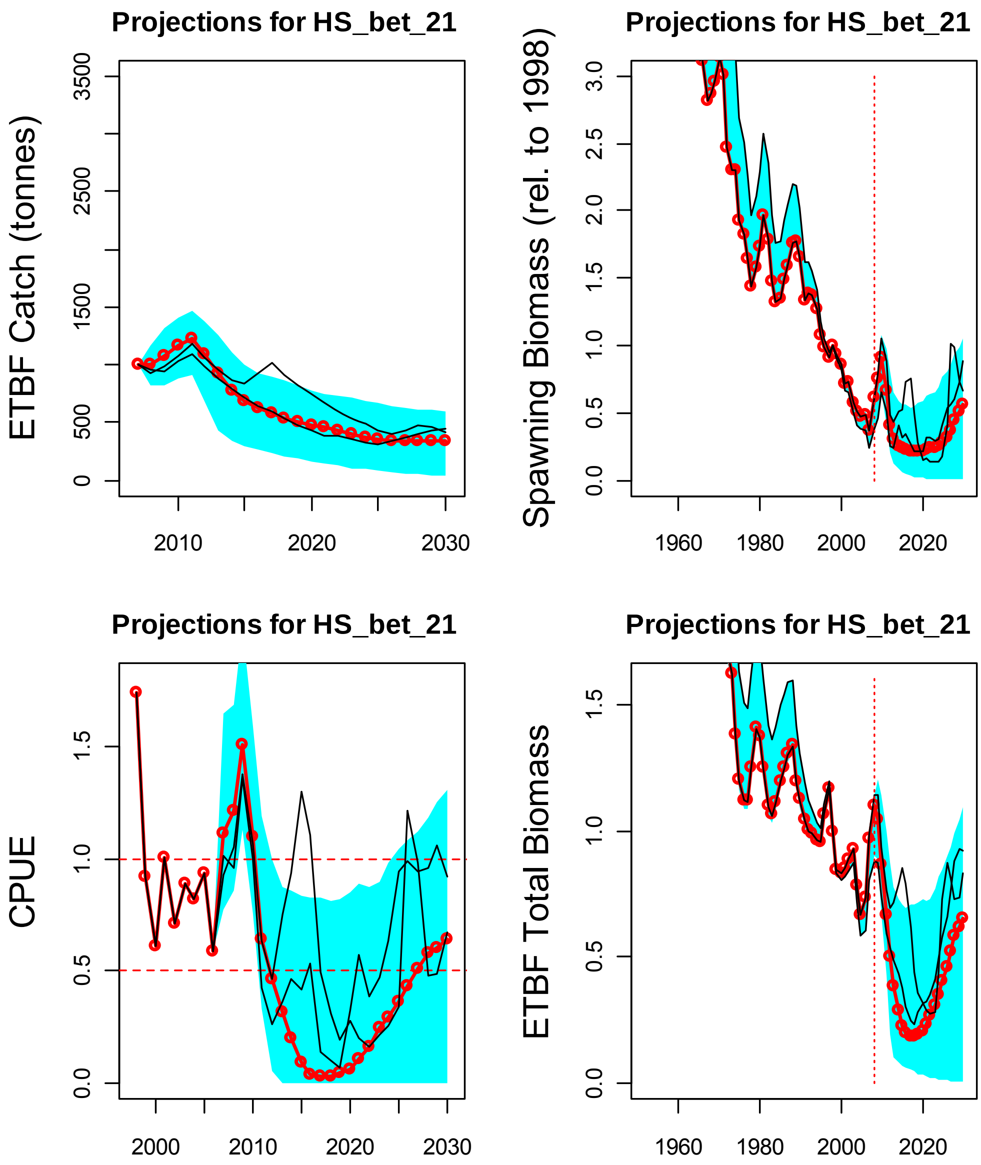


Figure 67. Time series trajectories for the adopted bigeye tuna HS (HS_bet_21) when evaluated against the restricted spatial robustness set in which 25% of the region 5 population was allocated to the ETBF fishery. Spawning biomass refers to the combined ETBF and non-ETBF, while total biomass refers to all ages in the ETBF region only.

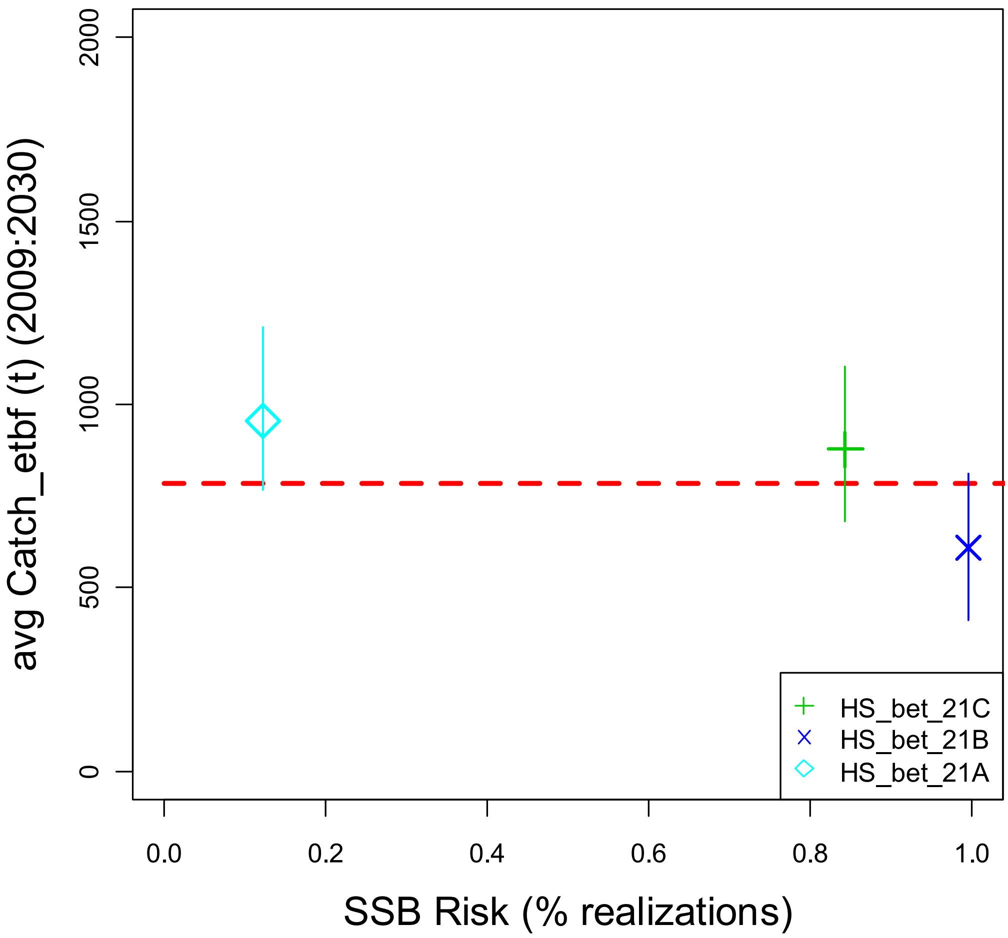


Figure 68. Biomass risk plot comparing the adopted harvest strategy (HS_bet_21) with the three different spatial assumptions. A=Reference Set, B= 25% region 5 robustness scenario, C=50% region 5 robustness scenario.

Yellowfin Tuna MSE

Yellowfin Tuna Reference Set Operating Models

The most recent yellowfin stock assessment for the region (that was available in time to be incorporated in this project) is described in Langley et al. (2007). The spatial structure of the assessment covers the whole Western and Central Pacific Ocean (Figure 69). The global fishery is estimated to be in a reasonable state, with moderate depletion ($B_{(T)}/B_{(no\ fishing)}$ = 0.51), largely attributed to the equatorial region. The current assessment estimates that there is relatively low mixing between the southern and equatorial regions (though movement estimates are highly uncertain), and the depletion in the ETBF region (5) is estimated to be minimal ($B_{(T)}/B_{(no\ fishing)} > 0.95$). Given that the equatorial region accounts for the majority of the catch, and the population connectivity is poorly understood, it is not clear how well the assessment represents local processes in the ETBF fishery.

Population connectivity scenarios might be more difficult to quantify and justify for the tropical tuna populations than the temperate species. For swordfish, striped marlin and albacore, there seem to be substantial populations in the south Pacific latitudes of the ETBF, and the degree of connectivity to the east is poorly understood. However, bigeye and yellowfin populations span the Pacific, with the bulk of the catch and population located in the equatorial regions. The different lines of evidence related to spatial structure and connectivity are not very conclusive for any of these species:

- Conventional tagging studies in the 1990s (Hampton and Gunn 1998) indicated that a substantial proportion of bigeye and yellowfin tagged in the Coral Sea were subsequently recaptured in the equatorial fisheries. There did not seem to be an equivalent number of fish tagged outside of the Coral Sea subsequently recaptured in the Coral Sea. It is unclear if this represents source-sink dynamics, or unrepresentative fishing effort and reporting rates. More recent conventional and archival tagging studies are underway, but have not been analysed to date.
- Gunn et al (2002) found that the primordium of yellowfin otoliths carry chemical signatures that can be used to make useful probabilistic assignments of individuals to natal regions. On this basis, yellowfin from NSW fisheries were estimated to be much more likely to come from the Coral Sea spawning region than the other regions sampled. However, the study did not sample any spawning regions between the Coral Sea, Solomon Islands and Fiji. The study further suggested that there might be interannual variability in migration among regions.
- Genetic studies identified differences between Western and Eastern Pacific yellowfin populations, but could not resolve differences within the Western Pacific (Ward et al 1997).
- Indirect evidence and anecdotal reports:
  - ETBF industry have intermittently reported two morphologically distinct yellowfin tuna types that might represent different populations, but this has never been formally described (Robert Campbell, pers. comm.)
  - CPUE in the ETBF seems to be consistent with the abundance trends estimated for the broader region 5 stock assessment estimates (and hence presumably the Japanese CPUE outside of the ETBF). This could indicate rapid mixing, or similar external forces driving the CPUE variability.

The reference set of operating model features are described in Table 15. Key assumptions included:

- MPD estimates consisted of a single model run that was judged by the developers to be preferable or representative for MSE purposes (Adam Langley, pers. comm.).
- The south-west region (5) was assumed to correspond to the ETBF component of the stock, and the south-east region (6) to the non-ETBF component (Figure 69). The reference case assessment model illustrated in Langley et al. (2007) suggested that these two regions were reasonably discrete from each other, and the equatorial regions. However, it is also recognized that tagging studies have not covered these regions very well. It can probably be argued that region 5 is more closely related to the equatorial region than region 6, and the adoption of region 6 as the non-ETBF component in the operating model should be recognized as only one possible scenario that reflects the fact that the ETBF may be a small pool of fish that is connected to another pool of substantial size. Two additional spatial assumptions are described in the robustness sets, and represent more localized populations. These more localized scenarios were proposed as alternative possibilities, that might seem equally plausible to the reference set, but at least one of them is not for reasons described in the subsequent section. Additional spatial assumptions:
  - The migration linkage between the ETBF and non-ETBF regions is assumed to be an equal mix of scenarios with 1%, 20% and 60% per quarter diffusive mixing.
  - The stock recruitment relationship is re-scaled from the aggregate WCPO assessment, such that steepness is the same, and R0 is reduced by the fraction of recruitment in areas 5 and 6 relative to the whole WCPO.
  - 72% of the recruitment is assigned to the ETBF, and represents the proportion of the equilibrated population in the absence of harvesting.
- Future non-ETBF effort is assumed to remain constant at 2005 levels because the distant water fishing fleets are responsible for most of the catch. The WCPFC has not taken strong action with respect to yellowfin to date, however, actions affecting purse seine effort will presumably have an effect on yellowfin catches.
- The selectivity of the ETBF fleet was adopted from the assessment estimates (LL AU 5), while we assumed that the non-ETBF fleet was adequately represented by the major longline fleet in area 5 (LL ALL 5). The validity of this selectivity assumption is closely intertwined with the spatial assumptions (i.e. selectivity is the combined effect of gear selectivity and spatial availability). If the ETBF population is closely linked to the equatorial regions, then purse seine fishery selectivity could be important. However if purse seine activity is stable, the selectivity implications for the longline fleet might be manifested in the ETBF primarily as reduced recruitment.
- Recruitment is quarterly. The recruitment variability used in the reference set operating model was adopted from the empirical estimates in the assessment (sd(log) = 0.87, autocorrelation rho = 0.41). It is generally assumed that the recruitment estimates for the tropical tuna are better than for the billfish species because there is usually better size composition sampling, the resolution of distinct length modes are observed in the frequency distributions, and there is a

general perception that other biological characteristics are more reliably quantified. However, as with the billfish species, weakly recruited cohorts are not well estimated, and additional stochastic error was introduced to the MPD estimates of the youngest cohorts (age 0 sd(log) = 0.5, age 1 sd(log) = 0.25).

- The magnitude of the CPUE observation error variability was assumed to be relatively low (sd(log) = 0.2) and strongly autocorrelated (rho = 0.7), identical to the other species.
- The reference set consisted of 1200 projections = (1 MPD estimates) X (3 migration rates) X (2 size composition sampling errors) X (2 implementation error assumptions) X (100 stochastic realizations per scenario).
- The depletion level corresponding to B_{MSY} (i.e. B_0/B_{MSY}) was 0.24 when B_0 was defined as the mean unfished biomass in the 1980-2004 period, and 0.25 relative to the equilibrium B_0. This is substantially lower than the 0.4 B_0 proxy value suggested in the HSP.
- Other biological and fishery assumptions correspond to those described in Langley et al. (2007).

Figure 70 illustrates that there is reasonable agreement between the observed yellowfin CPUE for the ETBF, and the predicted values from the operating models. However, the agreement is not as good as for bigeye tuna, and there is not much contrast during the period of overlap. Figure 71 indicates that there are large discrepancies between the predicted and observed size composition. This may reflect errors in basic biological inputs (as is probably the case in swordfish and striped marlin), or it may indicate heterogeneity of yellowfin within region 5.

Figure 72 illustrates the dynamics estimated to occur if fishing was stopped completely. The median biomass is roughly consistent with the historical average from 1960-present. The 10^{th}-90^{th} percentiles look to be consistent with this period as well, with the large fluctuations presumably driven primarily by the recruitment variability.

Main concerns about the reference set of yellowfin tuna operating models:

- Use of a single MPD estimate probably results in a gross underestimate of the uncertainty in the yellowfin assessment. However, if the optimistic stock status estimates for region 5 and 6 are anything to go by, this may not matter very much.
- Migration dynamics are poorly quantified in the assessment. The assumptions used in either the reference or robustness sets cannot be rigorously defended at this time, but should be adequate to qualitatively demonstrate how the HS framework performs under alternative situations.
- As with all of these species, large changes in the effort distribution of the non-ETBF fleet could undermine the results. However, assuming that the WCPFC continues to pursue effective management measures that do not result in the unintended redistribution of effort, this should not be a problem for yellowfin in this region.

Yellowfin Tuna Robustness Set Operating Models

The arguments for defining the yellowfin robustness scenarios are similar to those of bigeye. In the reference set, we assume that there is a sizable pool of fish that may or may not be closely linked to the ETBF. The merging of the region 5 and 6 populations is probably sufficient to qualitatively demonstrate the effect of having a very large pool of fish (i.e. such that the ETBF cannot have a strong impact with current effort levels). Two additional robustness scenarios were defined, in which the yellowfin population was assumed to be restricted to area 5 only. In the first scenario, the ETBF population is assumed to correspond to 50% of the area 5 population (and the non-ETBF the remaining 50%). In the second scenario, the ETBF population is assumed to correspond to 25% of the area 5 population (and the non-ETBF another 25%). In the latter case, the non-ETBF catch was calculated as 50% of the total region 5 catch minus the ETBF catch. These scenarios were not reconditioned to these spatial assumptions (i.e. ideally the data should be disaggregated according to the proposed spatial structure and the model parameter estimation should be repeated). It was assumed that partitioning the assessment estimates would produce a rough approximation of something that would qualitatively resemble a more localized population. But unintended artefacts could also be introduced (e.g. in an extreme case, there might not be enough fish in one of these restricted areas to account for the catches that were extracted).

Figure 73 and Figure 74 illustrate the dynamics that are estimated to occur if fishing was stopped completely for these two robustness sets. The two patterns are very similar to each other, and more optimistic than the reference set. As with bigeye, this emphasizes that the spatial patterns of fishing and production dynamics are not uniform across the southern hemisphere regions of the yellowfin assessment domain. We would expect that patterns would also be different if alternative patterns that included equatorial populations and fisheries were considered as well.

Table 15. YFT Reference Set of Parameters

Dimension	Option 1	Option 2	Option 3	Number of Reference Set grid elements
M growth maturity Stock-Recruitment steepness selectivity	**1 model** Most population and fishery characteristics are adopted from the assessment inputs or Maximum Posterior Density (MPD) estimates			1
N(initial) and future Recruitment Bias	**0 (i.e. MPD estimates are used)**			1
*Stochastic replicates	**100**			100
Recruitment SD(log(dev)); autocorrelation	**τ=0.87 ; ρ=0.41**			1
CPUE obs. error SD(log(dev)); autocorrelation	**τ=0.2 / ρ=0.7**			1
Migration Rate	**20%/qtr**	**1%/qtr**	**60%/qtr**	3
Effort in the non-ETBF fishery	**Constant at 2007 levels**			1
size sample / mag distortion / autocorrelation	**70% unbiased = 0.7 / 0 / 0**	**0.7 / 0.2 / 0.7**		2
RBC implementation error SD(log(dev))	**0**	**0.2**		2
Data Time Lag for HS Application	**6 months**			1

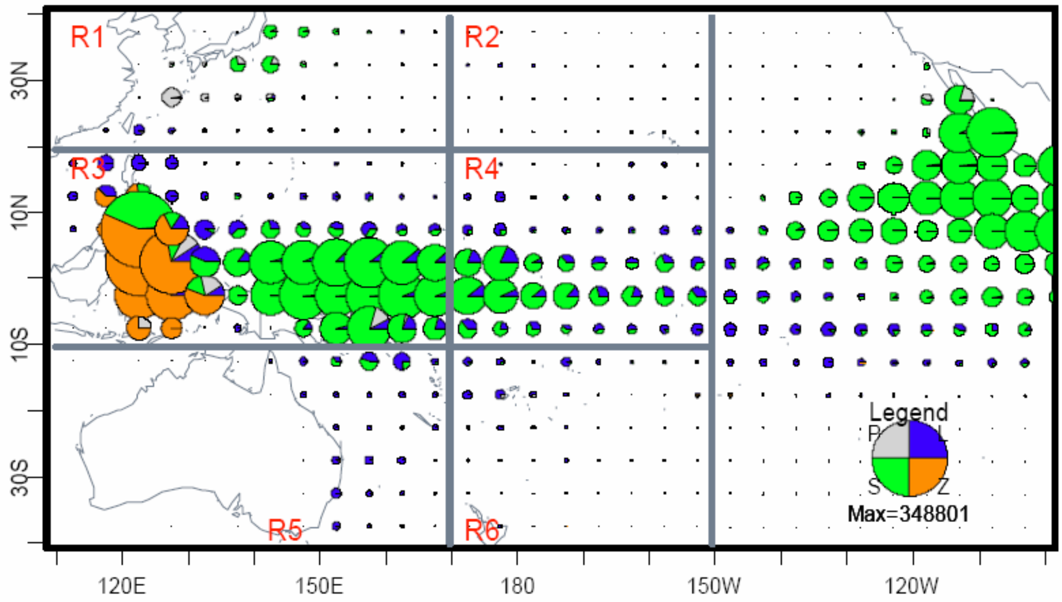


Figure 69. Yellowfin tuna assessment model spatial domain from Langley et al (2007 Figure 5). Distribution of cumulative yellowfin tuna catch from 1990−2005 by 5 degree squares of latitude and longitude and fishing gear; longline (L, blue), purse-seine (S, green), pole-and-line (P, grey) and other (Z, dark orange). The grey lines indicate the spatial stratification. In the ETBF HS operating model, area 5 is defined as the ETBF, area 6 as the non-ETBF.

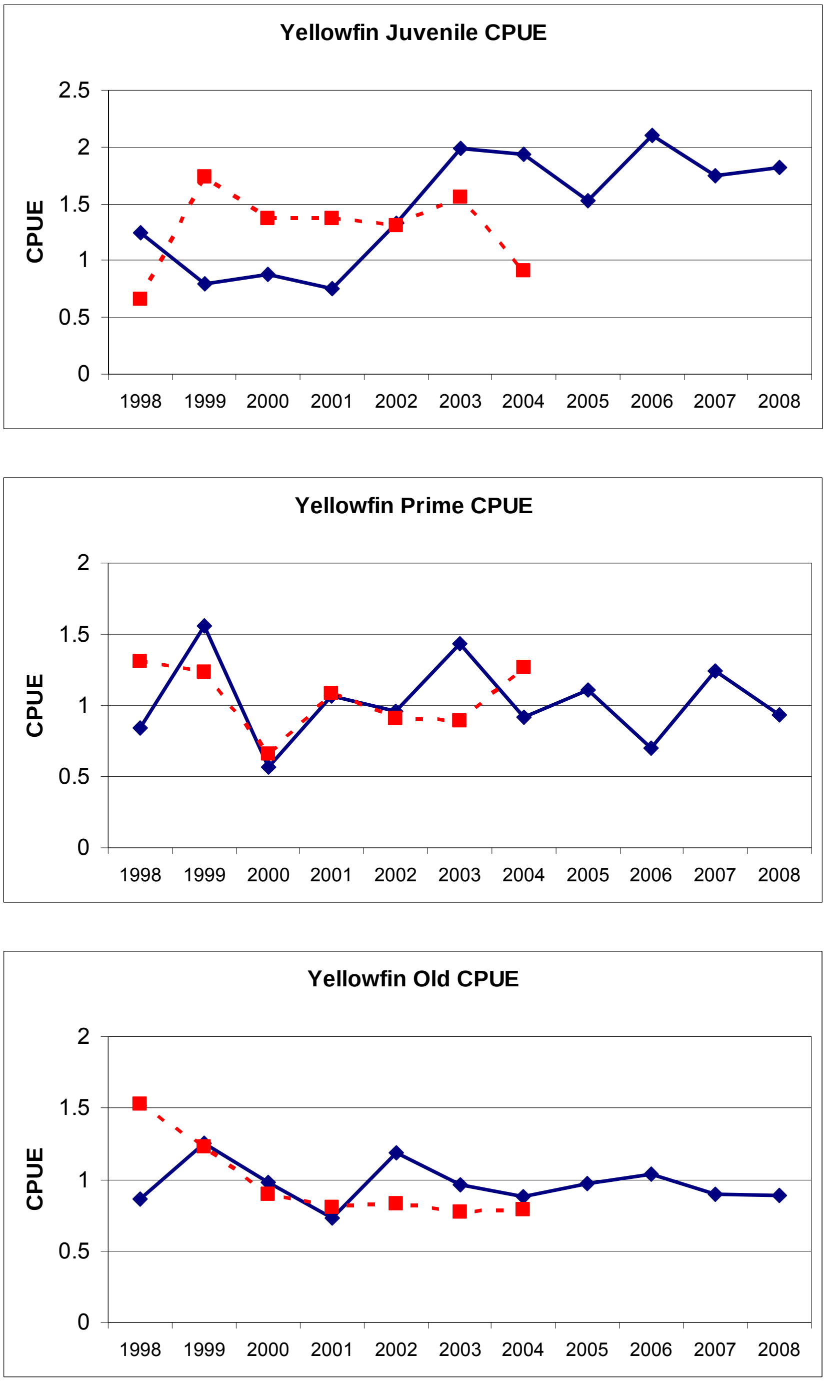


Figure 70. Yellowfin tuna comparison between predicted and observed CPUE for the Australian ETBF. Solid black lines (diamonds) are the observed standardized CPUE by juvenile, prime and old size classes; broken red lines (squares) are the equivalent assessment model estimates (later years are not shown because they consist of stochastic projections).

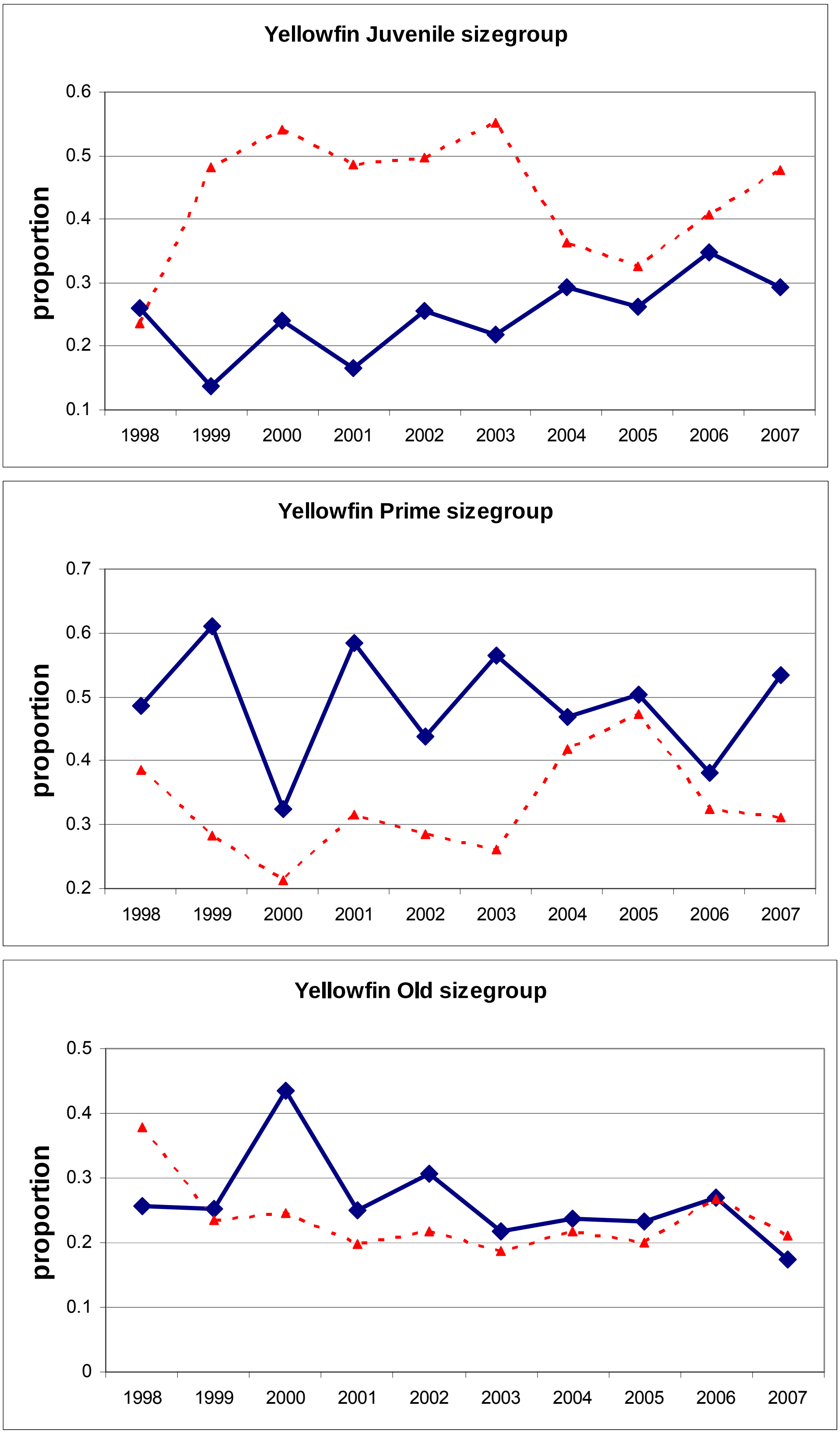


Figure 71. Yellowfin tuna comparison between predicted and observed proportions for the Australian ETBF. Solid black lines (diamonds) are the observed data. Broken coloured lines are the operating model proportions (projections start in 2005).

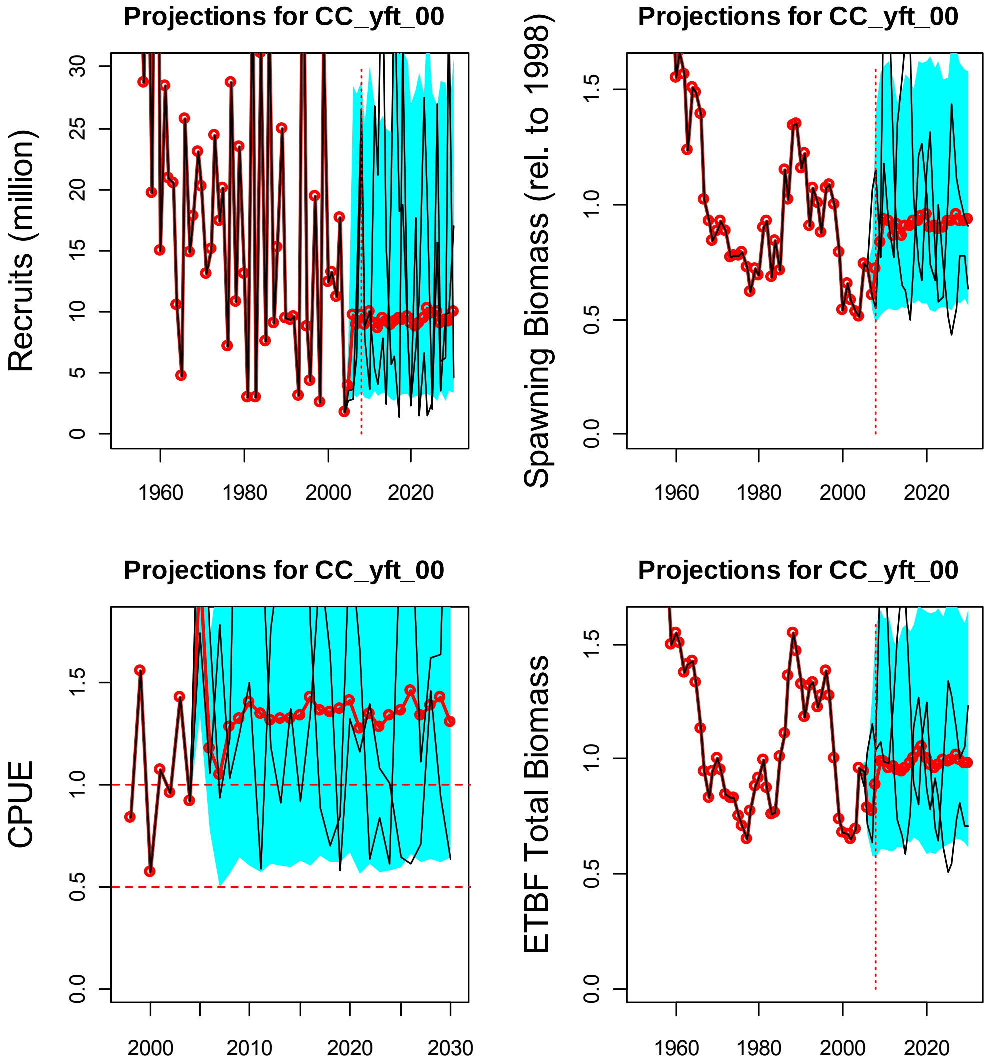


Figure 72. Yellowfin tuna operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

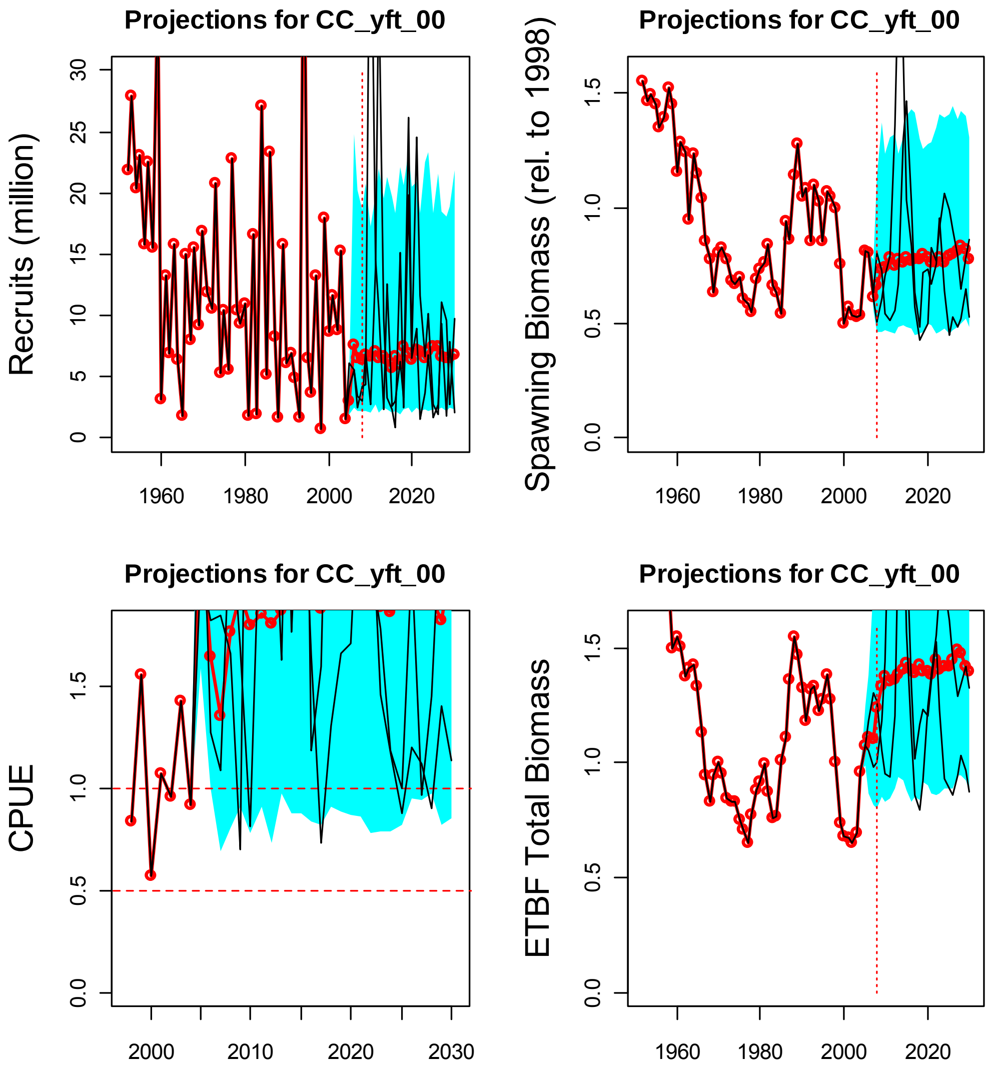


Figure 73. Yellowfin tuna robustness set operating model (50% of the region 5 ETBF population assigned to the ETBF and 50% assigned to the non-ETBF) showing time series resulting when fishing was stopped in the ETBF and non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two randomly selected trajectories.

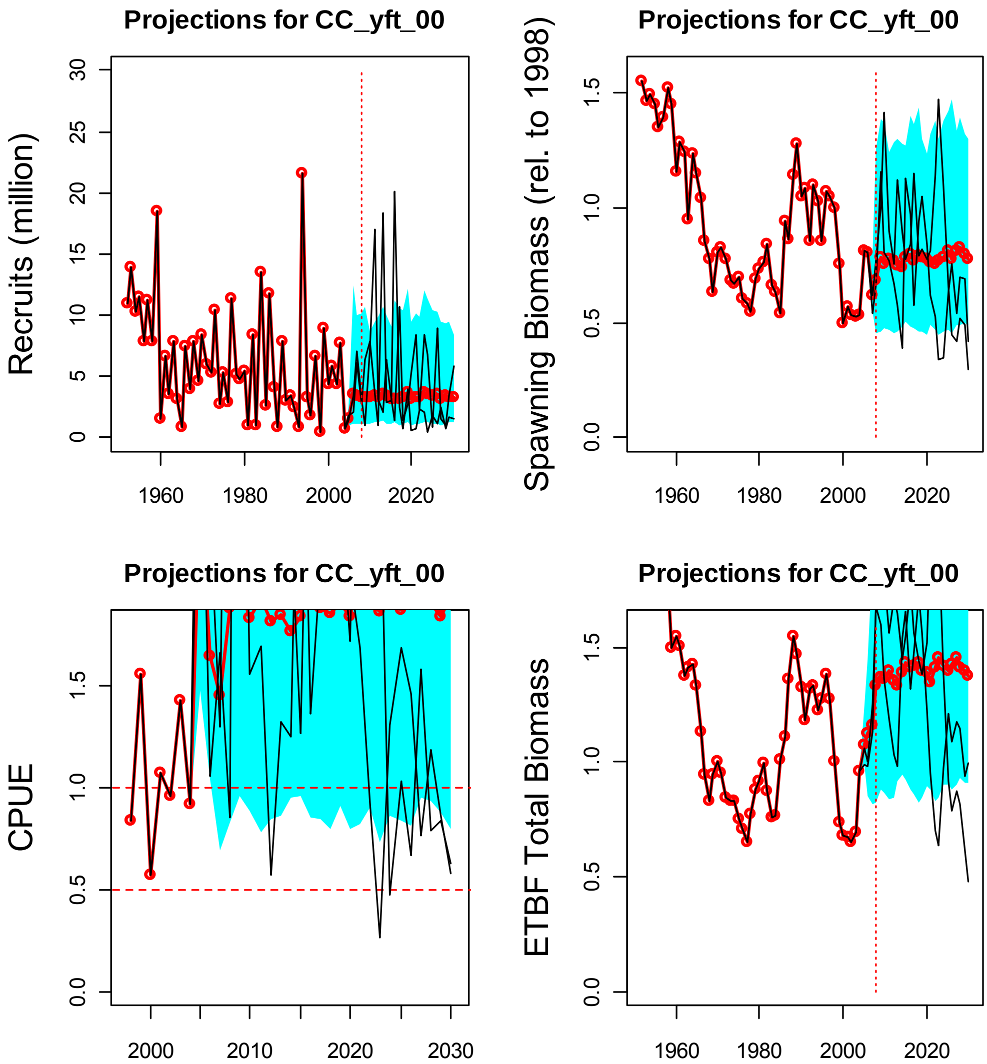


Figure 74. Yellowfin tuna robustness set operating model (25% of the region 5 ETBF population assigned to the ETBF and 25% assigned to the non-ETBF) showing time series resulting when fishing was stopped in the ETBF and non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two randomly selected trajectories.

Yellowfin Tuna Harvest Strategy Evaluation

Reference Set

Figure 75, Figure 76, Figure 77 and Figure 78 illustrate the estimated catch, CPUE, spawning biomass and total biomass trajectories for four ETBF Harvest Strategies that were selected to demonstrate a range of behaviours.

Figure 79 illustrates the estimated relationship between catch and CPUE for a range of Harvest Strategies. Figure 80 illustrates the estimated relationship between catch and biomass risk associated with the different harvest strategies. Both plots strongly suggest that the ETBF does not represent much risk to the reference set yellowfin population (within the range of catches prescribed by the selected HSs, or likely to be plausible in the foreseeable future).

Figure 81 illustrates the average annual variation in RBC for a range of harvest strategies for the reference set.

Figure 82 and Figure 83 compare 4 ETBF Harvest Strategies which differ in the number of years used in the CPUE slope calculations (3 or 8 years), and the responsiveness of the decision tree (RBC change scalar = 0.85 or 0.95). These tests were included specifically to explore the effect of the number of years in the slope calculation. The median catch trajectories all show long-term trends either up or down. Presumably too many years would result in a rule that is very stable but too slow to respond to important signals, while too few years would result in an over-reactive rule that chases observation errors. It was expected that yellowfin might be the most interesting test case because this species has the fastest life history characteristics and most variable recruitment dynamics. However, since the ETBF has such a small effect on the population in the reference set of operating models, all of these harvest strategies have a minimal biomass risk and no real effect on the CPUE. However, it is interesting that the median catch of the most aggressive rule is more than 40% higher than the least aggressive rule. These scenarios are not very useful for concluding how many years to include in the CPUE slope calculations, but they are useful for illustrating two other points about the HS. First, the behaviour of the HS can be rather sensitive to some parameters in ways that are not easily predicted without the simulation testing (i.e. the targets and thresholds are the same for the 4 HSs, but median catches differ by more than 40%). And second, if the HS does not have a meaningful feedback effect on the stock, the RBC recommendations can meander in unpredictable directions that might appear to be strategically oriented, but which do not really contribute to the attainment of management objectives.

While these results are optimistic, it is clear that there is a lingering question of the appropriateness of the assessment model for resolving questions of spatial importance for the ETBF.

Robustness Sets

Time series trajectories for the adopted HS (HS_yft_21) are shown in Figure 84 and Figure 85 for the two spatially-restricted robustness scenarios. In both cases, the simulations suggest that the localized populations will tend to result in increased catch and CPUE, with minimal risk to the stock over the time period examined.

This provides a certain level of confidence that the yellowfin stock might be resilient to localized harvesting effects within the ETBF. However, as with bigeye, it remains unclear whether these scenarios have much relation to the local population structure and migration dynamics. Without reconditioning the yellowfin operating model with the data disaggregated in an appropriate spatial structure, it is difficult to comment on the validity of the simulation testing. Reconditioning would represent an improvement over the current testing in that internally consistent models could at least be developed and used for MSE. However, even the reconditioning is not likely to resolve the spatial connectivity uncertainty, unless additional informative data can be collected.

Yellowfin Tuna MSE Conclusions

- The reference set and spatially-restricted robustness sets suggest that the ETBF is likely to have a very small impact on the local yellowfin population within the timeframe of the simulations unless there is an exceptional increase in effort.
- If these simulations are valid, it suggests that the adopted HS may be disconnected from the basic feedback principle on which it was developed, whereby the RBC catch trajectory could meander in different directions for reasons independent of the fishery effect, and which result in no strategically useful management of catches and stock size.
- However, it is not clear that the simulation testing is very reliable for the ETBF fleet. Without specifically reconditioning the models to disaggregated data to a spatial resolution more appropriate to the ETBF, we do not know if the spatially restricted scenarios are internally consistent, or span an adequate range of plausible uncertainty in spatial structure. Reconditioning may resolve the internal consistency problem, and possibly provide useful bounds on the spatial uncertainty. However, reconditioning is not likely to reduce the spatial connectivity uncertainty, unless additional informative data can be collected from tagging or other methods for determining stock structure and connectivity.

Table 16. Yellowfin Tuna specific cut-off weights for the definition of juvenile, prime and old sized fish, and length to whole weight parameters (Campbell et al, 2009; Robert Campbell, pers. comm.).

Yellowfin	
Upper cut-off whole weight for juvenile size group	25.2 kg
Lower cut-off whole weight for Old size group	47.6 kg
Length to whole weight parameters (wwt=a*len^b)	a= 0.00002512 b= 2.9396

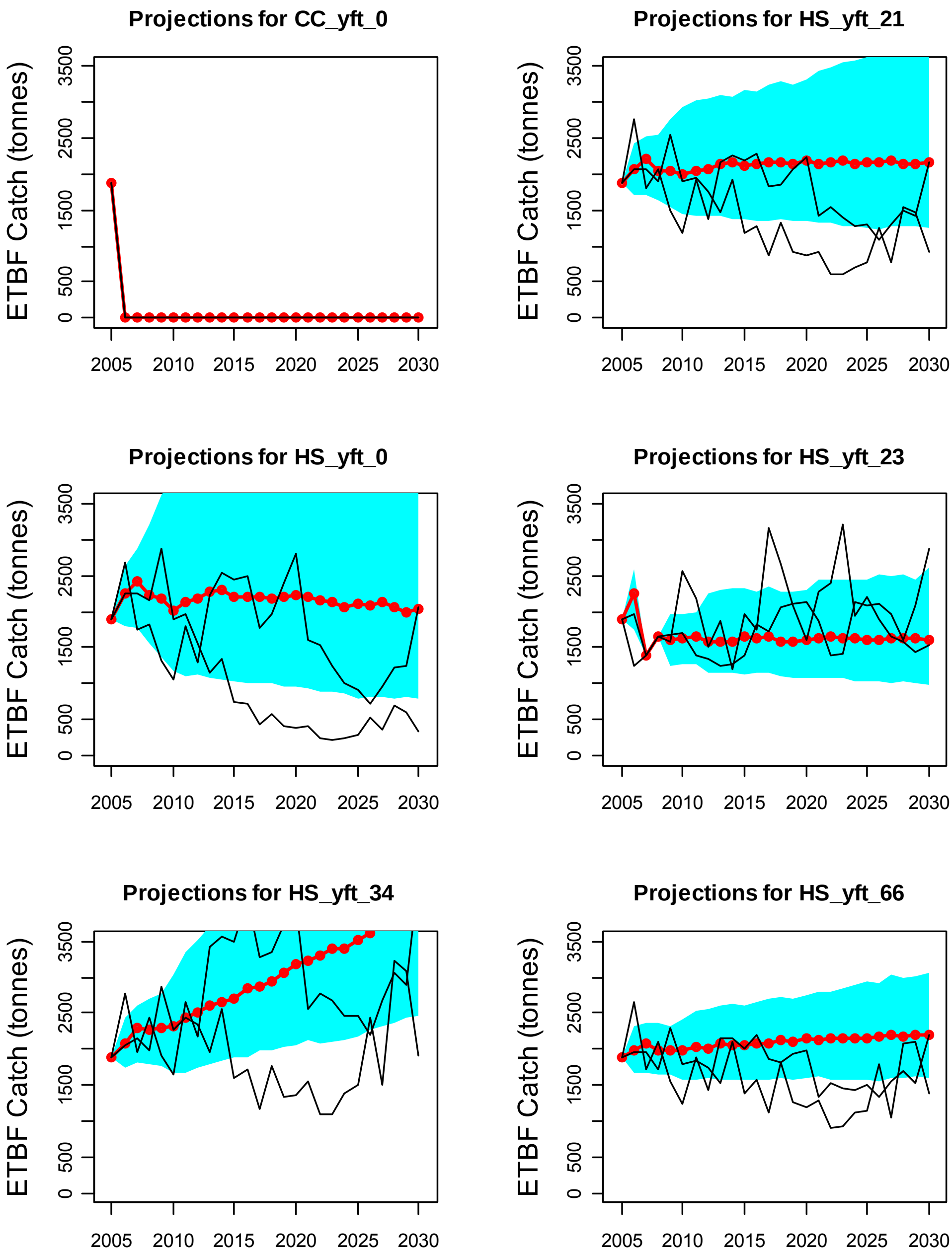


Figure 75. Yellowfin tuna estimated catch trajectories for four ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

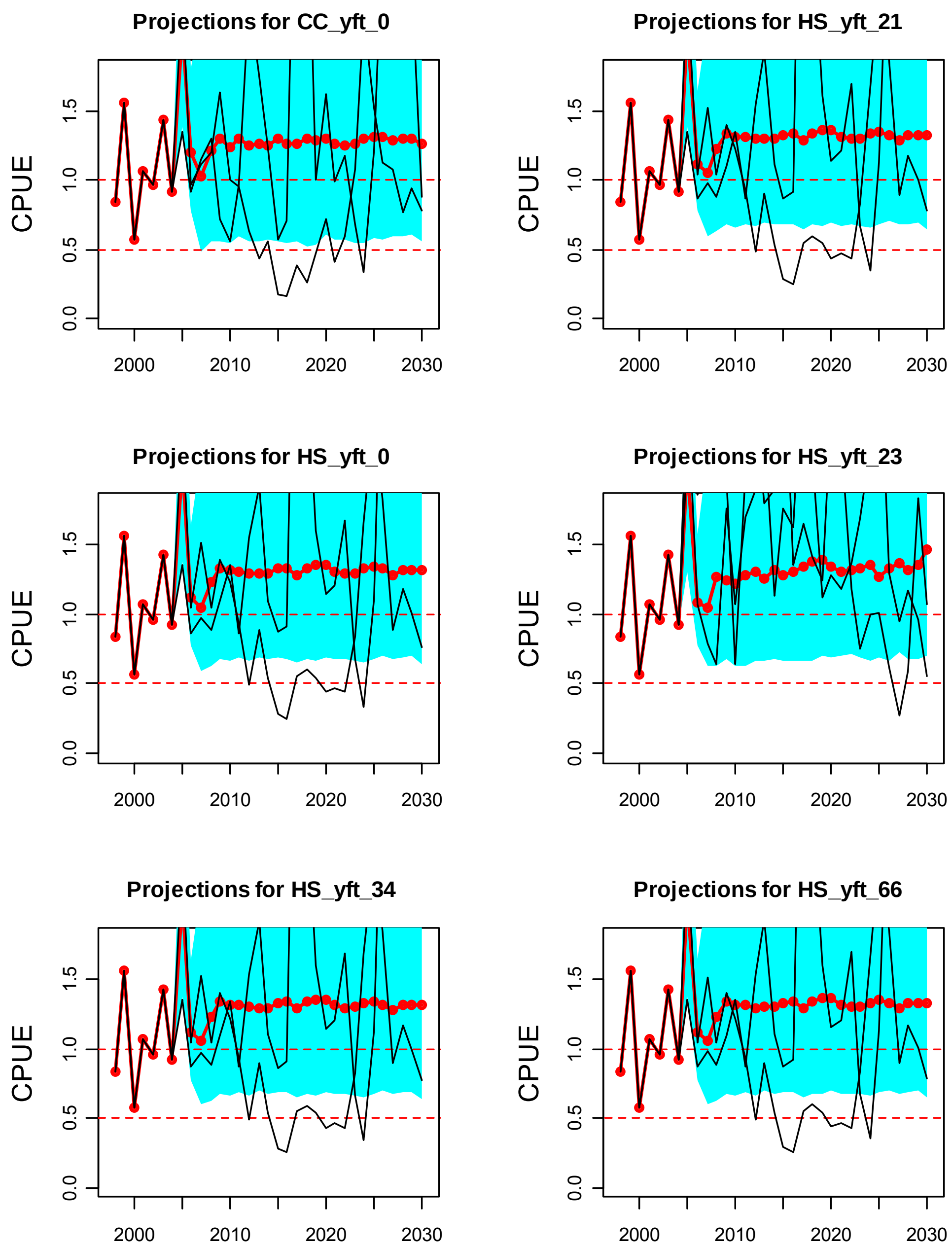


Figure 76. Yellowfin tuna estimated CPUE trajectories for four ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

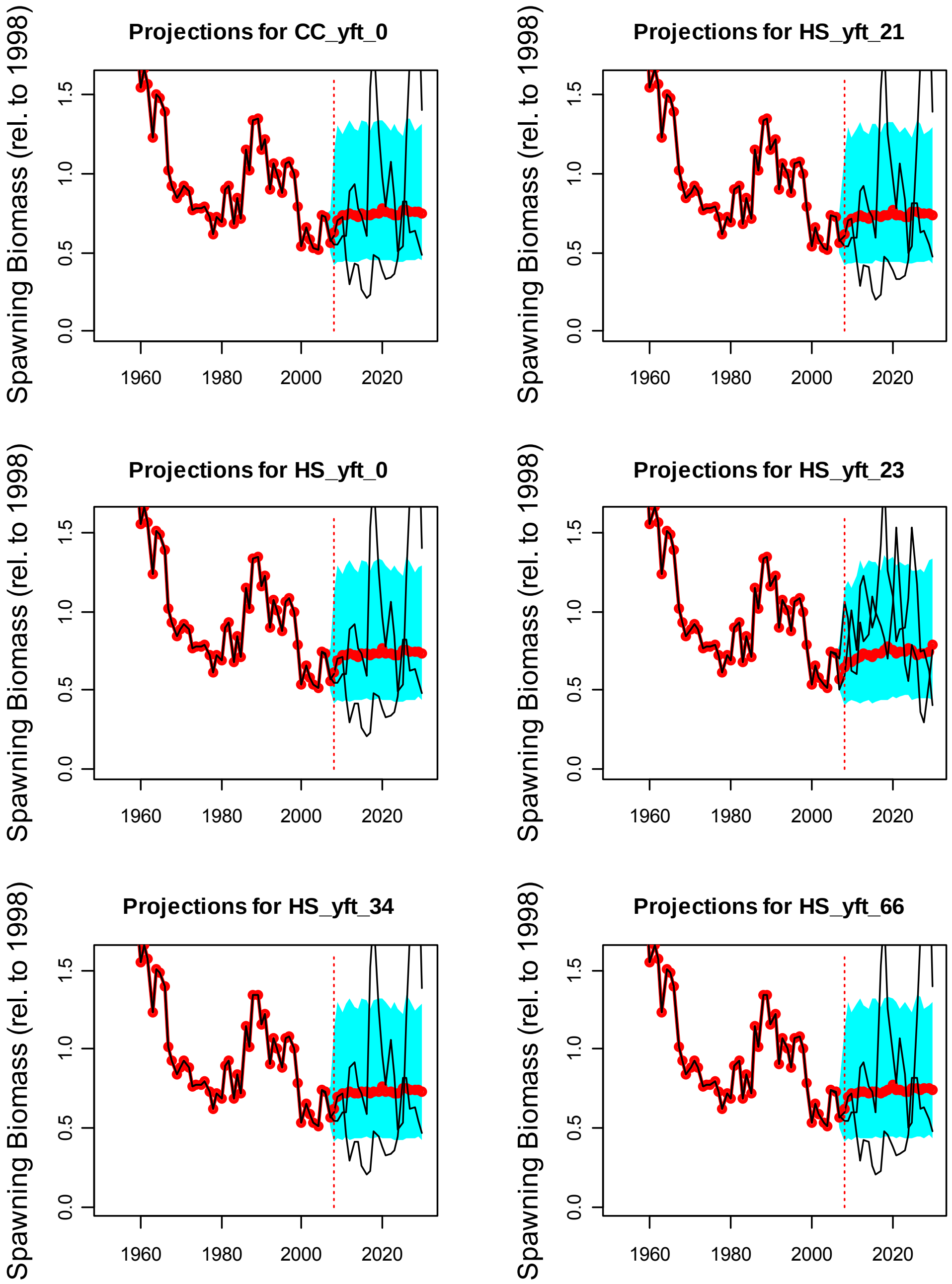


Figure 77. Yellowfin tuna estimated spawning biomass trajectories for four ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

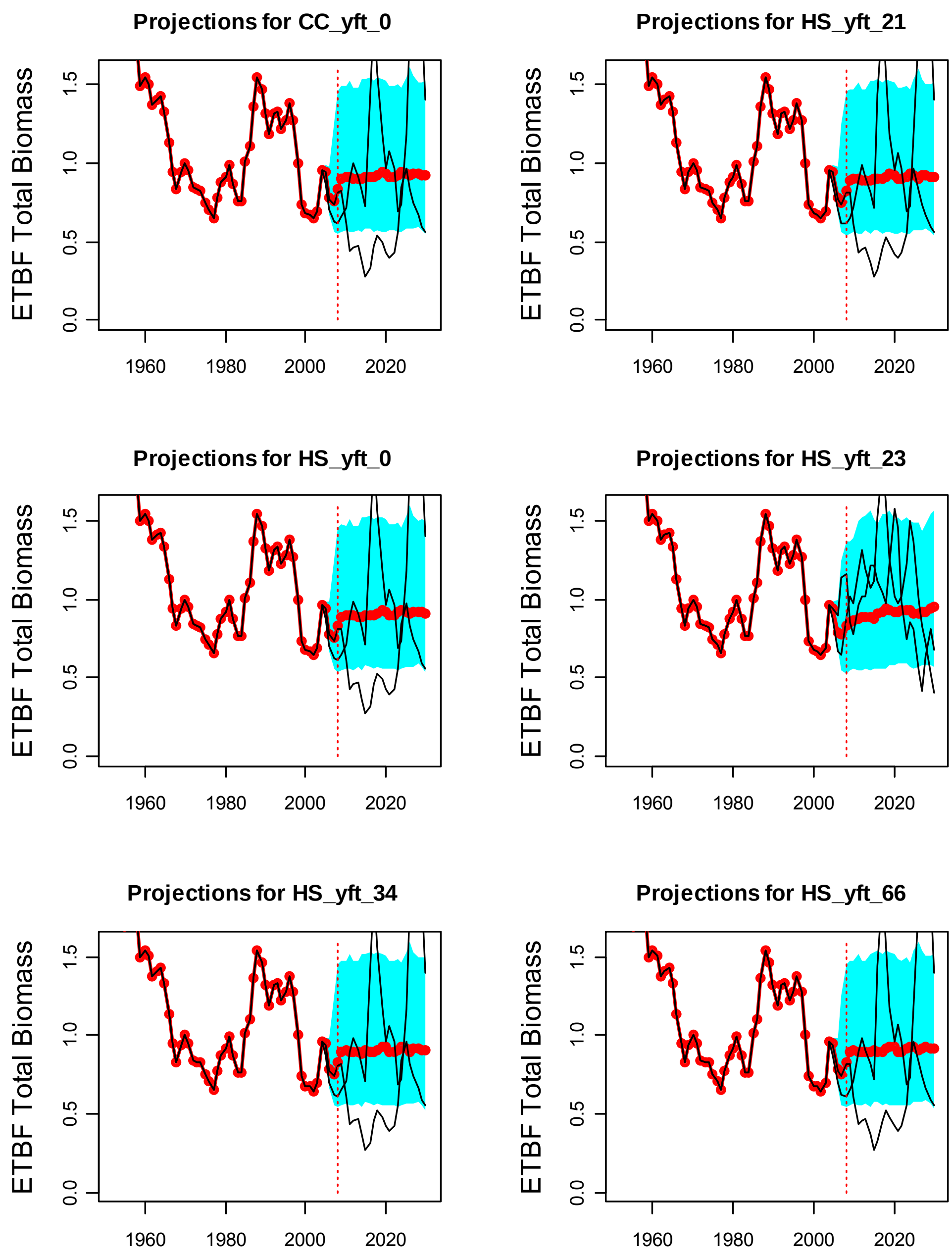


Figure 78. Yellowfin tuna total biomass (for the ETBF region) trajectories for four ETBF Harvest Strategies. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

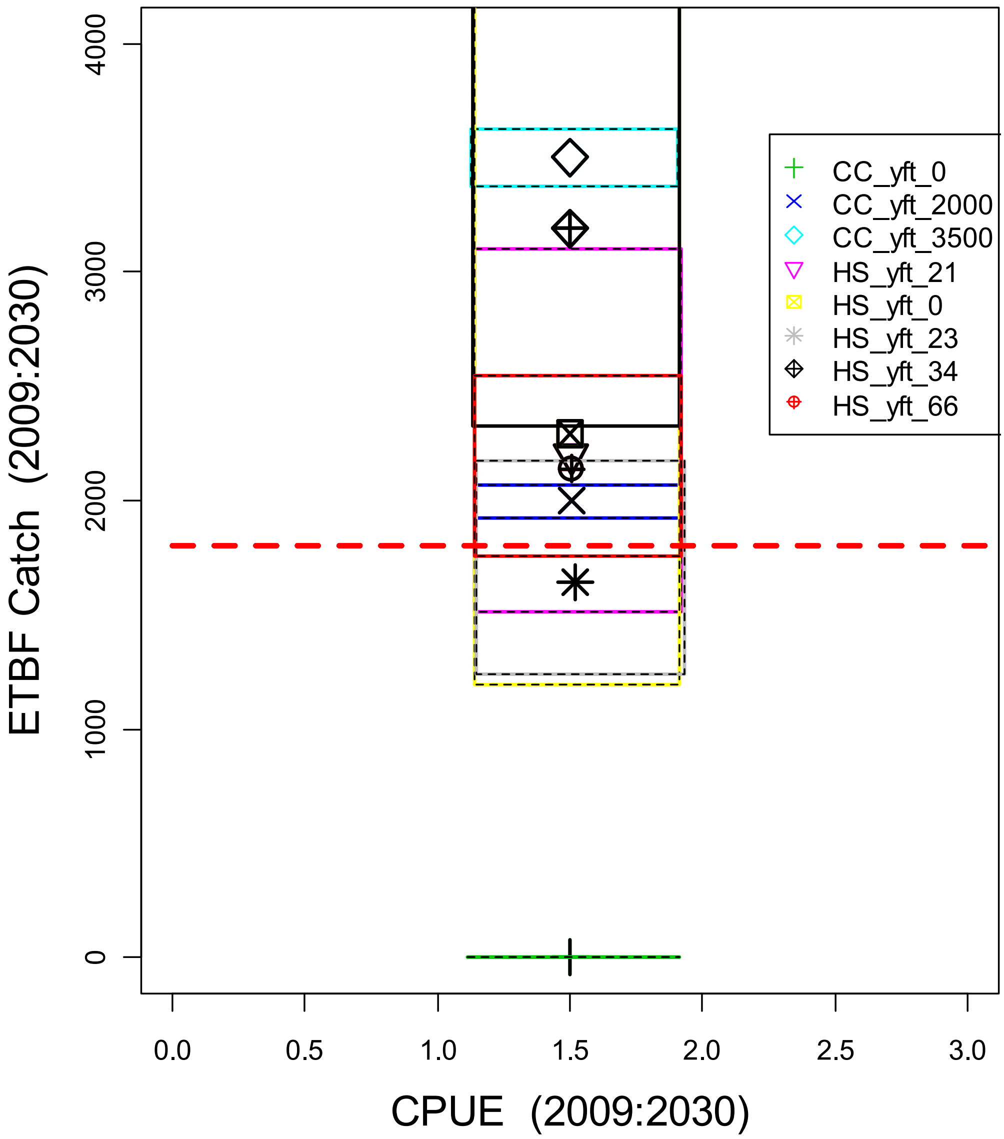


Figure 79. Yellowfin tuna trade-off plot illustrating the estimated relationship between Catch and CPUE for a range of Harvest Strategies. Symbols represent the median performance (averaged over time) for all realizations; boxes bound the 10th-90th percentile region in both dimensions. The broken red horizontal line indicates the 2007 catch level.

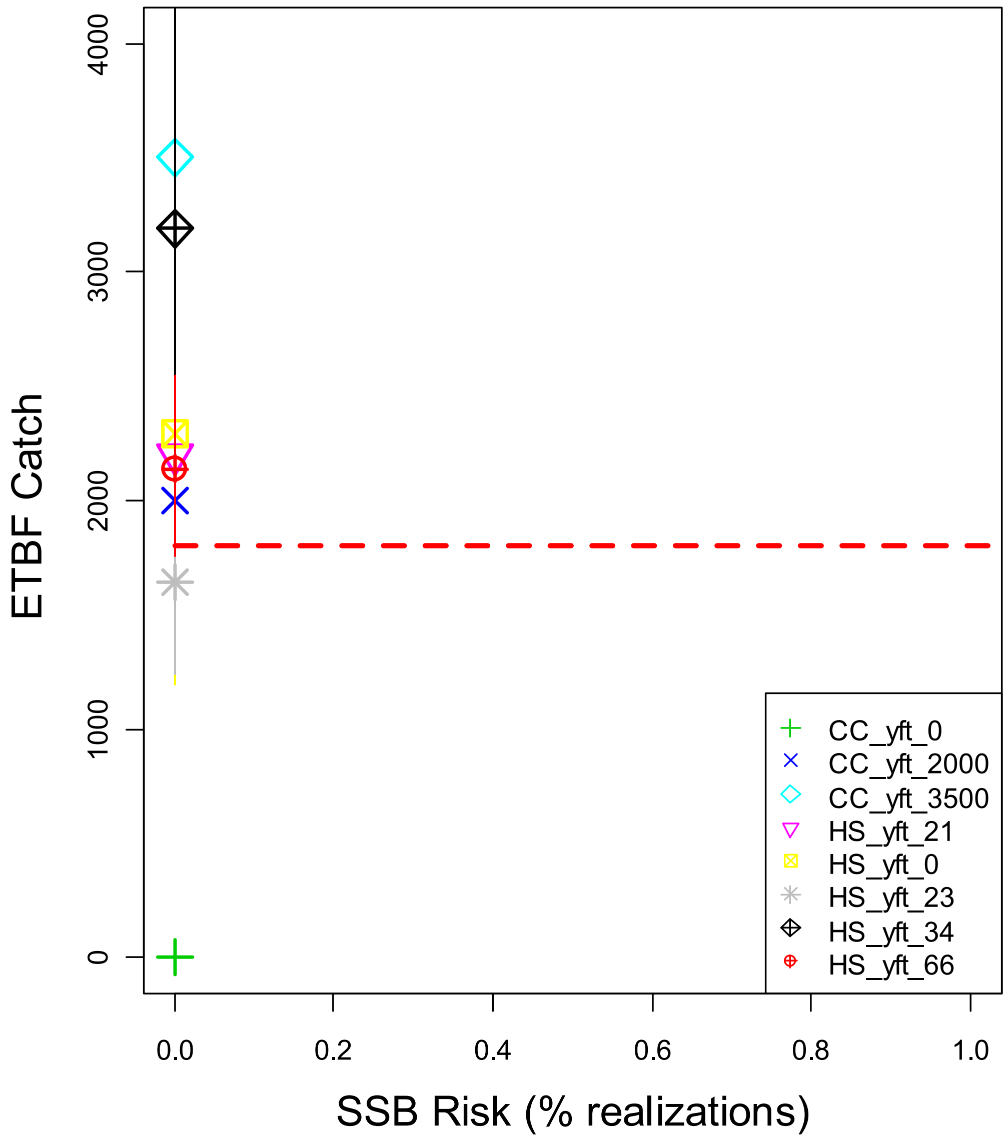


Figure 80. Yellowfin tuna trade-off plot illustrating the estimated relationship between Catch and biomass risk. Risk is defined as the proportion of stochastic projections in which spawning biomass (*SSB*) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Dotted vertical lines show how specific levels of risk might be used to remove some candidate HSs from further consideration. The broken red horizontal line indicates the 2007 catch level.

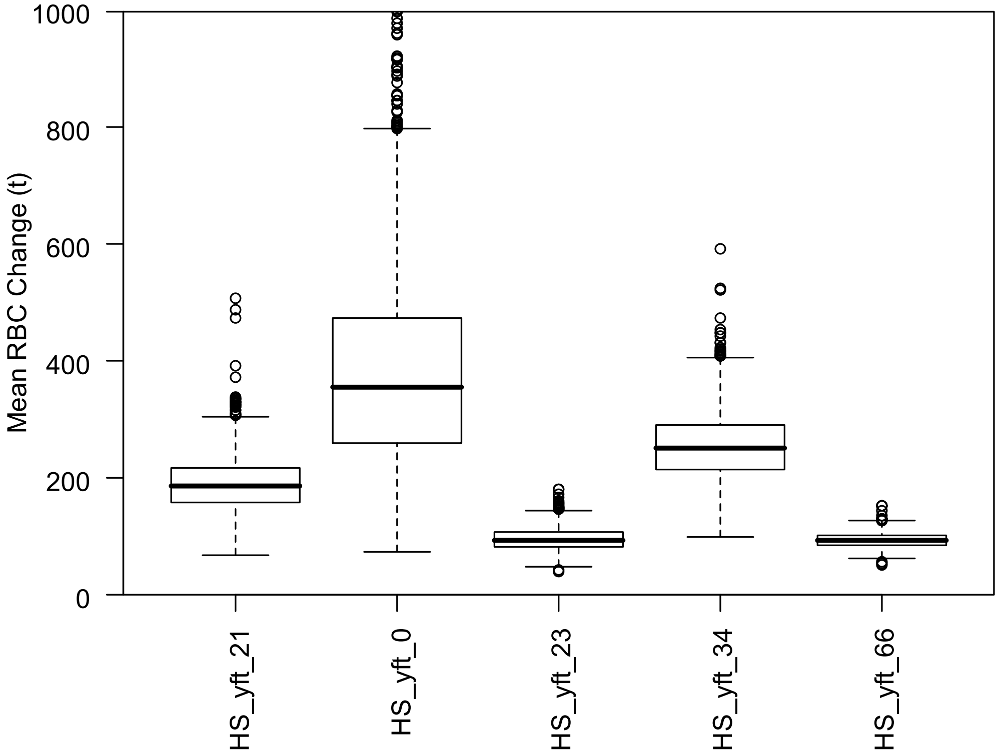


Figure 81. Reference Set yellowfin tuna RBC variability statistics for a range of Harvest Strategies. Boxplots represent the distribution of the average absolute value of the change in RBC associated with each HS (i.e. each observation within a boxplot represents the mean value from a single stochastic realization). The dark line represents the median of the distribution, the box represents the 25th-75th percentiles, whiskers represent the range or 1.5 of the interquartile distance (whichever is smaller), and circles represent outliers that exceed the whiskers.

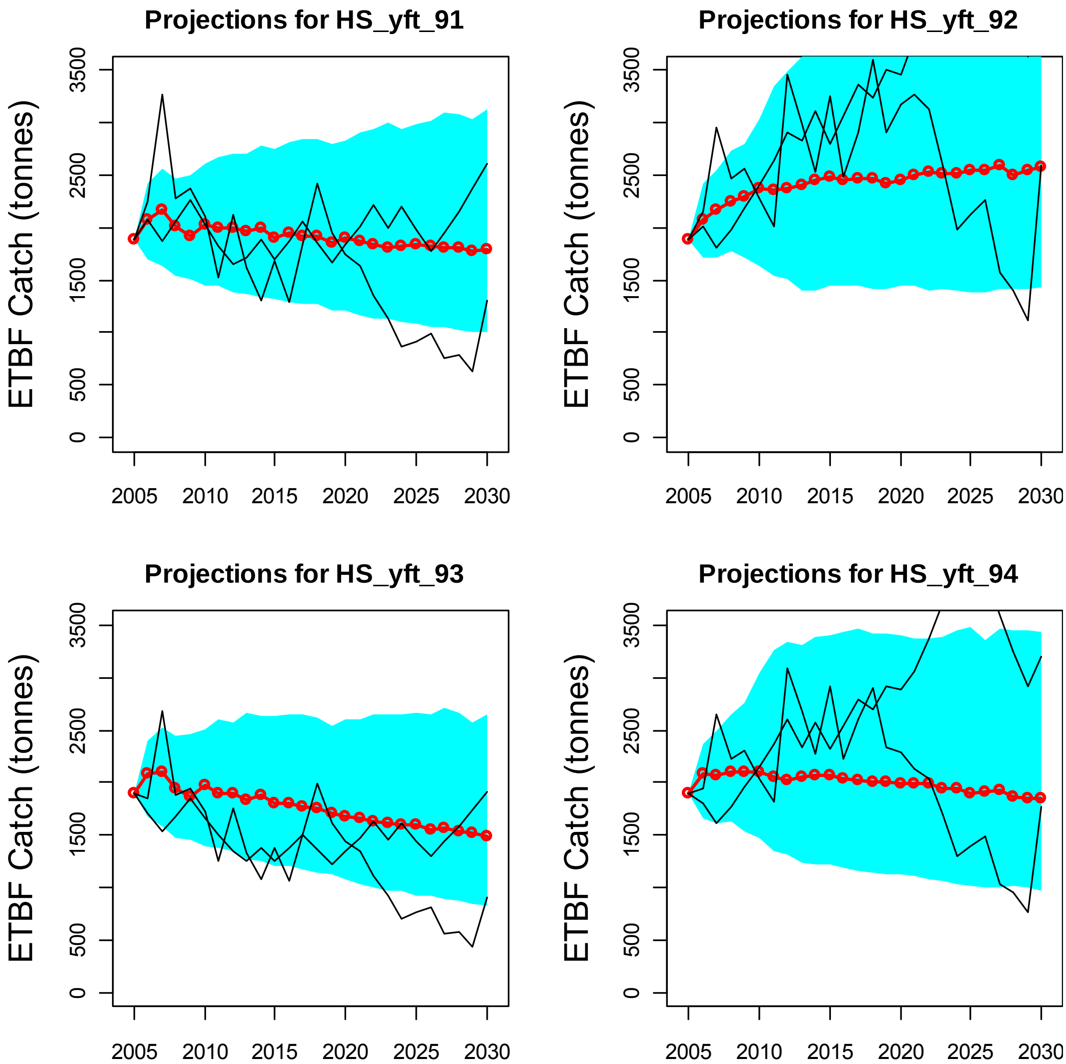


Figure 82. Yellowfin tuna estimated catch trajectories for four ETBF Harvest Strategies which differ in terms on the number of years used in the CPUE slope calculations (3 or 8 years), and the responsiveness of the decision tree (RBC change scalar = 0.85 or 0.95). Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

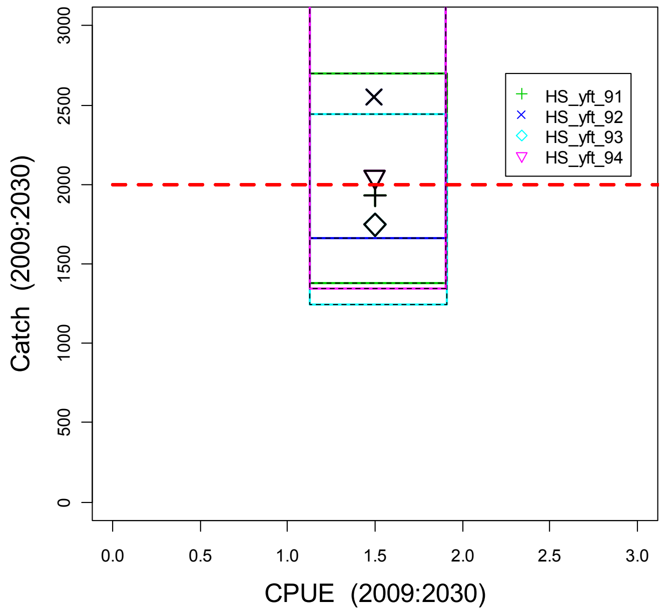


Figure 83. Yellowfin tuna catch and CPUE trade-offs for four ETBF Harvest Strategies which differ in terms on the number of years used in the CPUE slope calculations (3 or 8 years), and the responsiveness of the decision tree (RBC change scalar = 0.85 or 0.95).

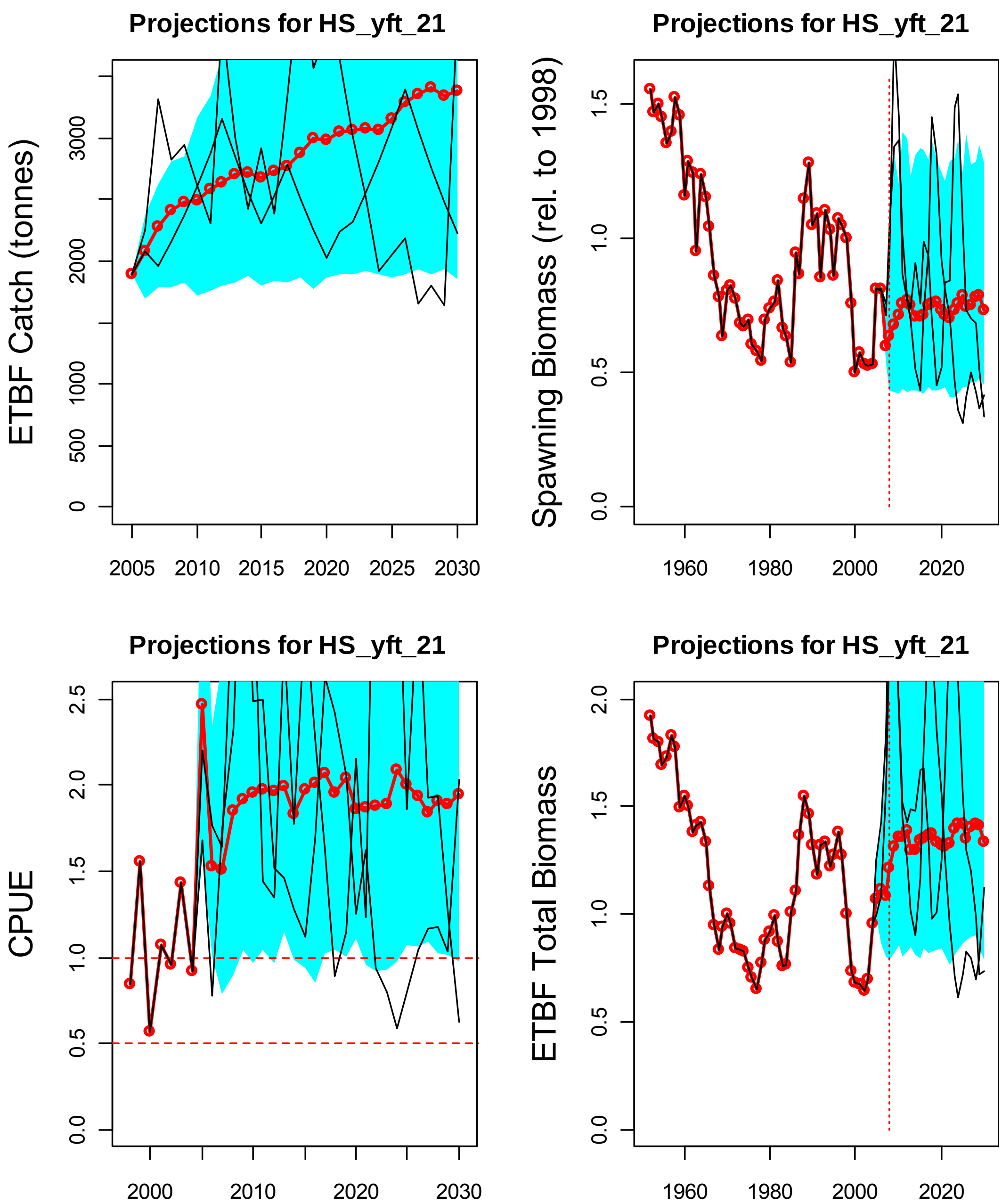


Figure 84. Time series trajectories for the adopted yellowfin tuna HS (HS_yft_21) when evaluated against the restricted spatial robustness set in which 50% of the region 5 population was allocated to the ETBF fishery, 50% allocated to the non-ETBF fishery.

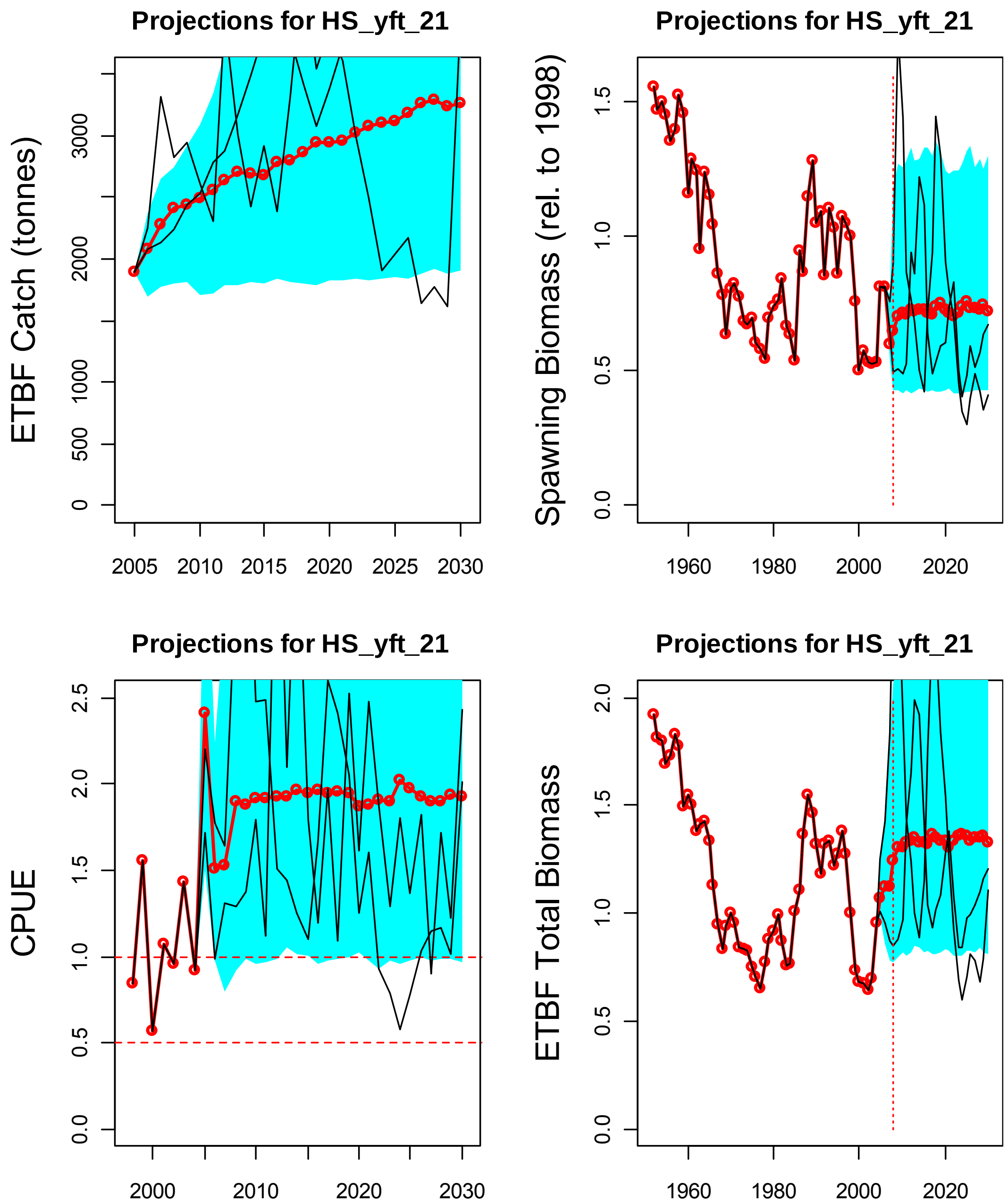


Figure 85. Time series trajectories for the adopted yellowfin tuna HS (HS_yft_21) when evaluated against the restricted spatial robustness set in which 25% of the region 5 population was allocated to the ETBF fishery, 25% allocated to the non-ETBF fishery.

Albacore Tuna MSE

Albacore tuna reference set operating models

The most recent albacore stock assessment for the region (that was available in time to be incorporated in this project) is described in Hoyle et al. (2008). The spatial structure of the assessment covers the whole southern hemisphere Pacific Ocean (Figure 86). Six sub-regions are used to define relatively homogeneous fisheries, however, the population is spatially aggregated over the whole domain. The regional population was estimated to be in a reasonable state, with moderate depletion ($B_{(T)}/B_{(no\ fishing)}$ = 0.7; $SB_{(T)}/SB_{(no\ fishing)}$ = 0.5). However, the assessment was recognized as having a number of issues that warranted further investigation.

The reference set of operating model features are described in Table 17. Key assumptions included:

- MPD estimates consisted of a single model run that was judged by the developers to be preferable or representative for MSE purposes (Simon Hoyle, Secretariat of the Pacific Community, pers. comm.), with the advice that that the assessment model was likely to evolve rapidly in the future.
- The large homogenous spatial region of the assessment is problematic for the development of ETBF operating models (i.e. it seems very unlikely that population changes in the south-east Pacific would be closely linked to changes in the ETBF region). A more spatially-restricted robustness set is described in the following section.
  - 20% of the recruitment is assigned to the ETBF, and represents the proportion of the equilibrated population in the absence of harvesting. This figure simply represents an approximate geographical split at 165°E.
  - The migration linkage between the ETBF and non-ETBF regions is assumed to be an equal mix of scenarios with 1% and 20% per quarter diffusive mixing.
- Recruitment is annual. The recruitment variability used in the reference set operating model was assumed to be the same as the billfish species (sd(log) = 0.6, autocorrelation rho = 0.7). This is somewhat more variable than the empirical estimates that came out of the assessment, because concerns about seasonal and interannual selectivity variability undermine confidence in the recruitment variability estimates from the assessment.
- Future non-ETBF effort is assumed to remain constant at 2007 levels. The WCPFC has not taken action with respect to the albacore fishery to date. The continuous increasing catch trend over the past 20 years (particularly in the western region) suggests that this assumption may prove incorrect.
- The selectivity for the ETBF fleet and non-ETBF fleet was adopted from the assessment estimates for the region 1 fishery (LL AU 1), in the most recent time period. The nature of the albacore fishery is such that there seem to be large selectivity changes by season and among years, and this is one of the issues in the assessment that is still under investigation. Thus any selectivity assumption is difficult to justify at this time.

- The magnitude of the CPUE observation error variability was assumed to be relatively low (sd(log) = 0.2) and strongly autocorrelated (rho = 0.7), identical to the other species.
- The reference set consisted of 800 projections = (1 MPD estimates) X (2 migration rates) X (2 size composition sampling errors) X (2 implementation error assumptions) X (100 stochastic realizations per scenario).
- The depletion level corresponding to B_{MSY} (i.e. B_0/B_{MSY}) was 0.19 when B_0 was defined as the mean unfished biomass in the 1980-2004 period, and 0.22 relative to the equilibrium B_0. In both cases this is substantially lower than the 0.4 B_0 proxy value suggested in the HSP.
- Other biological and fishery assumptions correspond to those described in Langley et al. (2007).

Figure 87 illustrates that there is poor agreement between the observed albacore CPUE in the ETBF, and the predicted values from the operating model. This suggests that either the assessment model did not fit the CPUE series very well, or the Australian CPUE series are not consistent with the distant water fisheries (DWF) series that were used. This could indicate changing catchability, in one or more of the fleets, in a way that is not captured in the catch rate standardization. Or it might indicate that the relative abundance trends differ by region in a way that simply cannot be described by the spatially aggregated model.

Unlike the other ETBF target species, the monitoring data currently available for albacore do not include size composition. As such, the HSs evaluated were limited to specifications that used only a single size-aggregated CPUE series in place of the *CPUE-Prime* series, and the lower levels of the HSWG decision tree were not used.

Figure 88 illustrates the dynamics estimated to occur if fishing was stopped. The spawning biomass and CPUE is estimated to almost triple if fishing stops, which would result in biomass on average comparable to the period from the 1970s to mid-1990s, but less than that in the 1960s. This seems like a large CPUE increase for a fishery that is estimated to be at 70% of virgin levels. This may be possible, but could be an artefact of dubious spatial partitioning and selectivity assumptions.

Main concerns about the albacore operating model:

- The spatial assumptions in the assessment model are not very conducive for the needs of the ETBF operating model, and are the worst of all the target species.
- Fishery selectivity seems to vary substantially by season for albacore, and possibly also in relation to shifting targeting. This is poorly quantified in the current assessment model (and a topic for review). Selectivity is assumed to be constant in the operating model.
- Only a single ‘preferred’ assessment model was adopted for the operating model, so the uncertainty is understated.
- There are substantial discrepancies between the predicted and observed albacore CPUE for the ETBF. At this time we do not know if this is due to spatial partitioning and/or selectivity assumptions in the operating model, or the problems of standardizing effort in a rapidly developing fishery.

Albacore tuna robustness set operating models

The connectivity between the ETBF and the broader South Pacific albacore tuna population is poorly understood. The reference set represents a fairly extreme situation in which there is a single spawning population, though differential exploitation can occur in the ETBF and non-ETBF regions. An alternative, spatially restricted robustness set was defined in which the ETBF and non-ETBF regions each corresponded to 10% of the assessment population. The catch in the non-ETBF fishery was calculated as 20% of the total minus the ETBF catch. As in the tropical tuna scenarios, these alternative models were not explicitly reconditioned to these spatial assumptions (i.e. ideally the data should be disaggregated according to the proposed spatial structure and the model parameter estimation should be repeated). It was expected that partitioning the assessment in this way would produce a model that qualitatively resemble of a more localized population. But no effort was made to assess the plausibility of this scenario, and unintended artefacts could have been introduced.

Figure 89 illustrates the dynamics estimated to occur if fishing was stopped in this robustness set. Similar to the reference set, the median biomass (spawning and total) recovers to levels observed around the period 1970-2000. This is very similar in relative terms, to what happens in the references set, but in absolute terms the biomass is about 20% of the reference set). However, the CPUE dynamics are not very similar to the reference set, and the unfished CPUE does not recover to the levels observed in the reference set.

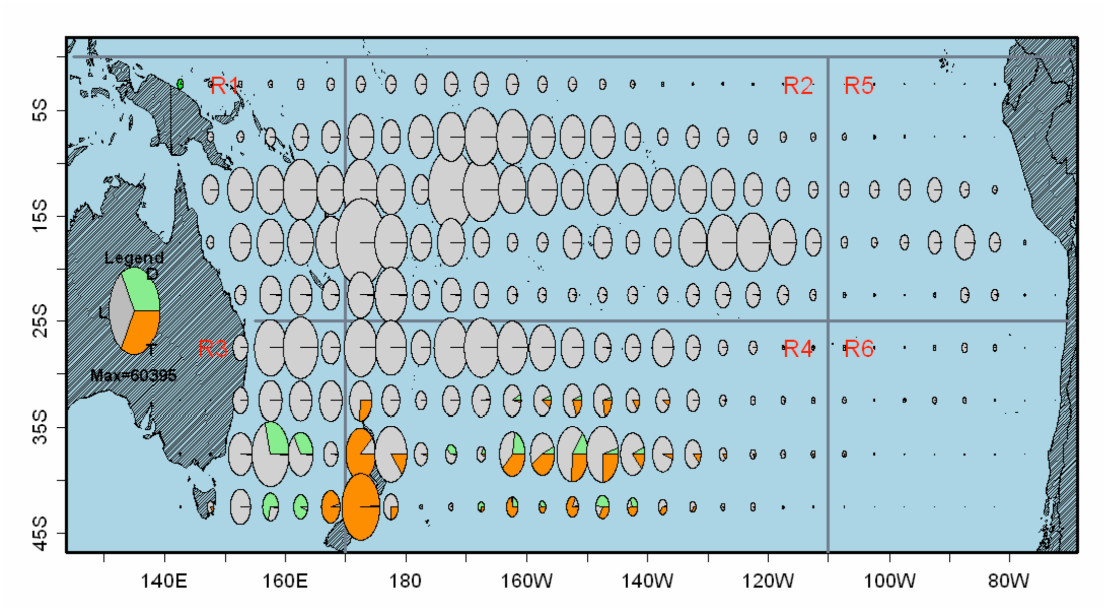


Figure 86. Albacore assessment model domain from Hoyle et al. (2008). Note that regions R1-R6 are used to define fisheries, but the fish population is aggregated.

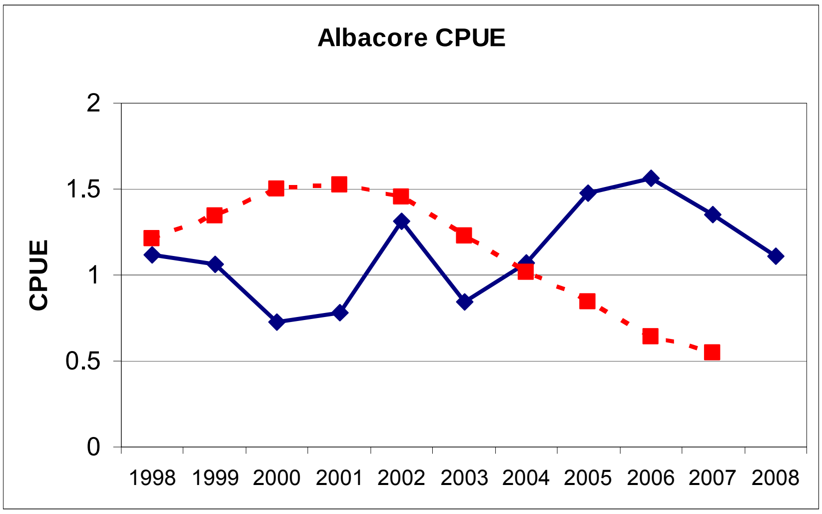


Figure 87. Albacore tuna comparison between predicted and observed CPUE for the Australian ETBF. Solid black lines (diamonds) are the observed standardized CPUE (aggregated across all size classes); broken coloured lines are the equivalent assessment model estimates (later years are not shown because they consist of stochastic projections).

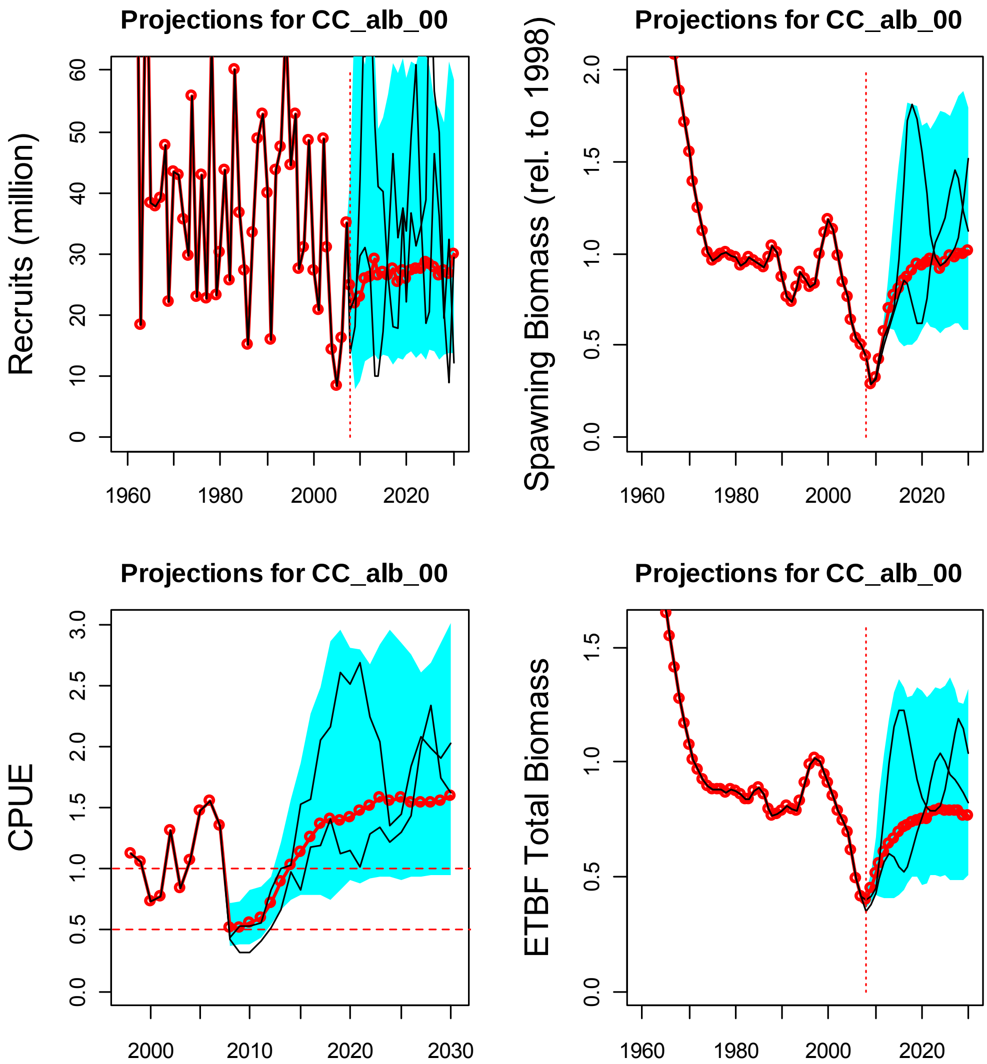


Figure 88. Albacore tuna operating model projections assuming that fishing was stopped in the ETBF and adjacent non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

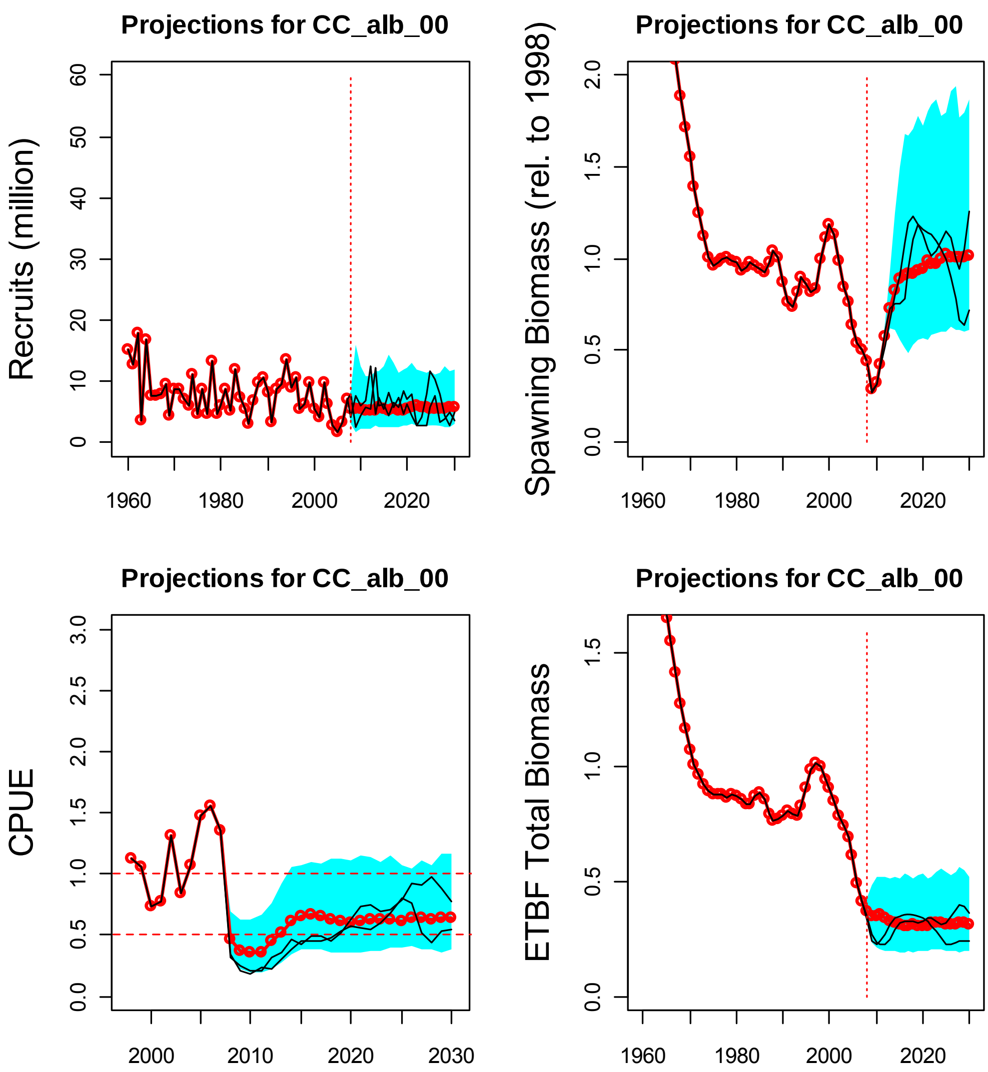


Figure 89. Albacore tuna spatially-restricted robustness set operating model projections assuming that fishing was stopped in the ETBF and non-ETBF fishery. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

Albacore tuna harvest strategy evaluation

Reference Set

Figure 90, Figure 91, Figure 92 and Figure 93 illustrate the estimated catch, CPUE, spawning biomass and total biomass trajectories for four ETBF Harvest Strategies that were selected to show a range of options. All of the HSs presented prescribe immediate catch reductions, and there is a large drop in the CPUE in the first year of the projections. This decline is related to the discrepancy between predicted and observed CPUE, such that the model estimates the biomass to be much lower in 2008 than the ETBF CPUE suggests.

Figure 94 illustrates the estimated relationship between catch and CPUE for a range of Harvest Strategies. The operating model suggests that the ETBF fishery is likely to have a relatively small effect on the regional population dynamics of albacore, relative to the non-ETBF fleet.

Figure 95 illustrates the estimated relationship between catch and biomass risk associated with the different harvest strategies. The plot indicates that there is a reasonable amount of biomass risk associated with the non-ETBF fishery (e.g. CC_alb_0 suggests that the risk is substantial even in the absence of the ETBF fishery). The impact of the ETBF fleet is estimated to elevate the biomass risk to some degree, but not to the same extent as with bigeye. These projections seem pessimistic relative to the current stock status estimate in the assessment, and presumably reflect the consequences of the rapid recent effort rises in both the ETBF and non-ETBF. However, given that the ETBF CPUE trend is actually increasing while the operating model trend is decreasing, it is difficult to take the projections too seriously at this time.

Figure 96 illustrates the variability in average annual RBC for Albacore for a range of harvest strategy using the reference set.

Figure 97 illustrates the time series trajectories for the HS adopted by the MAC (HS_alb_32), with results partitioned according to the migration rate. These results emphasize that the HS performance is very different depending on the assumed migration rate, with higher migration associated with a more pessimistic outcome for the ETBF (i.e. suggesting that the non-ETBF is under higher fishing pressure)

Robustness Set

The time series for the HS adopted by the MAC (HS_alb_32) when challenged by the spatially restricted operating model is shown in Figure 98. The dynamics are considerably more pessimistic in terms of the catch and CPUE trajectories than the reference set. These latter results are qualitatively similar to the reference set in that the restricted non-ETBF region is also under higher fishing pressure than the ETBF.

Figure 99 illustrates the effect of redistribution rates in the spatially restricted robustness set, with higher migration associated with a more pessimistic outcome.

As with the tropical tuna species, we do not have a lot of confidence in the usefulness of these improvised spatially-restricted operating models. However, the results again emphasize the possibility that the adopted HS might not perform as envisioned by the HSWG.

Albacore Tuna MSE Conclusions

- We consider the albacore results to be the least reliable of the five target species for several reasons:
  - The WCPFC assessment is considered preliminary, with important avenues for additional work identified by the analysts.
  - The large spatial domain of the assessment cannot resolve ETBF dynamics adequately.
  - There is a substantial inconsistency between the predicted and observed ETBF CPUE time series which are the primary abundance indices in the operating model and HS.
- The assessment and reference set operating model suggests that there may be a substantial risk to the regional albacore population if current effort levels are maintained or increased. The ETBF fishery has some capacity to elevate the risk, but the risk is largely driven by the non-ETBF fleet.
- We do not have much confidence in the pessimistic results of the spatially-restricted albacore robustness set. However, they do suggest that the dynamics of the ETBF might be very sensitive to the connectivity assumptions, and the HS might not perform as expected

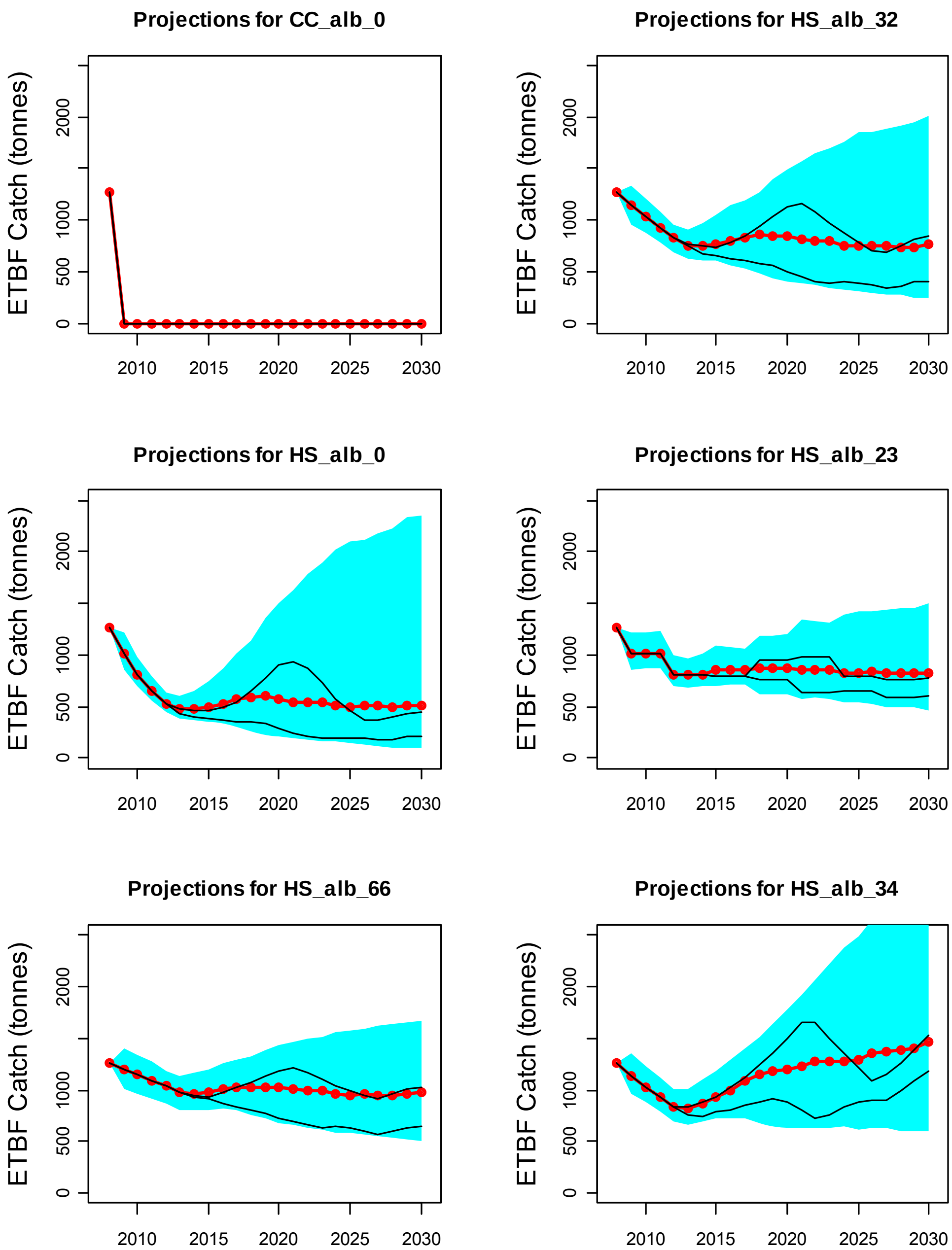


Figure 90. Reference Set albacore tuna catch trajectories for six ETBF Harvest Strategies. HS_alb_32 was the decision rule recommended by the ETBF RAG and MAC. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

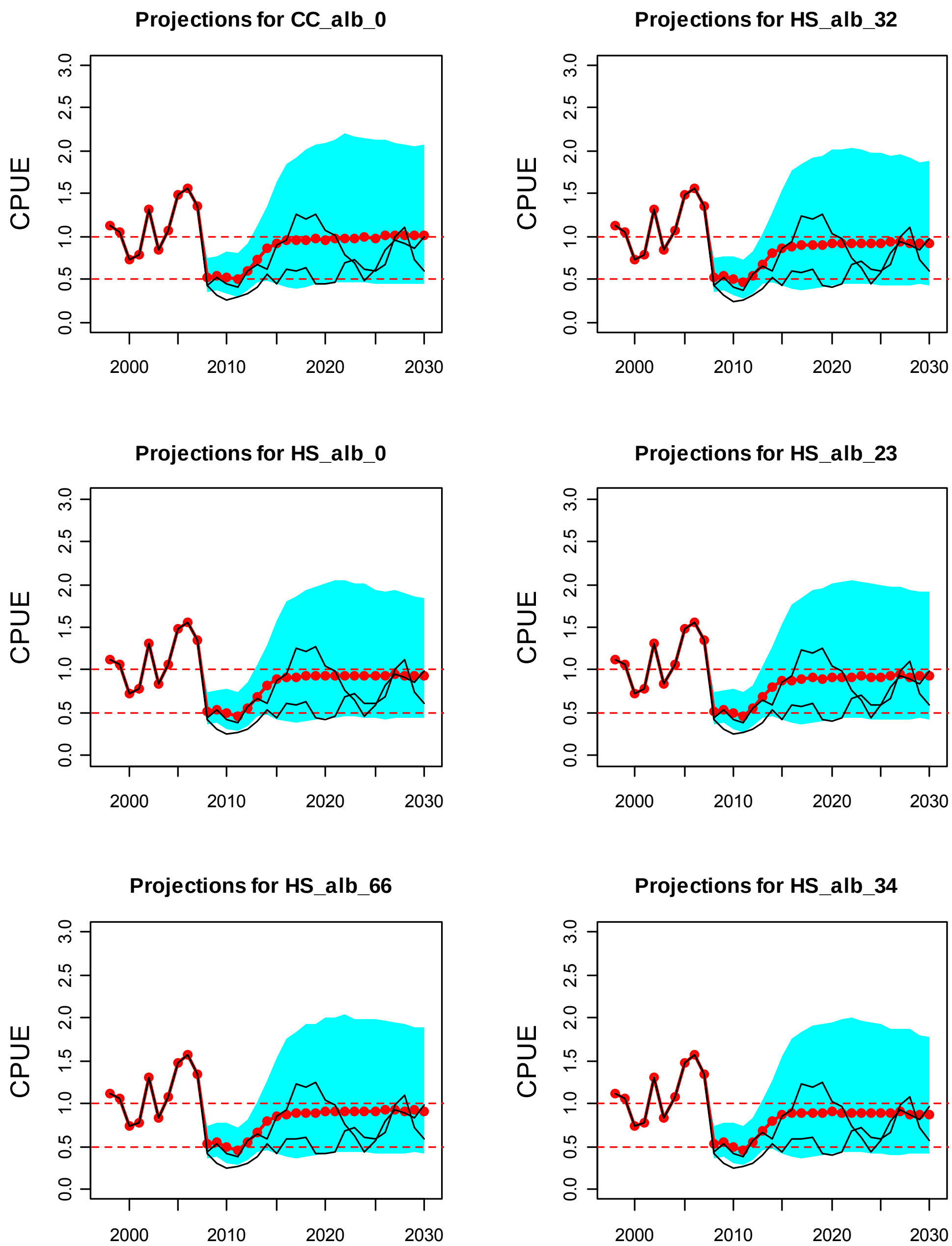


Figure 91. Reference Set albacore tuna CPUE trajectories for six ETBF Harvest Strategies. HS_alb_32 was the decision rule recommended by the ETBF RAG and MAC. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

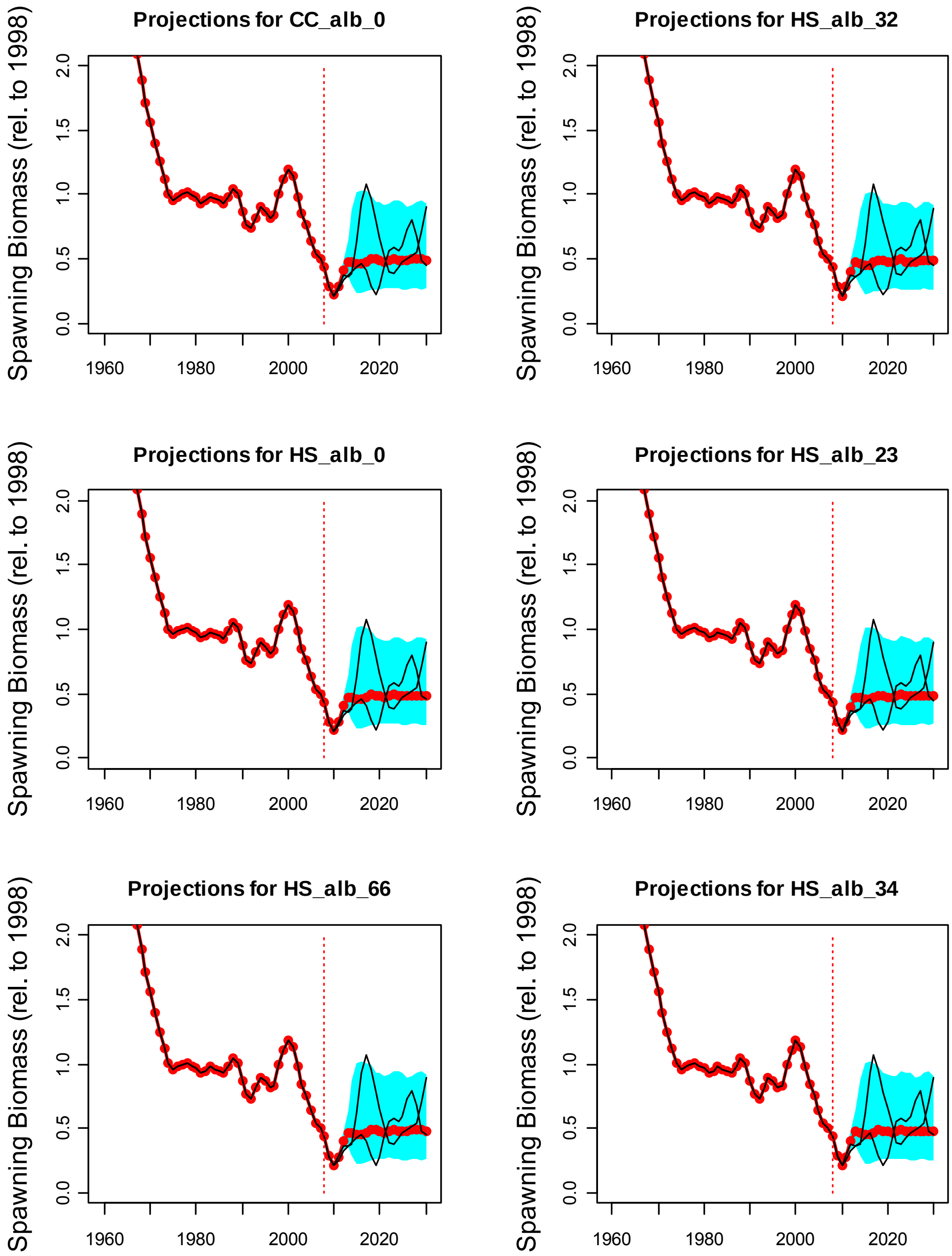


Figure 92. Reference Set albacore tuna spawning biomass trajectories for six ETBF Harvest Strategies. HS_alb_32 was the decision rule recommended by the ETBF RAG and MAC. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

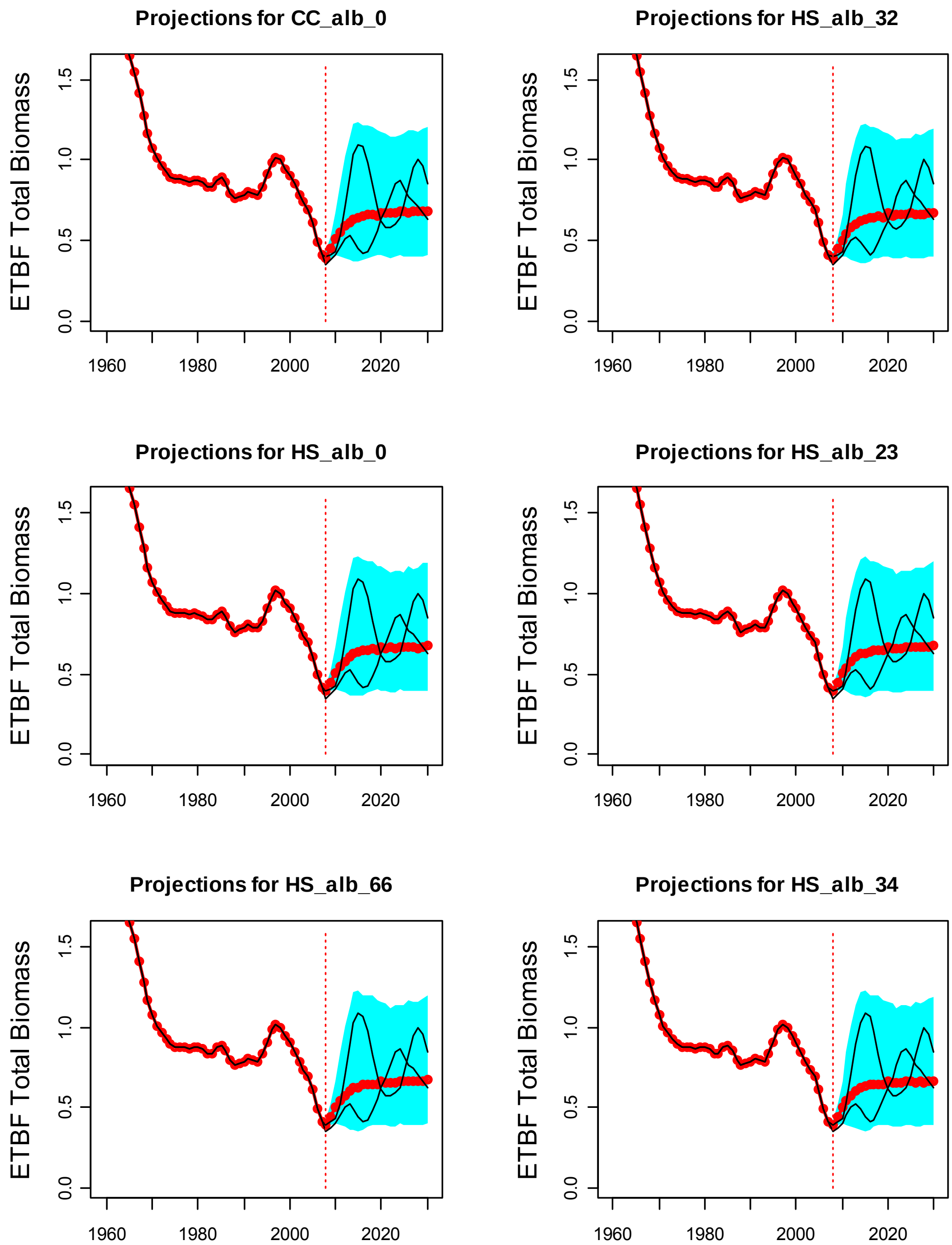


Figure 93. Reference Set albacore tuna total biomass (all ages, ETBF region only, scaled relative to 1998) trajectories for six ETBF Harvest Strategies. HS_alb_32 was the decision rule recommended by the ETBF RAG and MAC. Red circles indicate median projections, shaded blue region represents the 10th and 90th percentiles of the distribution, and thin black lines represent two random trajectories.

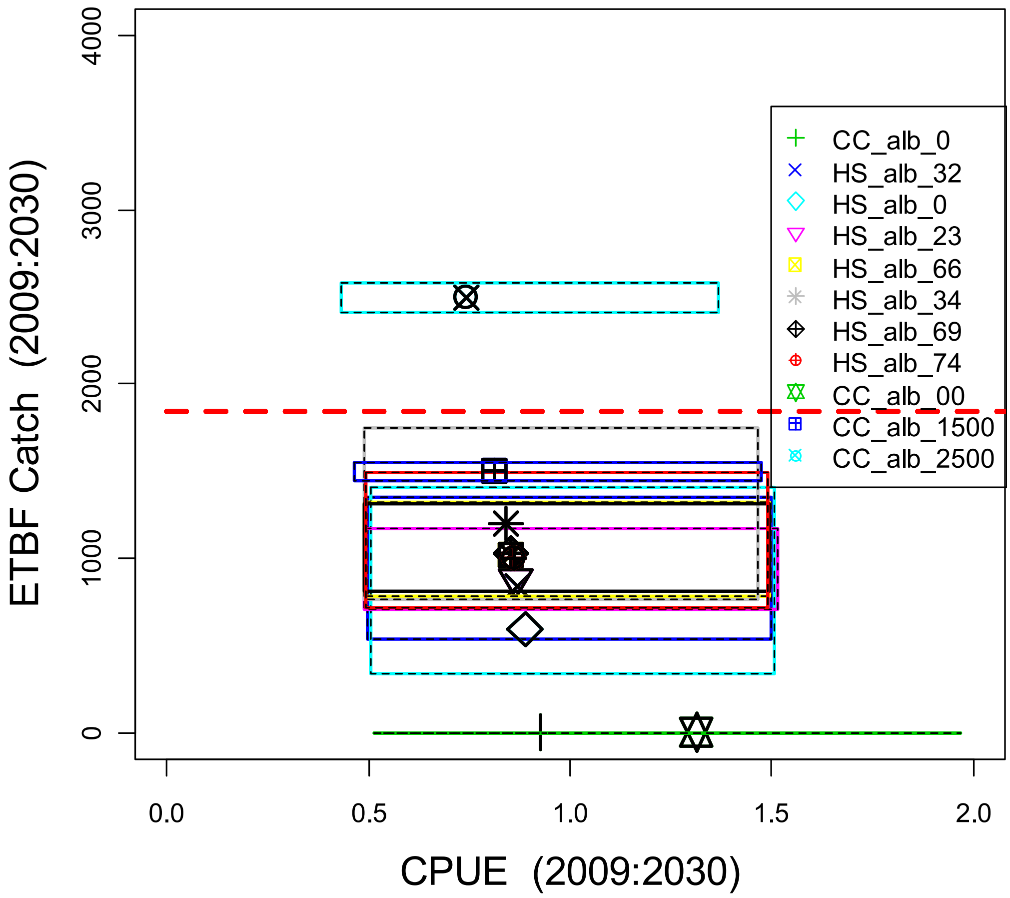


Figure 94. Albacore tuna trade-off plot illustrating the estimated relationship between Catch and CPUE for a range of Harvest Strategies. Symbols represent the median performance (averaged over time) for all realizations; boxes bound the 10^{th}-90^{th} percentile region in both dimensions. The broken red horizontal line indicates the 2007 catch level.

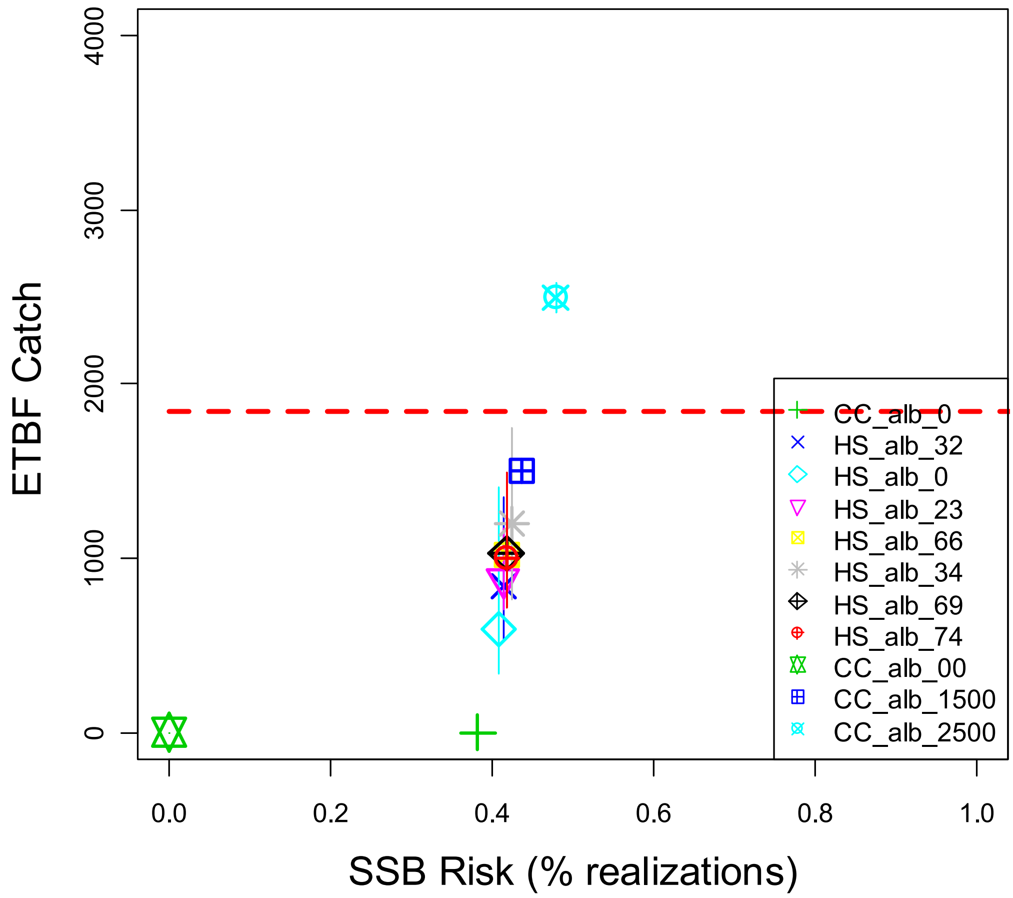


Figure 95. Albacore tuna trade-off plot illustrating the estimated relationship between Catch and biomass risk. Risk is defined as the proportion of stochastic projections in which spawning biomass (*SSB*) drops below 20% of unfished levels (0.2B_0) more than 10% of the time (3 or more years). Dotted vertical lines show how specific levels of risk might be used to remove some candidate HSs from further consideration. The broken red horizontal line indicates the 2007 catch level.

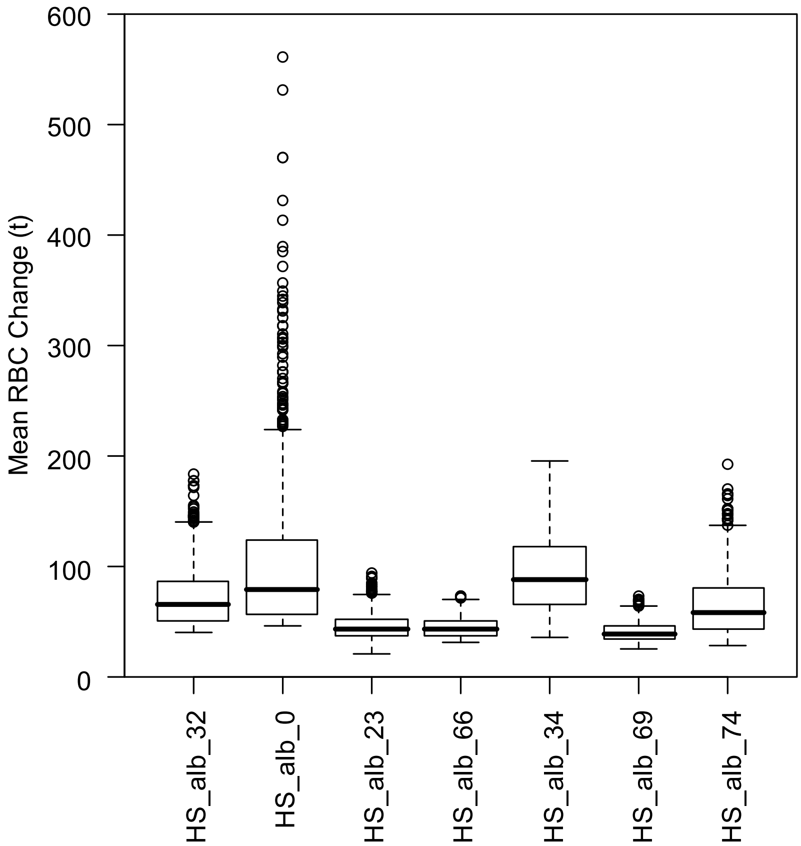


Figure 96. Reference Set albacore tuna RBC variability statistics for a range of Harvest Strategies. Boxplots represent the distribution of the average absolute value of the change in RBC associated with each HS (i.e. each observation within a boxplot represents the mean value from a single stochastic realization). The dark line represents the median of the distribution, the box represents the 25th-75th percentiles, whiskers represent the range or 1.5 of the interquartile distance (whichever is smaller), and circles represent outliers that exceed the whiskers.

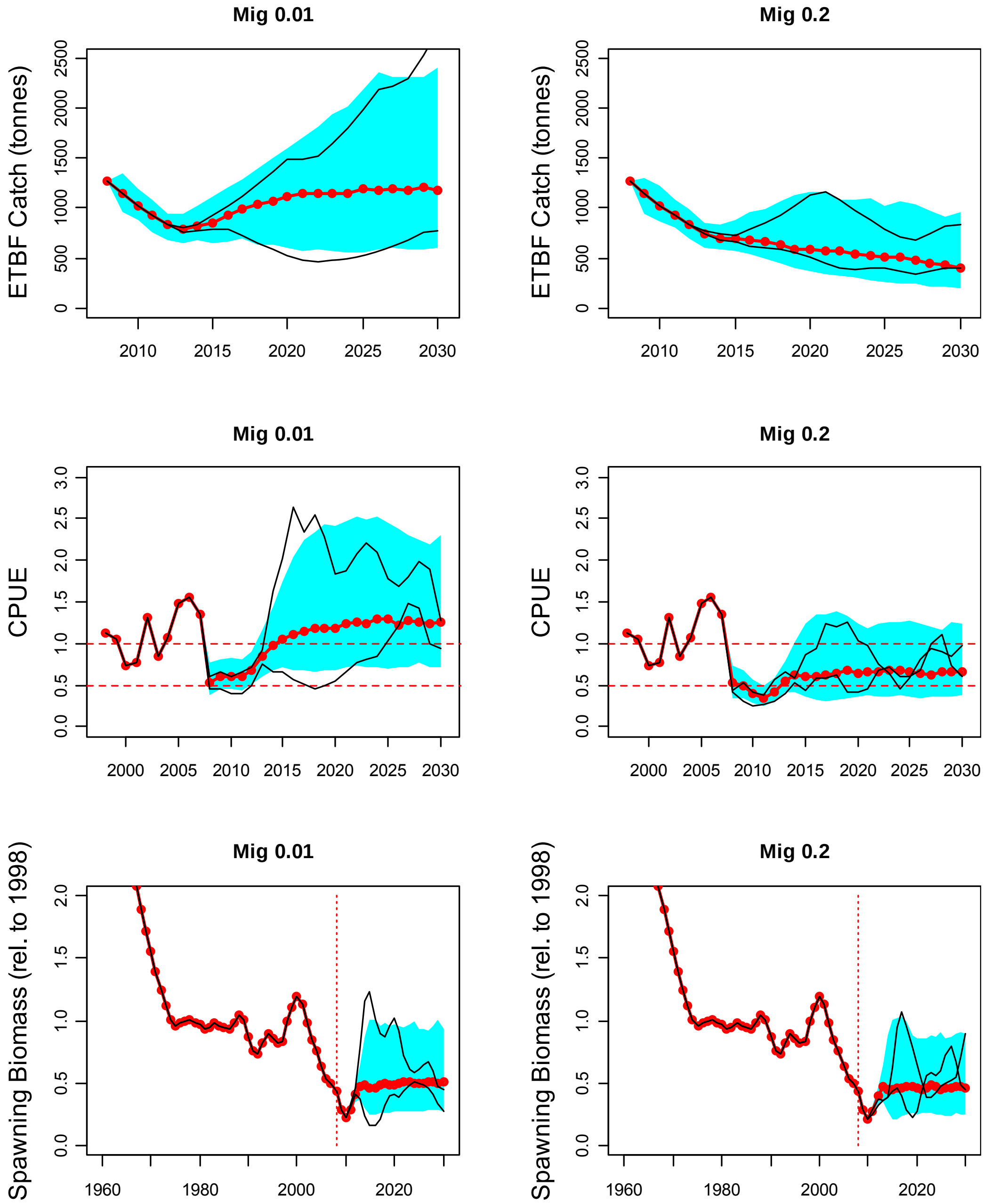


Figure 97. Time series trajectories for the albacore tuna HS adopted by the MAC (HS_alb_32) when the reference set of operating models is partitioned by the migration rate (redistribution rates are low on the left and high on the right).

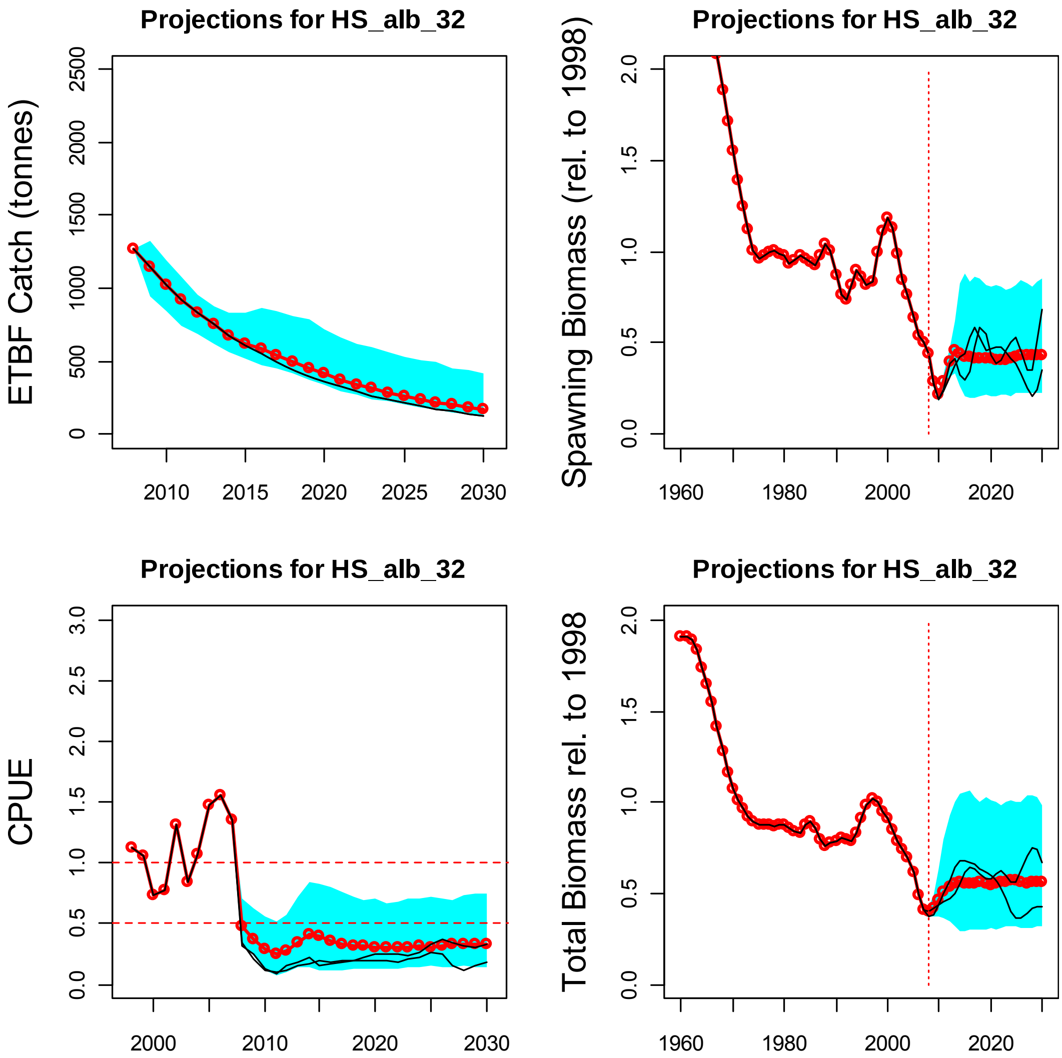


Figure 98. Time series trajectories for the albacore tuna HS adopted by the MAC (HS_alb_32) when evaluated against the spatially-restricted robustness set in which 10% of the total South Pacific population was allocated to the ETBF fishery, and 10% allocated to the non-ETBF fishery.

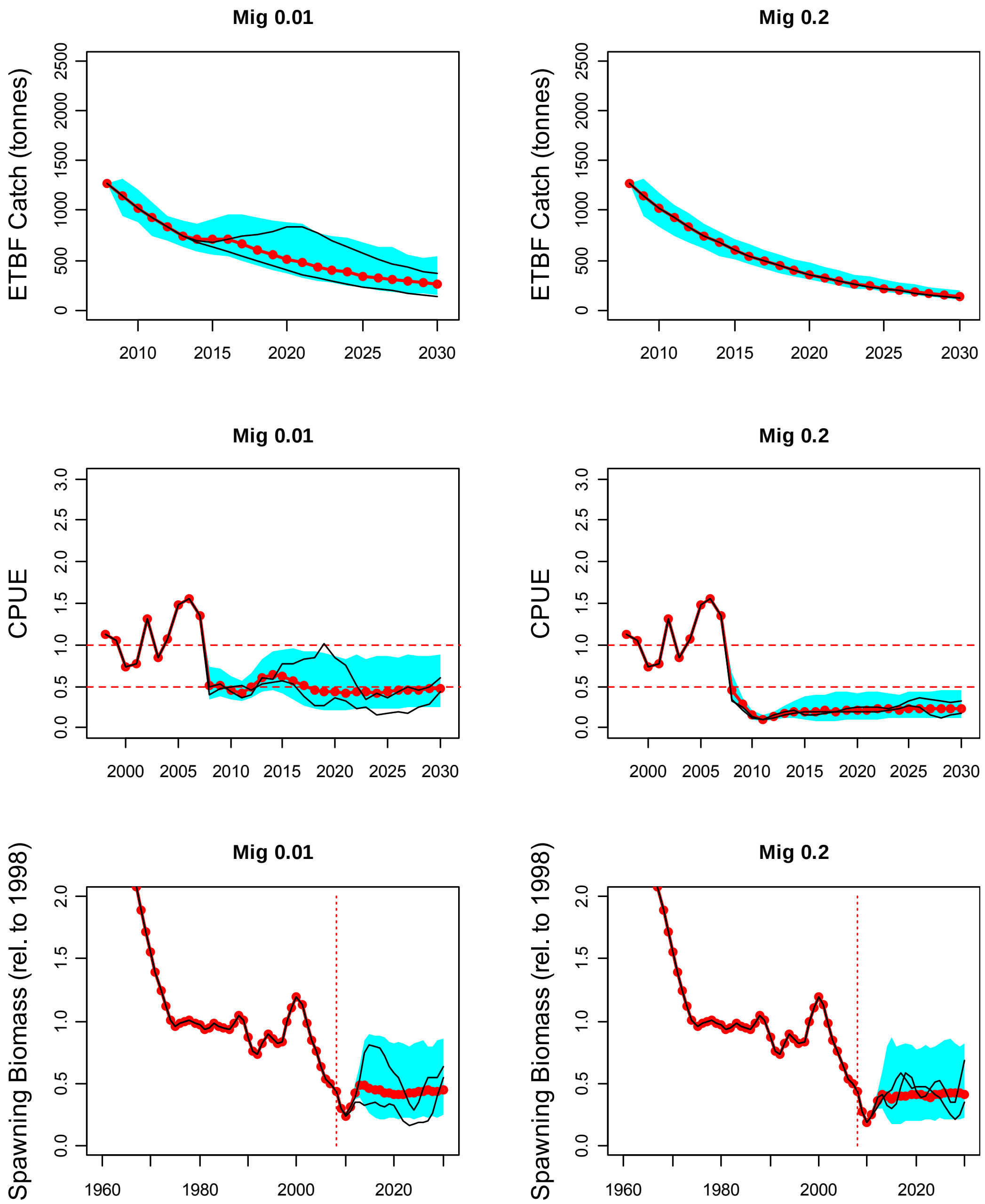


Figure 99. Time series trajectories for the albacore tuna HS adopted by the MAC (HS_alb_32) when the spatially-restricted robustness set of operating models is partitioned by the migration rate (redistribution rates are low on the left and high on the right).

Table 17. ALB Reference Set

Dimension	Option 1	Option 2	Option 3	Number of Reference Set grid elements
M growth maturity Stock-Recruitment steepness selectivity	1 model Most population and fishery characteristics are adopted from the assessment inputs or Maximum Posterior Density (MPD) estimates			1
N(initial) and future Recruitment Bias	0 (i.e. MPD estimates are used)			3
*Stochastic replicates	100			100
Recruitment SD(log(dev)); autocorrelation	τ=0.6 ; ρ=0.7			1
CPUE obs. error SD(log(dev)); autocorrelation	τ=0.2 / ρ=0.7			1
Migration Rate	20%/qtr	1%/qtr		2
Effort in the non-ETBF fishery	Constant at 2007 levels			1
size sample / mag distortion / autocorrelation	70% unbiased = 0.7 / 0 / 0	0.7 / 0.2 / 0.7		2
RBC implementation error SD(log(dev))	0	0.2		2
Data Time Lag for HS Application	6 months			1

Summary Comments on Operating Model Development

The preceding sections discuss various concerns about the HS evaluation operating models, as parameterized from the WCPFC assessment models. There are a number of concerns about all of the models. We think that it is reasonable to expect that management would not go badly wrong in the short term if the HS is used to recommend the RBC for swordfish and striped marlin. The outcome for yellowfin and bigeye is much less clear, due to the uncertainties about stock structure and connectivity, but if the stocks are well mixed with the adjacent waters, unilateral action by Australia will likely not have much effect on the stock, and could cause economic impacts on the ETBF without any appreciable conservation benefit. However, it does not seem as though urgent unilateral action by Australia is required with respect to these stocks at this time, provided that catches are in line with recent history, and management is consistent with WCPFC Conservation and Management Measures. We have a number of concerns about the albacore tuna HS. The stock assessment was problematic, does not resolve spatial structure well, and was not very consistent with the ETBF CPUE data. While this gives us very little confidence in the HS, the assessment does not suggest that there is an urgent need for restrictive management action. However, the recent and rapid expansion of this fishery raises concerns about the interpretation of the data and suggests that the situation should be monitored closely.

Summary Comments on Harvest Strategy Performance

This project has helped to illuminate a number of potential problems in relation to the development and implementation of the HSWG HS. Our degree of confidence in a successful management outcome varies according to the target species. In many cases, the degree of uncertainty in the stock assessment leaves doubts about the appropriateness of the simulation testing. It is also not clear that the HSWG decision framework actually performs in the manner that was initially envisaged, and some of the conceptual foundations of the decision rule might lead to a false sense of security about the ability of the rule to manage the over-fishing risk or come up with an economically desirable outcome.

The HSWG decision rule framework was developed with a number of features that were expected to be desirable for the specific needs of the ETBF management, and more generally. We provide a critique of these features below in relation to the results observed in this project. While there are many negative comments about the HSWG framework below, it is important to keep in mind that these are intended to be constructive criticisms for future consideration. We note that the simulation testing reported here is generally consistent with that reported in Davies et al (2008), however, the more comprehensive testing has further clarified a number of important issues. In some cases, we speculate that an alternative HS might perform better, but until this has been demonstrated under appropriate simulation conditions, there is no reason to reject the HSWG framework. The first 7 points below discuss the HSWG framework advantages explicitly identified in Davies et al (2008), while the remaining points relate to other issues identified by the HSWG, ETBF RAG, or this project:

1. **The decision framework is target driven, i.e. it is designed to keep you where you want to be (above [near] the Target Reference Point), rather than keep you away from where you don't want to go (near/below the Limit**

Reference Point). The core feature of the HS is the target level of the prime-sized CPUE. The ETBF RAG agreed that the target CPUE was to represent a biomass that was profitable for industry, and this was expected to correspond to a state of depletion that would not represent a significant level of stock depletion, and hence would be consistent with both the economic and conservation objectives of the HSP. Problems with this assertion include:

- The ETBF RAG industry members expressed a preference for CPUE levels near the 1998 levels. For the stocks that were initially lightly exploited (e.g. swordfish), this implies considerable stock rebuilding, after which only relatively small catches could be maintained. Profitability is a function of both the CPUE and the total catch. In contrast, for striped marlin, maintenance of CPUE near 1998 levels seems to ensure that the stock is kept in a highly depleted state, whereas some rebuilding is probably warranted.
- The HSWG expressed the expectation that it would be the task of this project to define CPUE target levels that were consistent with the HSP (e.g. Maximum Economic Yield). However, it was never an objective of this project to provide an economic analysis, or to choose among the HSs. A series of contrasting options were presented to the RAG and MAC, and the basis of their decisions in selecting the preferred HSs were not necessarily articulated in the currencies prescribed by the HSWG or the HSP.
- Adopting a *CPUE-prime target* parameter in the HS is quite different from actually attaining the CPUE. The realized CPUE is the result of the interaction between the target, the productivity of the stock, and a number of other HS parameters. Notably the responsiveness (‘gain’) parameter, and RBC change constraints, in the decision rule have an important effect in determining if the decision rule is under-reactive (e.g. potentially allowing the stock to collapse because it cannot reduce catches quickly enough to avert a problem) or over-reactive (tends to recommend large RBC changes, that result in large, potentially pathological, cyclic stock oscillations). In selecting the decision rule, it is important to focus on the realized CPUE outcomes from the simulation testing, rather than the HS decision rule parameter itself, which is likely to be rarely attained within the relevant time horizon (note that even in the ideal cases described in Davies et al (2008), several decades were required to equilibrate to the target CPUE level).
- A fixed CPUE target is also potentially a problem in the case of highly variable recruitment. For a short-lived stock with highly variable recruitment (e.g. yellowfin), there may be limited capacity to ramp up catches in time to take advantage of a large recruitment event. In the case of a recruitment regime shift, a high CPUE target may simply be unattainable even under very low catch levels.

2. **Relies on information from the Australian fishery (CPUE and size) to infer and “learn” about economically and ecologically sustainable catch levels.** Ideally, the ETBF data should provide information about the current population structure, to enable the HS to “steer” the fish population toward a desirable state with a stable age structure. However, we have two concerns about this advantage as stated:
   - Inferences about economics and ecology are imposed from sources external to the HS in the form of a number of fixed parameters. We would actually describe the HS as having a reduced capacity to “learn” relative to model-

based harvest strategies. By embedding a parameter estimation procedure into the harvest strategy, something more akin to learning might be achieved. A more sophisticated HS might use new data to learn about underlying population parameters (e.g. productivity), and adjust target and responsiveness parameters accordingly, before each RBC recommendation. For example, it was the general observation in the CCSBT that the HSs that included the re-estimating of simple dynamic population models outperformed those based purely on data-based decision rules because of this capacity to learn. However, more recent discussions in the CCSBT have also taken a positive view of data-based decision rules because of the simplicity of interpretation, and the avoidance of potential pitfalls associated with automated model-fitting (Basson and Davies 2008, Basson et al 2009, Anon 2009 SC).

- The HSWG downplayed the potential value of data from the international fleets for various reasons (e.g. the connectivity of the ETBF species is poorly understood, and Australian scientists do not have access to the high resolution data or firsthand industry information). We suggest that this data may be valuable and should be consulted in the context of HS oversight and meta-rules, as the ETBF fleet has a history of substantial operational changes such that the local data can be difficult to interpret. The size and CPUE signals in the international and domestic fleets are very similar for some of the species (e.g. swordfish and bigeye tuna at least). Similarities and differences should be regularly examined in the context of operational changes in one or more fleets.

3. **Including size indicators for growth and recruitment over-fishing through the decision tree makes it more "robust" to potential biases in CPUE.** The HS includes a hierarchy of levels, in which a number of size-based catch and CPUE indices can be used to refine the RBC recommendation that is initially derived from the *CPUE-prime target*. The size-based indices are intended to extract additional age-structure and stock status information, and potentially recommend further RBC reductions if there is evidence for falling spawning biomass and/or poor recruitment. In the simulation testing explored here, and in Davies et al (2008), it was evident that the additional size-based components in the decision tree can make the HS demonstrably more conservative, however, it is not clear that they will meet expectations:

- To date, there is no evidence to indicate that the additional size-based RBC modifications provided any improvement to the statistical behaviour of the HS that could not be achieved by simply setting a more conservative *CPUE-prime target* (and removing the lower elements of the decision tree). Individual simulation realizations can be identified, in which the decision tree seems to effectively reduce harvesting in a "risky situation", but there must be another set of realizations in which the decision tree recommends RBC reductions when they are not required, such that on average, there is no net benefit. The expectation was that the decision tree would be most effective in differentially reducing the risk of the most pessimistic scenarios. However, median performance and the lower 10th percentiles (e.g. of catch, CPUE and biomass risk) seemed to be related in a consistent fashion that is driven primarily by the *CPUE-prime target*, RBC change constraint and gain parameter.

- These results were observed from a broad range of HSs with alternative thresholds for the size-based indices, a range of *CPUE-prime* targets, a range of RBC change constraints (not all of these results are included in this document). These observations were also based on a range of operating models that included challenging scenarios with potentially problematic stochastic variability and systematic biases (e.g. including undetected effort creep), and scenarios with most of the stochastic process and observation errors removed.
- We cannot conclude that the lower levels of the decision tree would never be useful. But in the absence of a convincing demonstration that it is beneficial, other HS developers would presumably benefit from knowing that the extra complexity has not yet been justified. Conversely, however, given the state of acceptance and adoption of the current ETBF HSs, we do not see any need to remove the extra elements of the HS decision tree either, as it also has not been shown to have any detrimental effect on performance. A number of reasons have been proposed for the disappointing contribution of the size-based components of the HS decision tree:

  i. The size-based thresholds and indices were intended to represent a consistent set of stock attributes that correspond to a desirable equilibrium population structure. Unfortunately, there generally is no unique equilibrium population structure that meets this criteria for a suite of models which admit uncertainty in basic biological characteristics. At best, a compromise could be specified.

  ii. Any sort of equilibrium-based thresholds will be distorted by high recruitment variability, which appears to be a characteristic of the populations of the main target species of the ETBF. Size class proportions can be almost meaningless on their own, i.e. did the proportion of old fish drop because the spawning stock declined (a bad thing), or because there was a large recruitment event (a good thing). It might not be possible to weave together a reliable synthesis of the stock status and age structure without more explicit modelling in the decision rule that accounts more explicitly for the dynamics of the age structure.

  iii. It is possible that the error structures assumed in the simulation models might not allow the decision tree to perform as expected (e.g. if CPUE indices are very accurate and precise relative to the size-based data, the decision tree might not provide any additional insight about the stock). However, removal of virtually all of the stochastic process and observation errors in the swordfish operating models did not obviously improve the contribution of the size-based components of the HS decision tree. There is also a concern that any simulations that involve a purely separable assumption (i.e. stationary fishery selectivity) might lead to unrealistic expectations about the information content in a real fishery.

  iv. There is an element of inconsistency in the simulation testing presented here in that the actual data are not in perfect agreement with the operating model. Although the explicit conditioning ensures that the operating model and data should be reasonably consistent, they are not perfect. The ETBF CPUE series were not actually used in the stock assessments for any of the species other than swordfish. For the other species, CPUE series for a range of fleets are used in the broader WCPO stock assessments. In the case of swordfish, the CPUE trends are in reasonable agreement, but the fits to the size composition data, particularly for the larger fish, are not as good. For swordfish this could reflect the fact that the sex-dimorphism was not explicitly resolved in the assessment model (plus there are very few sex composition data). This inconsistency means not only that there are errors in the operating model, but also that the first five years of the simulations represent a transition period in which real and simulated data are mixed during the HS application.

4. **Should be "robust" to uncertainty about linkages between regional and broader WCP stocks. That is, it should respond to declines and increases in regional stock status, regardless of whether they are generated by domestic or international fleets**. The HSWG framework was predicated on the idea that the ETBF should respond to signals in the local fishery data and respond accordingly. This should result in domestic management action consistent with the HSP regardless of whether the ETBF harvests a local population or is part of a broader, well-mixed population, and irrespective of the behaviour of the international fleet. This raises a number of issues:
   - This assertion assumes that there are no complicated density-dependent migration dynamics. It is possible to contrive situations in which this would not be true. For example, the Coral Sea could represent a core area of high density habitat, that is a source of recruits for other regions. In the event of depletion, there could be a range contraction, with a minimal effect on the Coral Sea, but a high depletion of surrounding areas. There is not much evidence for this being the case, but it is consistent with the estimated dispersal pattern of yellowfin and bigeye tags in the 1990s (e.g. Hampton and Gunn 1992).
   - Ignoring the possibility of source-sink dynamics, local management by all fleets would probably work successfully irrespective of the population structure. However, at this time, the international community is not involved in any similar approach. For the tuna populations in particular, it is unclear whether there are relatively discrete local populations. It is known that the ETBF CPUE trends were reasonably consistent with the broader yellowfin and bigeye WCPFC assessments (even though these domestic CPUE were not used in the assessment). This does provide some evidence that either the local population is mixed with the broader population, or similar environmental/fishery factors are impacting both populations.
     - If the stocks are well mixed with the adjacent waters, unilateral action by Australia will likely not have much effect on the stock, and could cause economic impacts on the ETBF with no net conservation benefit (i.e. if the stock happens to drop below the target CPUE because of the international fleet, the ETBF could reduce catches substantially and see little or no positive response in CPUE). This could also result even if there is a HS implemented in the RFMO, if the ETBF target CPUE happens to be high relative to whatever target the RFMO decides to adopt.
     - If the stocks are small and localized, we do not have much confidence in the simulation testing that was conducted, because the operating model was only a rough approximation of a few likely ways in which the

population might be subdivided. The models were not explicitly reconditioned on the basis of a different data aggregation. If the alternative models are reasonable, they suggest substantially different outcomes than if there is a large regional population.

- Fortunately, this general problem is recognized by the ETBF RAG and admitted in the HSP. The HS has been recognized as a means of advocating a position within the WCPFC that is consistent with the HSP, but it does not necessarily mean that Australia will take unilateral action to pursue the position. Since there does not seem to be an immediate requirement for unilateral conservation action by Australia for the tuna species, this uncertainty in this aspect of HS performance is probably not urgent and it only likely to be addressed through availability of more primary information on stock structure and connectivity to provide a basis for alternative spatial structures for stock assessment and conditioning operating models.

5. **The approach is applicable to all target species and so provides a consistent framework for integrating multi-species considerations.** The framework is applicable to all of the target species, which is certainly an advantage for testing, stakeholder communication and implementation. However, it is not obvious how this provides any advantage for integrating multi-species management considerations.

6. **The HS framework should be cost neutral within current monitoring and assessment processes.** This is true, however, it is difficult to evaluate how reliable the current data sources are (particularly CPUE as an index of local stock abundance), which may lead to a false sense of security in the HS (or any other HS that is CPUE –dependent). Affordable opportunities for collecting fisheries independent (or semi-independent) data should be explored, including standard gear "sentinel" surveys and tagging (conventional, electronic and genetic).

7. **The decision rules are easy to reconcile directly with what the industry is observing in the fishery, and easy to understand for all stakeholders (unlike many model-based decision rules which might include complicated statistical assumptions and opaque mathematical equations).** This is probably true in that the concepts are relatively simple and more straight-forward to interpret. However, it seems to be the case that signals in catch rate and size composition observed at the operator level are difficult to interpret and often contradictory, such that statistical methods (e.g. catch rate standardization) are usually required to produce fishery level inferences. Hence, the apparent simplicity of the harvest strategy does not remove the potential for differences of view in the interpretation in the status and trends in the fishery.

8. The ETBF RAG considered that it would be very useful to reset the RBC at intervals of greater than 1 year (e.g. 2-3), if confidence in the HS could be acquired after a few years of successful implementation with annual RBC settings. A number of HSs were run with 3 year RBC intervals, and this was found to make very little difference to the overall performance of the HS. We expect that it would be worth pursuing multiple –year RBC settings in the future, noting that i) the RBC change constraint should be larger if the frequency

of setting is lower, and ii) if biomass targets are similar to biomass limits, the RBCs might need to be lower on average if the frequency of setting is lower.

9. The ETBF HS recommends a change to the RBC based on the RBC of the previous year. This could potentially causes problems if the RBC for the species is not met. Assuming that the ETBF does strongly influence the stock, and the RBC is set to hold the biomass stable – if the RBC is not met, then the CPUE will rise, and the RBC will rise again. After a number of years of this cycle, the RBC could become widely disconnected from the catch levels that the stock could sustain. This would create a potentially risky situation if the fleet was to suddenly start removing the full RBC due to, for example, a change in market conditions or the operating environment. The alternative approach of recommending a RBC on the basis of the actual catch in the previous year would prevent the RBC from drifting upward, but would have the converse effect of having the RBC decline consistently if the fleet chose to target other species for reasons that had nothing to do with CPUE or abundance of the RBC species. A third option might be to include a cap on upward RBC movements if catches are less than some fixed portion of the RBC (e.g. 90%), or to set the RBC on the basis of an effective RBC(y-1) which is intermediate between the actual RBC(y-1) and the catch(y-1).

10. It was initially expected that the RBC change constraint would be a tertiary consideration that was outside of the specification of the decision rule and added afterward as a preference from the ETBF RAG/MAC. However, the RBC change constraint proved to be an integral factor in determining the performance of the HS. The responsiveness of the decision rule was intended to be largely dictated by a 'gain' parameter. But most of the rules that were tested had a relatively high gain, and were dependent on the RBC change constraint to keep the rule from being over-reactive. Thus, much of the time, individual RBC changes were either up or down at the maximum level. There were HS parameter combinations which lessened the importance of the RBC change constraint (e.g. achieved primarily through a reduction in the gain parameter), but the dynamics were more difficult to predict in general, and given the broad similarities in the HS performance, there did not seem to be any specific performance advantages that could be identified in relation to these subtleties.

Benefits and adoption

The benefits from this project are directly aligned with the expectations outlined in the original proposal, subject to the modified objectives arising in relation to the evolving circumstances of the WTBF and ETBF:

1) The project directly addresses the 2005 Ministerial Direction requirement for the development and simulation testing of harvest strategies for the ETBF (and the capacity to replicate the process for the WTBF). The ETBF MAC developed a management plan that adopted harvest strategies for the ETBF target species, partly in relation to the outcomes of this project.

2) The ETBF is the primary beneficiary of the project, although the recreational sector and conservation NGOs should gain an increased level of confidence and certainty to the management decisions as underpinned by the completion of this project.

3) The ETBF Harvest Strategies provide a transparent process for making management decisions that is understandable for industry (i.e. the relationship between fisheries data and future TAC changes is clearly articulated and reasonably straightforward). This removes some of the uncertainty about future management and should assist in short-term fishing plans and long-term strategic investment decisions.

4) The project has helped to identify key uncertainties in the understanding of ETBF target species population dynamics (including the linkages between the domestic and international populations and fleets and the relative value of different data sources), and issues which could adversely affect the expected performance of the adopted harvest strategies.

5) The improved understanding of the effects of the link between domestic and international fisheries should help to support the Australian position in WCPFC and IOTC forums in relation to joint management measures, allocation claims and research priorities and collaborations.

The original proposal to evaluate the performance of output and input control management policies for multi-species longline fisheries was not formally addressed due to the planned movement of the ETBF and WTBF to quota systems with the adoption of the new management plans.

Further Development

The generic operating model and simulation testing framework developed for the project have considerable potential for future use. In particular, if additional vessels are activated in the WTBF, a similar exercise to that described for the ETBF could be conducted.

However, it is also a common experience in fisheries MSE that unexpected events will occur that warrant a revision of the HS evaluation. Even if the implementation is successful, it should be periodically reviewed, as new data is collected, management objectives change, or methods for improving performance are discovered.

The MSE framework and experience might also provide a useful example and working template for the WCPFC and IOTC, if they are to embrace MSE for regional management.

Planned outcomes

The project results facilitated ETBF RAG and MAC discussions about the management objectives for the fishery, and allowed an HS to be adopted for each ETBF target species, thus directly addressing the 2005 Ministerial Direction requirement for the development and simulation testing of harvest strategies for the ETBF. This has led to the adoption of HS-regulated management arrangements for the ETBF under interim TAE management arrangements from November 2009 and for quota-management from March 2011.

The development of operating models for the project has helped to identify key uncertainties in the understanding of ETBF target species population dynamics (including the linkages between the domestic and international populations and fleets and the relative value of different data sources), and potential problems which could adversely affect the expected performance of the adopted harvest strategies. This should assist the prioritization of future research activities to reduce these uncertainties and improve future management performance.

The project has helped to establish a broader dialogue with regional fisheries interests (WCPFC-SC) on how to address joint management concerns for the highly migratory and straddling stock fisheries of the WCPO. This was pursued, and largely achieved, through submission of papers reporting on the ETBF work to the Scientific Committee meetings of the WCPFC and undertaking commissioned projects for the WCPFC on the use of reference points and MSE in the application of the precautionary approach to management of tropical tuna and billfish stocks. As noted, the ETBF work has identified the spatial structure and connectivity of the tuna stocks to be a primary sensitivity for the performance of the HS. The successful engagement with the WCPFC processes has built the necessary awareness and relationships for future collaborative work.

Conclusions

1. The core technical objectives of the project were fulfilled, enabling the harvest strategy evaluation objectives of the 2005 Ministerial Direction for Commonwealth Fisheries to be met:
   - A generic MSE framework was developed that could be applied to each of the ETBF target species.
   - Operating models for each of the 5 target species were implemented on the basis of the WCPFC stock assessments (Key features are listed for the target species in points 3-7 below).
   - A number of harvest strategies were evaluated on the basis of the HSWG decision rule framework (Key performance features for the target species are listed in points 3-7 below).
   - The MSE results were used to illustrate management trade-offs for the ETBF RAG and MAC, and this facilitated the selection of specific harvest strategies for each target species, which are currently set for implementation in 2009.
   - The approach and results were presented to the WCPFC-SC in 2007 and 2009, to facilitate discussion about the parameterization of movement dynamics in operating models, and advocate the general utility of MSE for effective regional management.
2. Three of the original project objectives were revised during the course of the project due to changing circumstances and priorities in the management arrangements for the fisheries.
   - With less than 5 active vessels operating in the WTBF in recent years, quantitative evaluation of the HS was not warranted.
   - The WTBF and ETBF fisheries both agreed to implement a quota management system, so there was no further need to compare the trade-offs between input and output management systems.
   - The move to the quota system in the ETBF means that the responsibility and incentive for effective multi-species management is transferred directly to the fishing industry, so no attempts were made to integrate the single species harvest strategies into a multi-species framework.
3. **Swordfish.** We have the most confidence in the swordfish operating model because the assessment was developed with the MSE project in mind: the spatial representation partitions conveniently into ETBF and non-ETBF regions, there are good reasons for thinking that the assessment population is reasonably discrete from northern and eastern populations, and there was a concerted effort to quantify several important sources of assessment uncertainty. It is estimated that the ETBF potentially has a considerable impact on the SW Pacific swordfish population relative to the other fleets, and the HS seems to have a reasonable capacity to manage the uncertainty in the stock dynamics and achieve the objectives of the HSP.
4. **Striped marlin.** The striped marlin assessment is several years out of date, and was considered preliminary at the time. It was spatially aggregated across a broad region of the south-west Pacific, and the quantification of uncertainty was minimal. The data and assessment suggest that the ETBF region is the most important part of the fishery currently and historically (the Japanese fleet seems to have largely depleted this population in the 1950s-1970s). Despite the concerns about the assessment, the

operating model may provide a reasonable representation of the striped marlin population dynamics in the ETBF region. The simulation testing suggests that the ETBF may have a large effect on the population, such that the HS feedback mechanisms are relevant, and likely to have an important influence on the population. The target CPUE level in the HS adopted by the MAC is near the level observed during the rapid expansion of the ETBF fleet, and if effectively implemented will maintain the population in a depleted state. This may not be consistent with the Commonwealth Harvest Strategy Policy and should be revisited when the striped marlin assessment is updated. Given this and the availability of new information on the population biology of striped marlin from a recently completed FRDC project, updating this assessment should be a priority.

5. **Bigeye and Yellowfin tuna.** The MSE results shared many similarities for bigeye and yellowfin tuna. We have reasonable confidence in the WCPFC stock assessments because they are recent, supported by large amounts of data, and represent several years of iterative development. However, for both species, there is considerable uncertainty about the population connectivity between the ETBF region and adjacent equatorial and eastern regions. If the relevant populations are broadly distributed, then the ETBF has a minor impact on the stocks, and the feedback population regulation mechanism on which the HSs are predicated may be ineffective. This situation could cause an unintended economic impact on the ETBF with minimal benefit to the broader population. Conversely, if the stocks are very localized, then the ETBF has considerable potential to affect the stock, including a potential over-harvesting with the recommended HS (if the localised population robustness scenario reflected the real stock structure and connectivity). The broader WCPO bigeye stock is estimated to be much more depleted, and less productive than, the yellowfin stock and is presumably also more vulnerable in the ETBF, if the population is localized. The appropriateness of the HS for bigeye and yellowfin is discussed further. The ETBF RAG, MAC and AFMA are aware of the importance of additional management options for these stocks.
6. **Albacore tuna.** We have the least confidence in the albacore HS evaluation. The stock assessment was recognized as preliminary and problematic, the spatial structure did not resolve the ETBF region (it covered the whole South Pacific), and there was strong evidence for a systematic lack of agreement between the ETBF standardized CPUE and the stock assessment. The results suggest that the ETBF influence on the regional albacore population relative to the international fleets is unlikely to be negligible, and is likely to be substantial if the population is more restricted than the current assessment suggests.
7. **Critique of the operating models.** To some extent, the success of the MSE work will always be limited by how well the fishery dynamics and uncertainty are represented in the operating models. We encourage a number of additional analyses to refine these models, including:
    - Explicitly condition the operating models with the fisheries data disaggregated to represent plausible localized populations.
    - Encourage tagging studies and analyses at a scale that will help to resolve the spatial connectivity between the ETBF and broader WCPO.
    - Update the MSE using the most recent WCPFC assessments, in particular including the recent emphasis on model uncertainty the for yellowfin and bigeye assessments undertaken by SPC.
    - Formally evaluate the statistical characteristics of the ETBF data.

8. **Critique of the HSWG decision rule framework.** The simulation testing identified a number of potential issues with the HSWG framework, including:
   - The ETBF HS is not really robust to the uncertainty in population connectivity, in the sense that it could recommend unilateral management actions for some target species that have serious economic consequences for the domestic fleet and minimal conservation benefits for these stocks.
   - To date, there is no evidence that the size-based indices in the HS decision rule improve the management performance beyond that resulting from the use of a target CPUE level on its own. The size-based indices make the HS performance more conservative, but on average this seems to be equivalent to setting the target CPUE more conservatively (and removing the lower levels of the decision tree).
   - The short-medium term performance of the HS seems to be sensitive to the specification of several parameters that do not behave in an intuitive manner. This might not be of any substantial consequence if each HS is evaluated with reliable operating models, but it does indicate the importance of thorough testing.
   - We speculate that alternative (model-based) HSs might have a better capacity to "learn" over time (e.g. about stock productivity) than the HSWG framework, which may result in more robust performance. However, this would require a convincing demonstration under equivalently challenging simulation conditions, before we would recommend changing from the current framework.

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Appendix 1: Intellectual Property
No commercial or intellectual property arose from this work.

Appendix 2: Staff

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Appendix 3: Technical specification of the Generic Eastern Tuna and Billfish Fishery Operating Model

This appendix provides the rationale and equations for the population and fishery dynamics of the ETBF operating models used for the MSE project. While all elements of the model were used at some point in the development process, some features are adopted in the higher priority reference set of operating models, some features are only represented in the more speculative reference set of operating models, and some features might have been tested but subsequently dropped as they do not actually have much influence on the performance of the candidate harvest strategies.

The ETBF MSE Operating Model

The operating model is age-structured, spatially disaggregated (two regions), and based on the difference form of the Baranov catch equations. Within each quarter, processes happen in the following sequence:

1. Recruitment (not applicable in all quarters, depending on the species)
2. Migration
3. Natural and fishing mortality
4. Collection of fisheries data.

In the following, some sub-scripts and super-scripts have been intentionally omitted to improve readability, but should be self-evident from the context. The time subscript, *t*, represents quarters or years depending on the context. The model is always iterated on a quarterly time step, but the RBC, and HS indices are annual. Recruitment is quarterly for the tropical species and annual for the temperate species.

Recruitment

Recruitment is described by a Beverton-Holt Stock Recruitment (SR) relationship with serially-correlated lognormal deviates:

$$R_t = \frac{\alpha SSB_t}{\beta + SSB_t} \exp(\tau_t - \tfrac{1}{2}\sigma^2),$$

$$\tau_t = \rho\, \tau_{t-1} + \varpi_t \sqrt{1-\rho^2}$$

$$\varpi \sim \text{IID } Normal(\mu = 0, \sigma)$$

where:

R = recruitment,

SSB = Spawning Stock Biomass,

α, β = parameters of the stock-recruitment relationship,

τ = autocorrelated random normal deviate,

ρ = lag(1) auto-correlation co-efficient,

ω = a random normal deviate,

and subscript t corresponds to a quarterly time-step. The first recruitment deviation in the projections is not constrained by the preceding deviate derived from the assessment model. For species with annual recruitment, this equation is only relevant in the first quarter of every year, and recruitment deviations are correlated across years rather than quarters.

To maintain consistency with the assumptions used in the MULTIFAN-CL stock assessments, spawning and recruitment processes are assumed to operate at the level of the whole population. However, other population and fishery processes are disaggregated into two regions, the ETBF and non-ETBF (everything else):

$$SSB_t = \sum_r \sum_a N_{r,a,t} Maturity_a MAA_a \text{ , and}$$

$$N_{r,a=0,t} = P_r R_t$$

where:

N = population in numbers by age,

P = the proportion of recruitment assigned to each region (constant over time),

Maturity = a vector of the proportion mature by age, and

MAA is the vector of mass-at-age (kg),

and subscript a indicates the age-class (0 corresponds to recruits, A is a "plus-group" accumulator designating the oldest age-class), subscript r indicates the region (ETBF or non-ETBF).

Migration

Migration is modelled as an instantaneous redistribution of the population every time step. The form adopted here is somewhat different from that used in the MULTIFAN-CL assessment models. The numerical implementation difference is probably trivial relative to the alternative parameter values that were imposed (i.e. in the simulation testing, extremely high and low migration assumptions were used), and the alternative spatial assumptions adopted (i.e. for four of the five target species, the spatial assumptions differed between the assessment and operating models). The approach used here parameterizes migration in terms of equilibrium distributions and rates of redistribution, rather than the more traditional approach (i.e. a matrix describing the probability of movement from region i to region j):

$$N^{AM}_{r=ETBF,a,t} = (1 - migProp) N^{BM}_{r=ETBF,a,t} + migProp \cdot P_{r=ETBF} \sum_r N^{BM}_{r,a,t}$$

$$N^{AM}_{r=nonETBF,a,t} = (1 - migProp) N^{BM}_{r=nonETBF,a,t} + migProp \cdot P_{r=nonETBF} \sum_r N^{BM}_{r,a,t}$$

where:

migProp = proportion of fish potentially undergoing redistribution,

P = the proportion of fish in region r when the population is at equilibrium, and superscripts *BM* and *AM* indicate before and after migration respectively. For convenience (and in the absence of evidence to the contrary), the *P* parameters are assumed to be identical to those used to define the spatial distribution of recruits above.

Mortality

Fishing and natural mortality processes occur after migration:

$$N^{BM}_{r,t+1,a+1} = s_{r,t,a} N^{AM}_{r,t,a}; \quad \text{for } a < A,$$

$$N^{BM}_{r,t+1,A} = s_{r,t,A-1} N^{AM}_{r,t,A-1} + s_{r,t,A} N^{AM}_{r,t,A}; \ \text{for } a = A$$

$$s_{r,t,a} = \exp(-F_{r,t,a} - M_a),$$

where:

s = survival,

M = natural mortality (age-specific, but constant over time), and

F = fishing mortality,

The catch composition, C, is the proportion of total mortality attributed to fishing:

$$C_{r,t,a} = \frac{F_{r,t,a}}{F_{r,t,a} + M_a} N^{AM}_{r,t,a} (1 - s_{r,t,a}).$$

Fishing mortality follows a separable assumption, i.e. F is composed of a time-step component and age component for each fishery:

$$F_{r,t,a} = G_{r,t} H_{r,a},$$

where, for a single fishery, G_t is the time component of the fishing mortality term, and H_a is the age-specific fishery selectivity term (which is assumed to be constant over time). In the operating model, $H_{r,a}$ is a fixed input from the relevant assessment model.

The model ignores several details related to quarterly dynamics (e.g. catch is almost uniformly distributed across seasons), and the ETBF and non-ETBF fisheries are treated somewhat differently. In the ETBF, an approximate annual fishing mortality (G^{annual}) is first calculated corresponding to the RBC (plus implementation error if applicable, as described subsequently). This G^{annual} is then used to calculate the quarterly G_t assuming that $G_t = G_{t+1} = G_{t+2} = G^{annual}/4$, and the fourth quarter, G_{t+3}, is approximated separately to ensure that the four quarters of catch sum to the RBC. If the RBC is not attainable with a maximum of $F_{t,a} = G_t = 20$, then the catch corresponding to $G_t = 20$ is removed and the model continues on to the next iteration. This corresponds to an unrealistically high effort level, and is probably not a realistic outcome, but provides a useful indication that something has gone seriously wrong with the HS if it does occur.

RBC Implementation Error

We assumed two different scenarios with respect to RBC implementation error:

1. No implementation error (catch = RBC)

2. Implementation error (catch = RBC exp(ω)), which is analogous to the equation above, such that the implementation error can be thought of as deviations in catchability (or effective effort) in relation to operational changes (e.g. species targeting). This potentially results in relatively large deviations from the RBC that might result as a consequence of how the RBC is implemented.

Non-ETBF fishery Effort Scenarios

The non-ETBF fishery is assumed to follow one of three effort scenarios:

1. Non-ETBF effort is regulated according to the harvest strategy recommendation. In this case, $G_{r=nonETBF,t}$ is a function of non-ETBF effort, *E*, which changes proportionally to changes in the ETBF effort: $G_{r=nonETBF,t+1} = G_{r=nonETBF,} (G_{r=ETBF,t+1}/G_{r=ETBF,t})$
2. Non-ETBF effort (and hence $G_{r=nonETBF,t}$) is held constant over time (though catches vary with abundance in the non-ETBF region).
3. Non-ETBF effort increases or decreases linearly during the first few years of the HS implementation and then remains constant. Note that the first year differs by species (according to the assessment). Increasing effort scenarios were applied to all species as a robustness test. The reference set of operating models included an effort decrease for bigeye only (to be consistent with the WCPFC Conservation and Management Measure).

CPUE Data Simulation

Commercial longline CPUE is the only relative abundance index available for the ETBF target species. Every year considerable effort is spent attempting to standardize the fishing effort to account for changing times and areas of operation, changing gear configuration, etc. Methods of generating confidence limits for standardized effort (or CPUE) series are available, but there is a general recognition that these methods tend to understate the true uncertainty in relative abundance trends, and have not been routinely applied to the ETBF species. In the operating model, it is assumed that CPUE observations have lognormal, serially-correlated errors:

$$I_t^{obs} = I_t^{predicted} \exp(\tau - 0.5\sigma^2) ,$$

$$\tau_t = \rho\, \tau_{t-1} + \varpi_t \sqrt{1-\rho^2} ,$$

$$\varpi \sim \text{IID } Normal(\mu = 0, \sigma)$$

where *I* represents the standardized CPUE index, *t* is in annual units as required for the HS, and

$$I_t^{predicted} = q \sum_a N_{a,r=ETBF} H_{a,r=ETBF} ,$$

where *q* is the catchability coefficient. Note that this is the size-aggregated CPUE, which is only used in the albacore HS. For the other species, the CPUE index is broken down into size groups (recruits, prime and old), after the observation error is applied.

$$I_{sizegroup,t} = I_t S_{sizegroup},$$

where S indicates the proportion of fish in the size group. Catchability, q, is calculated for each size group independently,

$$q_{sizegroup} = \frac{\sum_{t}^{AM \cup Data} I_{sizegroup}}{\sum_{t}^{AM \cup Data} S_{sizegroup,t} \sum_{a} N_a H_a},$$

based on the years of overlap between the actual observed ETBF CPUE data and the predicted CPUE from the operating model (derived from the WCPFC assessment):

Serial correlation in CPUE errors is intended to reflect the fact that the standardization is imperfect, and the errors that limit the success of the standardization are probably correlated in time (i.e. due to long-term trends in fishing behaviour or oceanographic conditions). "Effort creep" is the result of a continuous progression of technological efficiency in the fishing industry which cannot be properly accounted for. It potentially results in CPUE hyperstability (in which fish abundance declines faster than the CPUE index). The ETBF HS decision framework includes a number of size-based indices in addition to the CPUE, and in part, this was intended to lessen the impact of reliance purely on CPUE, particularly in the context of potential effort creep. Some of the HS evaluation scenarios included a temporal effect on catchability (which was otherwise assumed to be constant):

$$q_{t+1}^{f} = q_t^{f} + \delta,$$

where δ is the positive bias term (2% of q in the first year of projections). This is purely an effort creep scenario going into the future. A similar process is sometimes included in the assessment process to evaluate the historical implications of effort creep on the assessment, but this sort of scenario was only included on a single set of the bigeye tuna MPD estimates.

Size Composition Data Simulation

The simulated catch length frequency distribution for each fishery is calculated:

$$C_{r,t,l} = \sum_{a} V_{a,l} \frac{F_{r,t,a}}{F_{r,t,a} + M_{a,t}} N_{r,t,a}(1 - s_{r,t,a}),$$

where $V_{a,l}$ is the proportion of age a fish in length-class l. Mean length-at-age is derived from the von Bertalanffy growth curve and each length-at age distribution is assumed to be normally-distributed, with standard deviation (σ_a), which is in turn a linear function of the mean length-at-age (μ_a):

$$\sigma_a = slope\mu_a + intercept\,,$$

Mass-at-age is assumed to be a function of length:

$$mass = a \cdot length^b\,.$$

The size-age relationships are all adopted from the species-specific assessments, and in some cases multiple growth curves for the same species are admitted in different operating models to admit uncertainty about these parameters. The model operates in whole mass (the units in which the RBC is defined).

The size composition is sampled from the deterministic catch distribution (above) using multinomial sampling roughly in proportion to that used in the ETBF (as the data from the non-ETBF fishery is not included in the HS decision rule, data does not need to be generated for this fishery). Most fisheries do not have truly random size composition sampling, and the multinomial sampling might result in unrealistically informative data. However, for some of the ETBF fisheries, the processor-based sampling rate is so high (e.g. ~70% for swordfish), that the assumption of truly random sampling is probably not a problem. However, there is a related problem in the model arising from the assumption of separable selectivity. While this is a convenient tool for reducing model complexity (and producing tractable estimators in assessment models), we would expect the changing nature of the fishery in terms of space/time distribution of sets and gear configuration (hook types and set depths) to result in some change in selectivity over time. To prevent the size composition data from being unrealistically informative, we added the option of introduced a random bias to the size composition sampling. It may have been more appropriate to introduce it as a selectivity bias, but the most important result is the same. Given a vector of catch-at-length proportions, C_l, a transformed vector (C^*_l) for size sampling is calculated:

$$C_l^* = \frac{C_l \exp(\tau \frac{l}{L})}{\sum_l C_l \exp(\tau \frac{l}{L})}\,,$$ (note that in practice, the sampling bias is based on catch-at-age)

where τ is a random normal deviate, N(μ = 0, σ) and serial correlation ρ, and l is the size composition index from 1 to L. The effect for σ = 0.3 is shown in Figure 100. While we do not claim that this particular function is the best for our purposes, we do consider that it is better to include it than ignore the effect of non-random sampling and/or variable selectivity in the operating model.

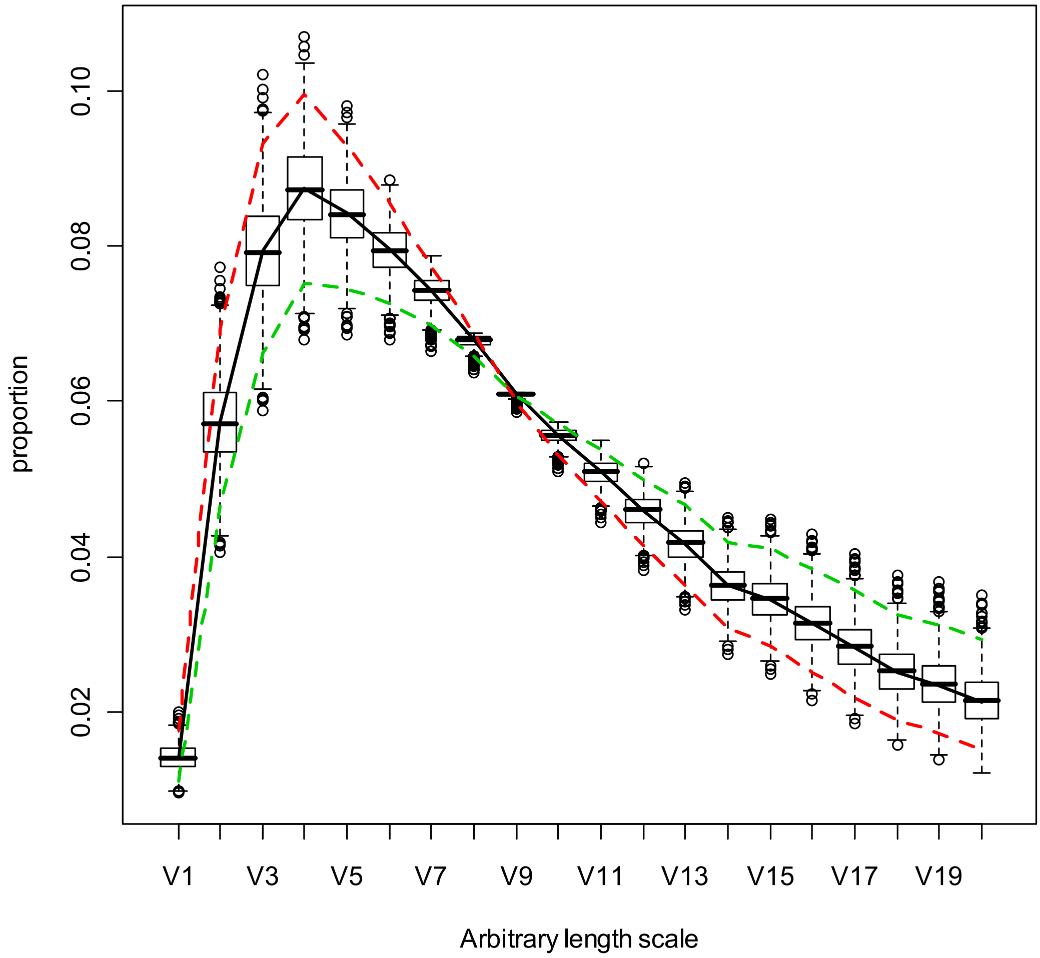

Figure 100. Illustration of the size composition sampling bias for an arbitrary catch size frequency distribution. Boxplots illustrate the outcomes from 1000 stochastic realizations. The true value is illustrated by the solid black line. The broken (red and green) lines indicate the 95% confidence limits (this particular form of size sampling bias will always shift the sampled distribution toward larger or smaller fish, while the mid-point of the size range is relatively unbiased).

Appendix 4: Report of the ETBF MSE technical review workshop, 26 Oct 2009.

Independent Review Workshop for FRDC Project 2007/017 "*Integrated evaluation of management strategies for multi-species long-line fisheries"*

Chair: Keith Sainsbury.
Formal Independent Reviewers: Nokome Bentley and Kevin Stokes.
Agenda and list of participants: Appendix A.

Background

Harvest strategies developed for the Eastern Tuna and Billfish Fishery (ETBF) have been formally tested using the Management Strategy Evaluation (MSE) approach as prescribed in the Harvest Strategy Policy and Guidelines. At each stage of the MSE process, stakeholders at the RAG and MAC meetings have been updated on progress, and have provided feedback and information for inclusion in the ETBF MSE project (e.g. management objectives and trade-offs between them, selection of proxies for target and limit reference points and selection of the final harvest strategy to adopt). The stakeholders have provided input and ongoing review of the project as it has progressed. The intention of this workshop was to invite scientist with expertise in stock assessment and MSE to a technical review of the MSE process adopted for this work, since limited technical review was possible during the RAG meetings. Participants were provided with an "advance draft" of the final report prior to the review workshop.

Summary of Project Objectives

- To address the requirements of the Ministerial Direction and the Commonwealth Harvest Strategy Policy for evaluation of harvest strategies for Commonwealth Fisheries
- To formally evaluate the Harvest strategy framework developed by the Harvest Strategy Working Group for the five primary target species of the ETBF using MSE.[2]

[2] The project was specifically designed to evaluate this agreed harvest strategy framework within the timeframe available prior to implementation. Therefore, there was not scope within the current project for exploration and testing of a broader set of harvest strategies.

Introduction

Dr Keith Sainsbury chaired the meeting, introducing participants. Dr Campbell Davies provided an introduction on the background to the project and its role in the development and implementation of harvest strategies for the Tropical Tuna fisheries. Dr Dale Kolody structured the description of the project through a power point presentation on the MSE approach, as applied to the ETBF, followed by details of the operating models and MSE for each target species. Participants were invited to interject with questions, comments and discussions throughout the presentation.

A summary of the major comments and suggestions made through the workshop are provided here. The draft final report of the project has been substantially updated from the advance draft circulated to participants prior to the workshop to reflect this input.

Overview of the MSE approach

Generic ETBF Single Species Operating Model

- The development of a generic two-region operating model (OM) was described. The population dynamics parameters and estimates of numbers at age etc, were adopted from existing stock assessment models to condition the operating models for each species.
- It was noted that the appropriateness of the underlying stock assessment to fit within the structure of the generic operating model varied from good for Swordfish to less so for other species.
- There were several real constraints on the work that could be done within the project relative to an "ideal" MSE process.
    - With the exception of swordfish, all the assessments are conducted by the Secretariat of the Pacific Community (SPC) as part of the international management requirements of the Western and Central Pacific Fisheries Commission. As such, these models generally do not have a strong emphasis on resolving the dynamics of the relatively small Australian fisheries. It was never in the scope of this project to conduct/update these assessments. The project team had to proceed with what was available.
    - The nature of the Harvest Strategy (HS), i.e. an empirical CPUE and size-based rule using commercial Catch & Effort data, was set. The focus of the project was to evaluate and specify variants of this rule, rather than explore alternative forms of HS.
    - Notwithstanding this, there had been considerable earlier work on the general behaviour of empirical rules for highly migratory species across a range of circumstances (Basson and Dowling, 2008; Davies et al., 2008).
    - The standardization of the commercial CPUE data used in the HS decision rule was also external to the project. This fishery has had a continuous history of rapidly reinventing itself, with substantive spatial shifts and targeting changes. It was assumed that some form of standardized CPUE would always be available for use as a relative abundance index in the HS, but it was recognized that attempts to directly quantify CPUE biases would be somewhat arbitrary (discussed below).

- A larger range of robustness testing was done than is presented in the report. The results presented were selected to demonstrate the most important features and behaviour of the HS under what were considered to be fairly extreme, but plausible, scenarios. The workshop suggested that details of the broader robustness testing that was conducted be included in the report.
- It was suggested that more detail on the background to the scope of the project and references to the preliminary analyses undertaken prior to this project needed to be added to the report.

- The workshop participants were interested in the MFCL assessment models used to condition the operating models for each species, and they suggested that the report should include some of the assessment model parameters and estimates. It was suggested that the report describe some of the uncertainties that have been incorporated into the assessment models, and their links in the operating models.

Management Objectives and performance criteria

- These were developed by the RAG and MAC, and agreed by AFMA to be consistent with Harvest Strategy Policy (HSP).
- The workshop questioned whether it was appropriate to use $0.2B_0$ as a proxy for $0.5B_{MSY}$ as the limit reference point. The flexibility admitted under the Australian HSP for limit and target reference points was explained, including the use of MSE to evaluate alternatives. In addition, the project participants recalled the issues specific to highly migratory stocks and connectivity with the broader WCPFC that had been identified during the development of the ETBF HS (Davies et al 2008). However, since the estimates of MSY related quantities were readily available, estimates of depletion relative to B_{MSY} have been added to the report.
- The workshop suggested that figures for average annual variation in catch and recruitment time series be added to the report.

Uncertainty and risk

- Several sources of uncertainty in the form of alternative biological parameters and observation error assumptions have been explored in the OMs using a range of robustness tests.
- Uncertainty in population connectivity between the ETBF region and the adjacent Pacific (non-ETBF) was examined with alternative assumptions about the relative size of the non-ETBF fleet, the mixing rate between the two populations, and the future behaviour of the non-ETBF fleet. These assumptions differed by species.
- Uncertainty in future changes in domestic fleet behaviour were addressed by introducing serially correlated observation errors and effort creep scenarios in CPUE. Serially correlated errors were also introduced to the size composition sampling (over time and among size classes) to reflect potential changes in selectivity associated with targeting shifts among species
- Uncertainty in management regimes was introduced with implementation error on the attainment of TACs.
- It was noted that there is an interaction between estimated biological risk to the stock (as defined in the HSP) and the level of uncertainty admitted in operating

model conditioning through various forms of model and parameter uncertainty. This raised the question of whether there should be guidelines for how various forms of uncertainty should be considered in MSE of harvest strategies for the policy.

Single species operating models and harvest strategy evaluation

Swordfish

- The process for including swordfish operating model uncertainty was more comprehensive than for other species. 14 "assessments" selected from a range of 192, were adopted to span the plausible uncertainty (Kolody et al., 2008). Additional robustness tests were applied on top of the uncertainty encompassed by this assessment uncertainty. The 14 alternative models were conditioned (fit) to the data, while the robustness tests were not. The relatively poor fit between the observed and predicted size data (particularly juvenile and old categories) was identified as a concern. While the trends in the model fit and indicators were generally similar, the absolute values were offset. A number of possible causes for this inconsistency were discussed: i) the OM fits the data from all south-west Pacific fisheries, while the size indicators are derived only from the Australian catch, and some compromise due to the conflict among the different data sources would be expected (e,g, due to simplifying assumptions about spatial homogeneity and shared fleet characteristics), ii) the process used to generate the data for the HS was not identical to the process used for the stock assessment, which could create discrepancies, iii) the assessment does not properly account for sex-dimorphism, and this is most likely to cause a problem with the size composition of larger fish.
- The workshop suggested that data from other international fleets (e.g. the NZ CPUE in particular) should be used as an independent indicator for the broader swordfish stock.
- The workshop suggested a number of alternatives for future exploration of model uncertainty, including using alternative stock-recruitment relationships (e.g. Ricker) and to consider the Francis review of uncertainty in commercial CPUE (Francis et al, 2003). It was noted that these and other suggestion would require reconditioning of the OM, which was not possible within the context of the current project, but should be considered in the future as part of a review of the implementation of the HS.

Review Conclusions for Swordfish: i) further exploration of uncertainty in the OM recommended in the future (see above); ii) the HS was likely to be effective in terms of adjusting catches in response to feedback from indicators; and, on the basis of the evaluations completed, was likely to meet the objective of the HSP.

Striped marlin

- The assessment was outdated (completed in 2006 with data up to 2003) and preliminary, additional biological work has been completed recently (Keller Kopf, PhD & FRDC project), which was not available for the assessment or MSE.
- Large discrepancies are observed between the CPUE data and predictions between the last year of the assessment and the first year of the HS projections (i.e. the available data that were not used in the assessment). This undermines confidence in the appropriateness of the current assessment and operating model.
- There is not likely to be sufficient stock structure/movement data to resolve the spatial dynamics. However, the historical data indicates that the ETBF region has been the source of most removals, so the spatial resolution might be reasonably appropriate.
- The workshop noted that the recruitment variation used may be too high and suggested exploring lower CV on future recruits.
- The workshop asked whether the stock assessment includes recreational catch from Australia and NZ, which it does.

Review Conclusions for Striped Marlin: i) current assessment indicates that striped Marlin is depleted and current catches are sufficient to prevent rebuilding; ii) the HS is unlikely to meet the HSP objective due to the depleted state of the stock; and, iii) given the preliminary and outdated nature of the assessment, a revised assessment should be a high priority

Bigeye

- The fit between the operating model and observed CPUE and size proportions was very good for Bigeye relative to other species. This was particularly unexpected, given that for Bigeye, the Australian CPUE and catch is a small proportion of the data for this fishery and the WCPFC assessment uses distant water longline fleet CPUE as the main abundance index in the assessment.
- The workshop questioned whether changes in management and operation of the fishery have affected Bigeye indicators (e.g. TAC on Swordfish and shift to deep setting for Albacore). While this could not be explicitly addressed in the current project, it should be investigated as part of the monitoring implementation of the harvest strategy, in particular through exploratory analyses associated with the CPUE standardisation.
- The workshop commented that the “apparent” recruitment pulse in 2008 has a large effect on short-term dynamics. This feature is apparent for other species as well and was questioned whether this may be an assessment artifact. It was noted that the operating model introduces additional uncertainty to recent recruitment that is derived from the latter years of the stock assessment. However, this process would not remove the possible bias associated with this estimate.

Review Conclusions for Bigeye: The effectiveness of the HS for the Bigeye stock is clearly dependent on stock connectivity assumptions, which are poorly quantified. If the stock is of moderate size with strong connectivity between the ETBF and broader Pacific, then unilateral action guided by the ETBF HS is likely to have a moderate positive influence on the conservation risk to the stock; however, any such benefit, would probably be realized by the broader Pacific fleet at the cost of the ETBF fleet. ii) In contrast, robustness tests, which assume that the ETBF population is a small, weakly connected, subset of the broader Pacific population suggest that the ETBF would have a strong effect on the stock and might be too slow to respond to the population decline, and potentially fail to meet the HSP objectives; and therefore: iii) Recognizing the arbitrary nature of the spatial scenarios as tested, it is obviously a high priority to establish the nature and extent of connectivity. At a minimum, there should be an explicit reconditioning of the OMs to derive alternative spatial options that are at least consistent with the available data, which may not be the case at present.

Yellowfin

- There is a substantial mismatch between observed and predicted proportions by size group in the OM. This probably reflects the dominating influence of the international fleet on the stock assessment, relative to the Australian fleet, and the likelihood that the population is not homogenously mixed in the assessment region.
- The model uncertainty was restricted to the robustness tests, because there was only one stock assessment model available to fit from SPC.
- The workshop recommended exploring scenarios with reduced recruitment CVs.
- The HS may not be effective for Yellowfin because the small catch of the ETBF, relative to the high abundance of Yellowfin estimated in the assessment, means that there appears to be a disconnect between the catches of the ETBF and the feedback decision rule of the HS.
- On the basis of the current assessment and OM, the ETBF has little impact on the Yellowfin population. This is the case even in the most spatially restricted scenario (which had serious consequences for Bigeye).
- However, only a single assessment model was available to condition the OM. Exploration of alternative spatial scenarios may not be reliable without reconditioning the operating model to an appropriately spatially structured assessment.

Review Conclusions for Yellowfin: i) On the basis of the current assessment and OM scenarios explored, the ETBF is unlikely to have significant impacts on the Yellowfin stock at current, or historical, levels of catch, ii) Similar to Bigeye, there is a need for better information on the spatial structure of recruitment and adult connectivity to improve the spatial parameterisation.

Albacore

- The HS as tested used only CPUE due to the absence of size composition data. A program is now in place to collect size data (Farley and Dowling 2009).
- The available stock assessment was considered preliminary, and has been targeted for further refinement by the SPC (Hoyle and Davies, 2009).

- There are large uncertainties in the CPUE standardization (extent of targeted effort and changes in targeting over time in international fleet, including seasonal selectivity changes). Some of these issues are currently being addressed by SPC and CSIRO (Biological parameters, stock structure and movement).
- The spatial structure of the assessment is very poor for describing the ETBF fishery, as a single region is used to describe the whole South Pacific population.

Review Conclusions for Albacore: The effectiveness of the HS for Albacore was not considered to be well tested, due to: the preliminary status of the stock assessment, the poor resolution of spatial issues, and the lack of size composition data for use in the HS. Albacore should be a high priority for future work.

Future considerations for the ETBF HS

- Ideally, future work should include explicitly reconditioning OMs to include alternative SR relationships, connectivity hypotheses, historical effort creep, distribution of SSB (stock structure); and to address multi-species issues such as technical interactions and targeting, which are likely to impact on the effectiveness of the CPUE standardization over time.
- The technical review members discussed the merits of fully conditioned operating models for MSE and less conditioned, but plausible, multi-species operating models. They concluded that there is a need to condition whenever possible, but not to let the absence of data for conditioning constrain the range of robustness testing to potentially major issues that are explored. It was agreed that there was a large element of ‘experience” in identifying and specifying appropriate range of robustness tests and that a synthesis of this experience would be a valuable resource for future MSE projects.
- Further consider changes in fleet operations and effects on CPUE standardization (see above). Monitor fleet dynamics for management induced changes that may be outside the robustness scenarios considered in this report. It was clear that further analyses of the CPUE standardisation, and recent fishery changes and how they manifest in CPUE indices, was outside the scope of this project. However, it was highlighted as a priority for implementation and ongoing monitoring, particularly given the pending shift from input to output controls.
- Spatial indicators other than the standardized CPUE and size indices used as inputs into the HS need to be monitored as part of implementation to provide insight into underlying spatial issues in the fishery. These could include a range of catch and effort derived statistics that assist in monitoring shifts in effort and targeting over time (e.g. number and type of shot/statistical cell.
- The workshop noted that the CPUE approach used in the ETBF HS potentially provides a disincentive to collect more useful data that could be used to test the underlying assumptions and uncertainties in the current assessments and HS that may lead to better performance. The requirement for fisheries independent monitoring in the HSP was noted, as was the challenge in designing and implementing such programs for highly migratory stocks.

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Appendix A: Agenda and Invited participants

ETBF MSE Review Workshop
26 October 2009 (full day)
Freycinet Room, 9am to 5pm
CSIRO Marine Laboratories, Hobart

List of Invited Participants:
Marinelle Basson (CSIRO), Nokome Bentley (Trophia – Independent Reviewer), Robert Campbell (CSIRO), Campbell Davies (Project PI), Natalie Dowling (Project participant), Ian Freeman (Tropical Tuna, Executive Officer), Malcolm Haddon (CSIRO), Dale Kolody (Project participant), Ann Preece (Project participant), Jeremy Prince (Biospherics), Keith Sainsbury (Chair), David Smith (CSIRO), Tony Smith (CSIRO), Kevin Stokes (Independent Reviewer), Trysh Stone (AFMA), David Wilson (BRS), Simon Hoyle (SPC), Cathy Dichmont (CSIRO).

Agenda:

(1) Project Objectives

- Ministerial Direction and the Commonwealth Harvest Strategy Policy
- Harvest Strategy Working Group Decision rule framework

(2) Overview of the MSE approach

- Generic ETBF Single Species Operating Model
- Management Objectives and performance criteria
- Uncertainty and risk

(3) Single species operating models and harvest strategy evaluation

- Swordfish
- Striped marlin
- Bigeye
- Yellowfin
- Albacore

(4) Future considerations

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