OCEANS AND ATMOSPHERE FLAGSHIP
www.csiro.au

Development of an approach to harvest strategy management of internationally managed multi-species fisheries

Rich Hillary, Ann Preece, Dale Kolody, Karen Evans and Campbell Davies

FRDC Project No. 2013/203
Fisheries Research and Development Corporation

Development of an approach to harvest strategy management of internationally managed multi-species fisheries

Rich Hillary

Ann Preece

Dale Kolody

Karen Evans

Campbell Davies

Published 24/06/2015

FRDC Project No **2013/203**

ISBN 9781486306565

Development of an approach to harvest strategy management of internationally managed multi-species fisheries
2013/203

Published in 2016

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details

Name: Rich Hillary
Address: CSIRO, Battery Point, Hobart TAS 7001

Phone: +61 3 6232 5452
Fax: +61 3 6232 5000
Email: Rich.Hillary@csiro.au

FRDC Contact Details

Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

Contents

Acknowledgments

The authors of the report would like to thank the attendees of the harvest strategy workshop for the ideas and contributions to this work.

Abbreviations

CKMR: Close-kin mark-recapture

EEZ: Exclusive Economic Zone

ETBF: Eastern Tuna and Billfish Fishery

HCR: Harvest control rule

HS: Harvest strategy

HSP: Harvest Strategy Policy

MSE: Management strategy evaluation

OM: Operating Model

PNG: Papua New Guinea

RFMO: Regional Fisheries Management Organisation

SPC: Secretariat of the Pacific Community

TTMAC: Tropical Tuna Management Advisory Committee

TTRAG: Tropical Tuna Resource Assessment Group

WCPFC: Western and Central Pacific Fisheries Commission

WCPO: Western and Central Pacific Ocean

WTBF: Western Tuna and Billfish Fishery

Executive Summary

This project was undertaken by CSIRO scientists working on one of the most complex fisheries management issues: how to manage a fish stock at the national level when the species is part of a much wider population, migrates across national boundaries, and is managed at the population level by an international fisheries management organisation. The project work was undertaken between 2013 to 2016 using the fishery for tuna (Yellowfin Tuna (*Thunnus Albacares*), Bigeye Tuna (*Thunnus obsesus*), Albacore (*Thunnus alalunga*)) and billfish (Swordfish (*Xiphias gladius*), Striped Marlin (*Kajikia audax*)) on the East coast of Australia as the example case study. Australia's Commonwealth Harvest Strategy Policy requires that fisheries within Australia's territory are managed according to that policy, even if the actual spatial population range (and international fisheries harvesting within) includes regions outside Australia's territory and international fisheries management protocols. Using state-of-the-art models and population dynamics modelling the project explored (i) when and where the national management is effective; (ii) where the current understanding is, and what remains uncertain, with respect to population connectivity and structure between Australia's and international waters; (iii) the cost and benefits of different monitoring strategies to reduce these uncertainties; and (iv) how all this can be brought together with the international management side of the problem given the clear feedback with the national approach.

Background

Australia has a number of fisheries that harvest stocks that are located both inside and outside of the

Australian EEZ and are harvested by other nations. Many of these stocks are managed at the international level in Regional Fisheries Management Organisations (RFMOs), but also at the national level within the Commonwealth Harvest Strategy framework. A key strategic issue in these cases is how to accommodate the interplay between national and international management processes and requirements, particularly when there is a specific national management framework (such as an agreed harvest strategy) but also advice given at the international level on appropriate harvesting levels that may or may not follow a specific (and different) harvest strategy, and possibly with different target and limit criteria for key sustainability indices than those employed at the national level.

This project was developed to address this key fisheries management challenge using the Eastern Tuna and Billfish Fishery (ETBF) as the example case study. The ETBF is a long-line fishery operating on the East Coast of Australia mainly targeting tuna (Albacore, Bigeye Tuna, Yellowfin Tuna) and billfish (Striped Marlin, Swordfish). Both the tuna and billfish populations are known to extend well beyond the Australian EEZ and are currently considered to form part of at least a wider Western Pacific Ocean population, though specifics on connectivity between various regions is still a major source of uncertainty. The tuna and billfish populations are currently assessed as an inter-connected single population across the wider western and central Pacific and at the international level are managed under the auspices of the Western and Central Pacific Fisheries Commission (WCPFC). The WCPFC considers the advice from the stock assessments and meets to recommend suitable Conservation Management Measures (CMMs) such as limits on spatial operations, capacity restrictions, or catch levels for member states.

A previous project used a detailed Management Strategy Evaluation (MSE) framework to explore the potential performance of empirical harvest strategies for the various target species caught by the

ETBF with the targets of the Commonwealth harvest strategy policy forming the major performance criteria. Arguably the most important factor influencing the performance of the various harvest strategies was the level of connectivity between the part of the population harvested by the ETBF and the wider western pacific population harvested by many different countries, the advice for which comes from the WCPFC. The level and form of connectivity between the localised ETBF fishery and the wider populations is an ongoing source of both discussion (at national and international levels) and uncertainty, and the recent introduction of the Coral Sea closed area has made this issue even more important as one will now have to consider both meta-population and localised connectivity. This makes the ETBF a very useful yet generic case study for the issue of the application of national harvest strategies to international fisheries. This is because the key issues of EEZ-to-international waters connectivity, relative impact of the various fisheries (national and international), and how to deal with potentially mismatched national and international management recommendations and sustainability criteria are arguably likely to be key factors in all such straddling stock examples.

At the national level, the project explored revisions to the currently used harvest strategies as applied to the ETBF species and the project scientists will be actively engaged in the TTRAG thereby ensuring that the project work is presented to this group, and feedback acted upon. Given that the process of management advice occurs through the TTRAG and TTMAC structures, the project will thereby directly assist managers in the ongoing management of the ETBF. The proposed workshop was envisaged as a way of ensuring the key stakeholders are informed on how the national and international processes interact, hopefully improving stakeholder understanding and buy-in at the national level. At the international level, given that the harvest strategies are to be evaluated using the MSE and precautionary approach, this ensures that any updates to the current harvest strategy – when presented at or viewed by the international management organisations – are adjudged to be scientifically sound. This will aid managers at the international level because the national management process is seen to be being carried out according to the definitions of best practice from the international viewpoint.

Aims/objectives

1. Update and recondition spatially disaggregated operating models, also including the Coral Sea closed area, for evaluation of existing and refined harvest strategies (HS) and evaluate the implications for the SW Pacific stock of alternative future harvesting scenarios, using MSE.

2. Undertake a review of the existing data and knowledge on stock structure for the primary target species and connectivity both within (Coral Sea closed area and outside) between the Australian and international RFMO managed fisheries and using the MSE software complete a cost benefit analysis of reducing that uncertainty.

3. With direct input from and consultation with both DAFF and AFMA, organise a stakeholder's workshop to discuss how all sectors, both commercial and recreational, fit into way the international (i.e. other management, exploitation and stock structure) dynamics are dealt with, outcomes from the stock structure review and cost-benefit analysis, and technical HS refinements.

Methodology

Project staff employed there long and detailed experience in constructing detailed simulation models for the stock, fishery and the management process to develop appropriate models for the various species targeted by the example case study fishery. The cost and benefit of various monitoring strategies and their potential to reduce the current level of uncertainty in population processes was addressed using state-of-the-art statistical design approaches. The government and stakeholder workshop was run by project staff with a long history of attending and chairing such meetings.

Results/key findings

For the billfish species (Striped Marlin, Swordfish), spatial connectivity, uncertainty in key processes like growth and maturity, and decisions being made in the full regional stock assessment still have a strong effect on the future likely performance of the current management approach. For the tropical tuna (Bigeye Tuna, Yellowfin Tuna), the yellowfin data are very noisy but suggest little impact on the stock by the fishery which would suggest that applying the harvest strategy to this species would in turn have little effect on the overall population. For bigeye the data are not informative enough to estimate local population size and so we cannot assess whether the harvest strategy would be applicable or not. Both the tropical tuna species were, in terms of the cost-benefit analysis, ideal candidates for using the recent CSIRO-developed close-kin abundance estimation method, using parent-offspring or half-sibling matches to estimate population size. For all species, recent genetic work has hinted at structure in the Pacific tuna and billfish populations below current understanding and the cost and precision of current genetics also makes this a clear and likely affordable priority for the region. The feedback between both national fisheries management and research projects and the assessment and wider international management of the South West Pacific stocks suggested that perhaps the key result of the project is that, even while having a national management approach, active engagement at the international level is still vital for the national approach to succeed.

Implications for relevant stakeholders

Revise and reassess research priorities for the key target stocks in the project. Continue with the regional engagement in the international management arena at all levels.

Recommendations

The harvest strategy is still likely to be effective at managing the billfish stocks at the national level, conditional on continued efforts to better define the target and limit reference points and understand local population connectivity and productivity. The harvest strategy is still unlikely to be applicable to the tuna species at present (at least for Yellowfin Tuna) but a wider South West Pacific stock structure research program is strongly recommended given recent results for yellowfin tuna.

Keywords

[Management Strategy Evaluation, tuna, billfish, harvest strategies, RFMOs]

Introduction

Background

Australia has a number of fisheries that harvest stocks that are located both inside and outside of the Australian EEZ and are harvested by other nations. Many of these stocks are managed at the international level in Regional Fisheries Management Organisations (RFMOs), but also at the national level within the Commonwealth Harvest Strategy framework. A key strategic issue in these cases is how to accommodate the interplay between national and international management processes and requirements, particularly when there is a specific national management framework (such as an agreed harvest strategy) but also advice given at the international level on appropriate harvesting levels that may or may not follow a specific (and different) harvest strategy, and possibly with different target and limit criteria for key sustainability indices than those employed at the national level.

This project was developed to address this key fisheries management challenge using the Eastern Tuna and Billfish Fishery (ETBF) as the example case study. The ETBF is a long-line fishery operating on the East Coast of Australia mainly targeting tuna (Albacore, Bigeye Tuna, Yellowfin Tuna) and billfish (Striped Marlin, Swordfish). Both the tuna and billfish populations are known to extend well beyond the Australian EEZ and are currently considered to form part of at least a wider Western Pacific Ocean population, though specifics on connectivity between various regions is still a major source of uncertainty. The tuna and billfish populations are currently assessed as an inter-connected single population across the wider western and central Pacific and at the international level are managed under the auspices of the Western and Central Pacific Fisheries Commission (WCPFC). The WCPFC considers the advice from the stock assessments and meets to recommend suitable Conservation Management Measures (CMMs) such as limits on spatial operations, capacity restrictions, or catch levels for member states.

A previous project (FRDC 2007/017) used a detailed Management Strategy Evaluation (MSE) framework to explore the potential performance of empirical harvest strategies for the various target species caught by the ETBF with the targets of the Commonwealth harvest strategy policy forming the major performance criteria. Arguably the most important factor influencing the performance of the various harvest strategies was the level of connectivity between the part of the population harvested by the ETBF and the wider western pacific population harvested by many different countries, the advice for which comes from the WCPFC. The level and form of connectivity between the localised ETBF fishery and the wider populations is an ongoing source of both discussion (at national and international levels) and uncertainty, and the recent introduction of the Coral Sea closed area has made this issue even more important as one will now have to consider both meta-population and localised connectivity. This makes the ETBF a very useful yet generic case study for the issue of the application of national harvest strategies to international fisheries. This is because the key issues of EEZ-to-international waters connectivity, relative impact of the various fisheries (national and international), and how to deal with potentially mismatched national and international management recommendations and sustainability criteria are arguably likely to be key factors in all such straddling stock examples.

At the national level, the project explored revisions to the currently used harvest strategies as applied to the ETBF species and the project scientists will be actively engaged in the TTRAG thereby ensuring that the project work is presented to this group, and feedback acted upon. Given that the process of management advice occurs through the TTRAG and TTMAC structures, the project will thereby directly assist managers in the ongoing management of the ETBF. The proposed workshop was envisaged as a way of ensuring the key stakeholders are informed on how the national and international processes interact, hopefully improving stakeholder understanding and buy-in at the national level. At the international level, given that the harvest strategies are to be evaluated using the MSE and precautionary approach, this ensures that any updates to the current harvest strategy – when presented at or viewed by the international management organisations – are adjudged to be scientifically sound. This will aid managers at the international level because the national management process is seen to be being carried out according to the definitions of best practice from the international viewpoint.

Need

Management of Australia's Tropical Tuna fisheries is complex because of the cross-jurisdictional nature of the stocks and governance through the Commonwealth Harvest Strategy Policy and Regional Fisheries Management Organisations (RFMOs). Previous work (FRDC project 2007/017) has indicated that uncertainty in the connectivity between the fish caught in the Australian fishery and the wider region may make the harvest strategy (HS) unsuitable for use for the tuna species, in particular Yellowfin Tuna. Currently the HS is not applied to the tuna species for precisely this this reason and further work is required to explore if and how this issue can be resolved. Recent levels of total allowable commercial catch (TACC) set by the current HS have the potential to increase risk to the regional stock biomass for Striped Marlin, and the upcoming closure of the Coral Sea to long-lining may combine with uncertain connectivity levels to increase localised risk to stock biomass for all species, so the HS urgently needs to be re-evaluated using updated Management Strategy Evaluation (MSE) models to ensure that the adopted HS meets the HS Policy guidelines and any Western and Central Pacific Fisheries Commission Conservation Management Measures (CMMs).

Clarification of different policy settings and processes for development of CMMs by the RFMOs, and their interaction with the Commonwealth Harvest Strategy Policy and implementation via the Australian Fisheries Management Authority, is required for improved stakeholder understanding of domestic HS management application. An evaluation of the costs and benefits of further stock structure and connectivity research, and a detailed examination of the existing data, was required. This provided transparent priorities and trade-offs for research focussed on the primary uncertainties underpinning management arrangements of these valuable stocks. Additionally it also provided confidence in the implementation of management advice based on MSE-tested HS.

Objectives

1. Update and recondition spatially disaggregated operating models, also including the Coral Sea closed area, for evaluation of existing and refined harvest strategies (HS) and evaluate the implications for the SW Pacific stock of alternative future harvesting scenarios, using MSE.

2. Undertake a review the existing data and knowledge on stock structure for the primary target species and connectivity both within (Coral Sea closed area and outside) between the Australian and international RFMO managed fisheries and using the MSE software complete a cost benefit analysis of reducing that uncertainty.

3. With direct input from and consultation with both DAFF and AFMA, organise a stakeholder's workshop to discuss how all sectors, both commercial and recreational, interact with current approaches to dealing with international management and stock structure, outcomes from the stock structure review and cost-benefit analysis, and technical HS refinements.

Method

For the MSE work project staff built upon previous OMs for these species. This involved updating both the input data and original structures of the previous OMs given changes in the WCPFC assessments that underpinned them. For the tropical tuna (Bigeye Tuna, Yellowfin Tuna) it involved the construction of standalone assessment models for the ETBF region, utilising the fishery data for those species. For Swordfish, the MSE specifications are detailed in Appendix 1. For Striped Marlin the MSE specifications are detailed in Appendix 2. For the tropical tuna (Bigeye Tuna, Yellowfin Tuna) "localised" OMs and the cost-benefit analyses, the specifics are detailed in Appendix 3. For the connectivity summary the details are given in Appendix 4.

Results, discussion and conclusions

Objective 1

For the billfish species MSE work the results are detailed in Appendix 1 (Swordfish) and Appendix 2 (Striped Marlin). For the tropical tuna (Bigeye Tuna, Yellowfin Tuna) the "localised" OM results are found in Appendix 3. In all cases, given the current uncertainty over the permanency of the Coral Sea closed area, this part of the objective was not explicitly explored for any species. Tagging and commercial catch size data suggest that juvenile fish spend more time in this Coral Sea before growing and moving into the main ETBF areas, but the two regions are still modelled as one in the WCPO assessments.

Currently, the ETBF Harvest Strategy (HS) is implemented for the billfish species only. Given recent updates in both the stock assessments used previously to condition the original Management Strategy Evaluation (MSE) models, and a slight change in the index used in the HS, these MSE models were rerun to assess whether the original expected performance of the HS had changed.

For Swordfish there are a number of general issues that came forth. In terms of the current stock assessment, the migratory and general population (and productivity) structure does not cover the whole range of likely spatial uncertainties. If the current assessment understanding is correct, and the recently increased level of international effort is maintained, the HS will act to strongly reduce catches in the ETBF, albeit ensuring the limit spawning stock biomass (SSB) level is not breached with significant probability. If international effort doubled there is little chance of the HS avoiding SSB limit violations, even with effective closure of the ETBF by the HS. There was also an apparent mismatch between the target Catch Per Unit Effort (CPUE) level in the HS and the target SSB depletion level (48% of the unfished level), both taken from a single year and assessment configuration.

For Striped Marlin key issues still outstanding from the previous MSE work were (a) scenarios where the HS did not function (i.e. no apparent feedback in the system); (b) scenarios where the HS did function, but the economic losses arising from catch reductions did not lead to any apparent conservation gain; and (c) levels of international effort, conditional on connectivity scenarios, at which the HS failed to function satisfactorily. The issue of HS functionality and adverse economic impact, and the potential to increase risk to the stock, was seen to be resolved with the limit level breached at levels well below the current stipulations of the Commonwealth Harvest Strategy Policy and CPUE being able to be maintained at the target level. With respect to international effort, for lower connectivity scenarios between ETBF and non-ETBF areas, the HS would actually still allow for increased catches at target level catch rates but not necessarily for higher connectivity scenarios.

Issues common to both MSEs were:

- Impact of recent inclusion of large amounts of "Eastern" Pacific catch and effort (that is those catches in the far north east of the Western and Central Pacific Fishery Commission area), and whether catches in that region are from the same stocks as the ETBF species
- Continued limited understanding of migration, stock structure and regional productivity
- Potential mismatch between the target CPUE and SSB depletion level used in the revised HS
- Better summary statistics for demonstrating whether the HS is "working" or not
- Perhaps some additional graphical work to better explain the mechanics of the HS

For the tropical tuna, “localised” operating models (OMs) were conditioned for Yellowfin Tuna and Bigeye Tuna using the catch composition and long-line CPUE data. For Yellowfin Tuna, while the data were very noisy and the resultant fits similarly noisy, there is no strong evidence that the current ETBF is having any notable impact on the stock. This reinforces the original decision not to implement the HS for this species given there will be no feedback in the system. For Bigeye Tuna the data are so noisy and, at times, contradictory that no stable estimates of local population abundance could be obtained. It was therefore not possible to judge whether the HS would be effective or not for bigeye tuna in the ETBF region.

Objective 2

Appendix 4 details the connectivity review as part of the project. For the billfish species (Striped Marlin, Swordfish), localised movement across the ETBF and eastern zones around New Zealand and the Pacific are observed, but with some fairly clear evidence of apparent residence in these areas. Currently a single spawning stock is assumed in both the WCPO assessments but genetic analyses of the wider Pacific region have shown structure below the levels assumed currently.

For the tropical tuna (Bigeye Tuna, Yellowfin Tuna) the vast majority of the tag recaptures released in the ETBF area are recaptured in the same general region and not moving into the equatorial zone to the North. Of the tens of thousands of tags released in the equatorial zone a miniscule fraction have been recaptured in the ETBF zone – even accounting for lower effort levels and attrition over time this is strongly suggestive of little movement between these zones. Satellite tags released on Yellowfin Tuna in the PNG region have also shown very localised movement within this region. The most recent genetic work on yellowfin tuna is perhaps the most revealing to date: for three sample locations (eastern Pacific, Tokolau in the South Pacific, the ETBF region) there was effectively complete genetic separation between all locations suggesting that, even for a limited number of sites within the WCPO, the current assessment configuration is both spatially and reproductively incorrect, and that there might well be several spawning sub-populations within the WCPO.

Appendix 3 details a summary of the cost-benefit analyses done looking at reducing the key current uncertainties: local population abundance, wider connectivity, and general stock structure in the WCPO. In terms of local abundance, when comparing traditional mark-recapture, genetic mark-recapture and CKMR the clear winner was CKMR as it obviates the high cost of tagging huge numbers of juvenile fish and releasing them, and the associated high attrition rates they incur before entering the exploited sub-adult and adult population. For stock structure, given recent advances in genetics and reductions in cost (as evidenced in the most recent yellowfin tuna analyses) these methods are by far the most cost effective way of reducing current stock structure uncertainty within the WCPO. With respect to connectivity, currently only archival tags are workable when it comes to understanding inter-annual connectivity patterns, and pop-up tags rarely if ever last long enough before deploying. Given current exploitation and expected return rates it would require a huge amount of archival tags (with associated large costs) to definitely reduce the current uncertainty in connectivity.

Objective 3

The ETBF HS workshop was held at CSIRO in Hobart on June the 2nd to the 4th 2015 and attended by various stakeholders and government department representatives. A report of that meeting can be found in Appendix 5.

General conclusions

For the HS as currently applied to the billfish (Striped Marlin, Swordfish) species in the ETBF, the key influences are still spatial: connectivity, regional productivity, reproductive structure, inclusion of eastern regions catch and effort. However, there is also the issue of the revised CPUE targets (and limits) as currently calibrated (via a single year and assessment realisation) to stock assessment SSB depletion estimates. For Yellowfin Tuna: new derived "local" abundance estimates show little apparent effect of the ETBF catches on the population, confirming previous work that showed little to no feedback in the HS system and therefore little point in applying it. For Bigeye Tuna the data are not informative enough and far too noisy to estimate local abundance so it is not feasible to assess whether the HS would illicit feedback if applied for this species. Cost-benefit analyses focussed on connectivity, stock structure and local abundance. The connectivity picture is still not entirely clear, but it is hard to gauge exactly how one couches the benefits associated with further electronic tagging work. For stock structure, given the initial Yellowfin Tuna results, genetic techniques are now at the point of making a WCPO-wide structure analysis for the major species affordable, albeit with some requirement for practical design in terms of sample locations. In terms of local abundance, when comparing conventional, genetic and close-kin mark-recapture methods, the clear winner in terms of cost-effectiveness and ability to provide robust estimates was CKMR, given it both obviates the need to tag juveniles and release them (and the associate high cost thereof) as it focusses on genotyping already-caught juveniles and permits estimation of the spawning population not the exploitable one. The summary of the gamefish data given at the workshop also emphasised the additional data not currently being used perhaps as much as it could be in relation to the billfish species (Striped Marlin, Swordfish) in the ETBF in particular.

The workshop discussed a lot of the practical challenges involved in establishing a HS framework within the WCPFC. The array of different priorities apparent for various members and/or fisheries suggested that perhaps one might have several different harvest control rules in place for the various fisheries/species under one overarching framework. The dependence of the MSE work in decisions made at the WCPFC assessment level, as well as the potential for more localised research like the recently published genetic structure work to strongly affect the assessment process, reinforces the idea that continued engagement at all levels of the WCPFC is essential for assessing the efficacy of the current HS as applied at the national level in the ETBF.

Implications

For the billfish (Striped Marlin, Swordfish) for which the HS is applied, the project did answer a key outstanding question from the previous MSE work – that the HS could actually increase the risk to the stock in future. The results from this project seemed to indicate that this was no longer the case and that the HS should act to as maintain the sustainability of both the fishery (in terms of achieving the economic targets) and the population (by not breaching the limit levels for the spawning stock). For Swordfish, the current levels of uncertainty in connectivity and local productivity made this picture less clear than for Striped Marlin, but the project did suggest ways in which to solve these issues in future. For the tropical tuna (Bigeye Tuna, Yellowfin Tuna), in conjunction with recent genetic connectivity work, the project demonstrated that local population abundance and productivity is poorly understood – particularly for Bigeye Tuna. The project demonstrated that a combination of genetic structure and novel close-kin mark-recapture could provide the basis for solving these issues. The final implication of the project and the workshop was the need to continue to engage at all levels with the WCPFC – there is a clear feedback between not just the national management via the HS but also national research projects and the WCPFC assessment and management process.

Recommendations

- Work both nationally and within the WCPFC to better understand the apparently more detailed stock structure within the target species of the WCPO.

- Continue to engage at all levels with the WCPFC to both improve stock assessment practices (as they impact the MSE work very strongly) and to assist in developing the HS framework being driven by Australia at the WCPFC

Extension and Adoption

- All results were presented at the TTRAG and project staff have attended various TTRAG meetings over the course of the project to assist in communicating the project work to the key national stakeholders.

- Continued engagement of project staff with SPC and WCPFC scientists and members to both assist in improving the wider assessment side of the WCPFC and in terms of a better understanding of stock structure and the MSE approach now being explored by not just WCPFC but all the tuna RFMOs at present.

Appendices

Appendix 1: Swordfish MSE Update

Swordfish MSE update

Introduction

It was beyond the scope of the current project to undertake a comprehensive re-evaluation of the Swordfish (*Xiphias gladius*) HS. This analysis was intended as a quick check to ensure that the adopted HS would still provide sensible management advice given the evolving understanding of the Swordfish population biology, and minor changes to the HS since the original testing described in Kolody et al. 2010. Specific objectives that we sought to address included:

- Update of the HS decision rule to reflect the new specification:
    - New target and limit reference points (Campbell 2013)
    - LOESS smoothing of the standardized CPUE before application of the HCR
    - Revised size-class definitions
- Brief evaluation of the updated SW Pacific Swordfish assessment (Davies et al. 2013) with respect to meeting the needs of the HS performance evaluation (in particular noting the changed perception of stock connectivity revealed by satellite tags).
- Specification of a reference set of operating models from the new assessment for simulation testing the HS.
- Evaluation of the management performance of the updated harvest control rule with the new operating models, noting the request from TTRAG (2013) "*…to determine at what proportion* [i.e. domestic vs: international fishing activity] *will Australia's catch of Swordfish render the Harvest Strategy ineffective in the management of total fishing mortality in Region 5* [the eastern Australian EEZ and adjacent international waters referred to as the western region below]."

Recommendations for the next update of the Swordfish HS are provided.

Revised Reference Points and Harvest Control Rule

The HCR was updated in consideration of the revised reference points described in Campbell (2013) and size category definitions shown in Table 1. The new Target Reference Point is a proxy for Maximum Economic Yield (MEY), still based on the ETBF standardized commercial longline CPUE:

TRP = $0.48\, CPUE_{prime,t=1997} \frac{SSB_{t=1997,f=0}}{SSB_{t=1997}}$ = 0.81,

where the CPUE time series (prime-sized fish) is scaled to have a mean of unity over the period 1997-2001 and $SSB_{f=0}$ is the spawning biomass estimated to have occurred in the absence of fishing in the reference case model reported in the Davies et al. (2013) stock assessment. $SSB_{f=0}$ is a dynamic B_0 concept that admits that biomass can change due to processes other than fishing (e.g. recruitment variability). The corresponding Limit Reference Point was defined in Campbell (2013) as:

LRP = $0.2\, CPUE_{prime,t=1997} \frac{SSB_{t=1997,f=0}}{SSB_{t=1997}}$ = 0.34.

Note that the reference points are described in terms of the CPUE of prime-sized fish, which is a conveniently observable quantity, which can easily be calculated in the context of operating models and observed by the industry stakeholders. However it is not the same as spawning biomass. In this document we present CPUE relative to the adopted CPUE reference points, and SSB relative to SSB_0 (where SSB_0 is defined as the mean spawning biomass estimated to have occurred in the absence of fishing over the period 1980-2008 in the stock assessment, calculated independently for each operating model, and with different spatial assumptions as described below).

The TTRAG also adopted a smoothing function for the CPUE time series used in the HCR. The Visual Basic code supporting the XL spreadsheet add-on (Peltier 2009) was converted to C++, and incorporated into the MSE code. This smoothing function was primarily intended for the highly variable tuna CPUE series, and has a trivial effect on the Swordfish HCR performance.

Table 1. The revised cut-points for size category definitions in the ETBF Harvest Strategy from Campbell (2014).

	YFT	BET	ALB	SWO	STM
	Cut-Off Processed Weights				
Small-Prime	21.4	20.5	11.0	20.0	53.9
Prime-Large	40.5	40.0	17.8	68.0	73.9
DWT-to_WWT ratio	0.85	0.84	1.00	0.726	0.726
	Cut-Off Whole Weights				
Small-Prime	25.2	24.4	11.0	27.5	74.2
Prime-Large	47.6	47.6	17.8	93.7	101.8
	Number of Measured Fish				
Small	112,356	56,387	14,086	65,339	10,107
Prime	223,816	112,373	28,484	129,371	20,102
Large	112,445	56,036	14,315	65,502	10,187
All Fish	448,617	224,796	56,885	260,212	40,396
	Percentage of Measured Fish				
Small	25.0%	25.1%	24.8%	25.1%	25.0%
Prime	49.9%	50.0%	50.1%	49.7%	49.8%
Large	25.1%	24.9%	25.2%	25.2%	25.2%

Swordfish Assessment Update

The most recent SW Pacific Swordfish assessment (Davies et al. 2013) provided the basis for the updated Swordfish operating models. Many key features of the assessment were similar to the previous assessment (Kolody et al. 2008), and remain broadly compatible with the needs of the ETBF operating model, but there are important differences (summarized in Table 2), and limitations in the context of the HS evaluation needs. Both approaches attempted to describe the uncertainty arising from multiple levels of different assumptions and their interactions. This is sometimes referred to as a structural uncertainty analysis, though “structural uncertainty” in this case is a misleading term, in the sense that most of the model configurations are associated with different fixed parameter values (which were not estimated in the stock assessment because the available data are not expected to be very informative). For each model, the Maximum Posterior Density estimates were reported and jointly used to represent the assessment uncertainty, while parameter estimation uncertainty associated with individual models was largely ignored.

Table 2. Key Swordfish assessment differences between 2008 and 2013.

Feature	Kolody et al. 2008	Davies et al. 2013
Spatial domain (fig. 1) Western area Eastern area	 140°E - 165°E 165°E - 175°W	 140°E - 165°E 165°E - 130°W
Final year of data	2007	2011
Number of fisheries	11	14
Stock-recruit steepness (h)	priors on h=0.4,0.65, 0.9	fixed h= 0.65, 0.8, 0.95
Recruit spatial partition	fixed 50% West, 50% East	estimated
Number of models in uncertainty grid	192	576 (561 plausible)
$SSB_{current}/SSB_{MSY}$ $F_{current}/F_{MSY}$ (lowest-highest)	1.20-3.46 0.18-0.67	1.15-3.53 0.33-1.77
Sensitivity to growth, maturity and natural mortality	Low	High

The 2013 assessment was based on the full WCPFC management area south of the equator, including a western sub-population in which the ETBF fishery is the dominant fishery in recent years, and an eastern sub-population that encompasses the remainder. This is a substantial change from 2008, in which the Western and Eastern areas were roughly the same size, and it seemed reasonable to assume that populations were of a similar magnitude. The 2013 assessment included a revision to the spatial structure as informed by a compilation of recent electronic tagging results from widespread, multinational releases (Evans et al. 2012). While tag sample sizes remain small (and periods at liberty relatively short), the tags illustrated a migration corridor between New Zealand and tropical waters as far east as French Polynesia. This connectivity clearly indicates that the eastern population defined in the 2008 assessment was inappropriate. Furthermore, the CPUE standardization undertaken in 2013 (including the addition of Spanish data) resulted in eastern abundance trends that are plausibly consistent with the western abundance trends (and stationary productivity assumptions), unlike 2008.

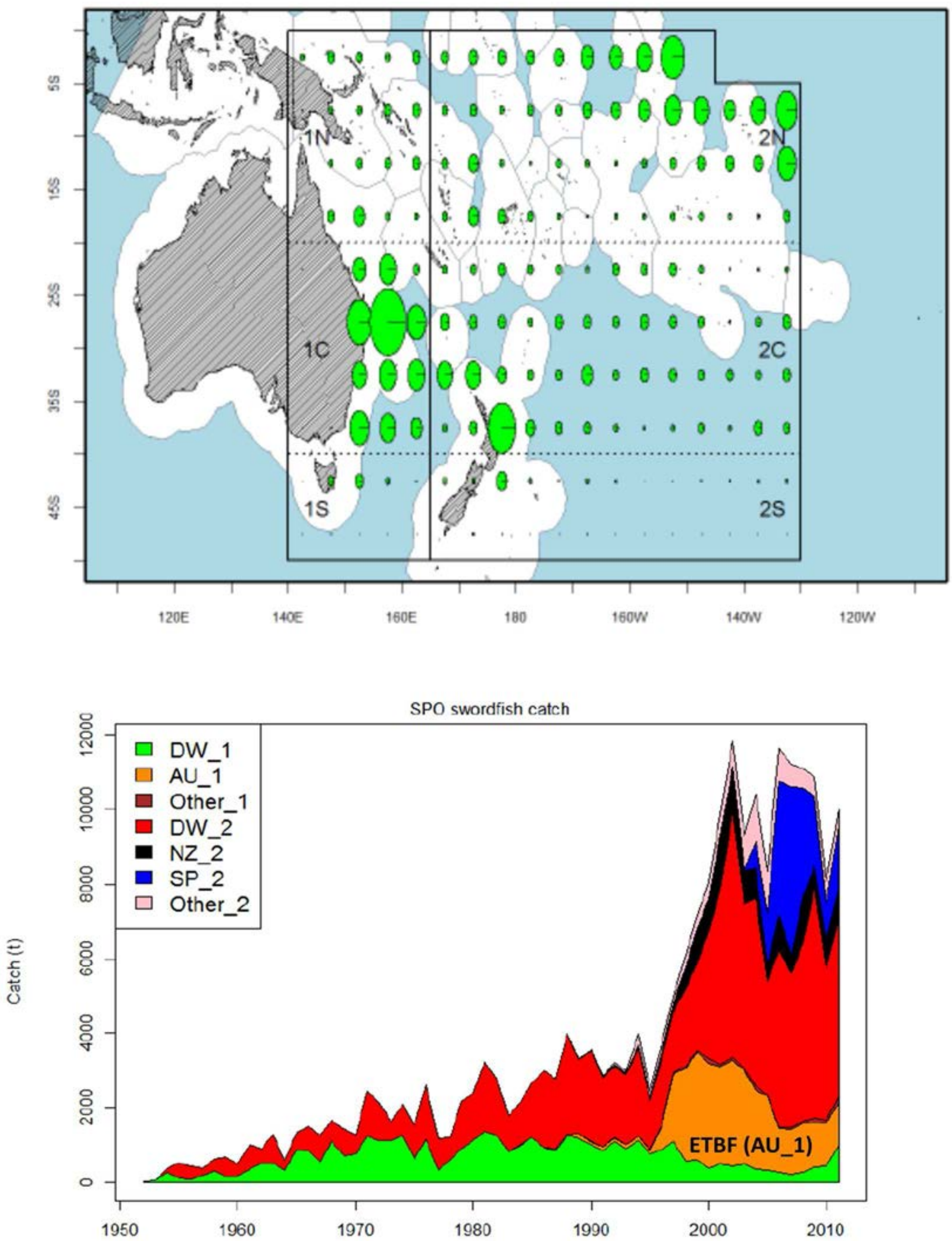


Figure 1. Top panel: Stock assessment domain showing the West-East population regions, and North, Central, South (N,C,S) fishery definitions. Bottom panel: catch history of the fleets. From Davies et al. (2103).

The assessment considered a range of movement rate assumptions linking the two areas, including the preferred estimate of 0.11 per quarter (corresponding to the best diffusion rate estimate from Evans et al. 2012, converted to an approximate quarterly bulk transfer co-efficient using the relationship described in Kolody and Davies 2008), with alternative values of 0, 0.05 and 0.25 also fit. This represents a good range of movement options in the context of diffusive mixing, however, as Evans et al. (2012) note, there is a good chance that diffusive mixing is simply the wrong model for describing the population connectivity. Despite the increased number of tag movement observations, the possibility of a reasonably distinct, self-recruiting western population still cannot be ruled out. Furthermore, large catches in the eastern equatorial region might be associated with separate populations from the north or east Pacific, with minimal links to the main population. No tag position estimates have been reported from that high catch region, but the closest observations were from releases in the north-east Pacific (Abecassis 2012), one of which crossed into the southern hemisphere. The zero migration option goes some way toward addressing the possibility of a distinct Australian population, however, these assessment models assumed a shared spawning population, and reported spatially aggregated reference points.

The 2008 and 2013 assessments both assumed a single spawning and recruitment process, however, there were important differences. Both assessments explored 3 levels of Beverton-Holt steepness. In 2008 this was attempted by using tightly constrained priors on the steepness values (h = 0.4, 0.65, 0.9), however in retrospect, it was evident that the priors were not adequately constraining, such that the point estimates for the lower values were higher than the mode of the priors (and variable among models). This was unintended, but it is generally expected that the lower steepness values were unrealistic for Swordfish anyway. The 2013 assessment appropriately used higher, fixed values (h = 0.65, 0.8, 0.95).

There are concerns about the recruitment variability in the assessment that have implications for the operating model. Davies et al. (2013) expressed the intent to not force the model to adhere too closely to an imposed stock-recruitment relationship, with the comment: "*A weak penalty was applied to deviation from the SRR so that it would have negligible effect on the annual recruitment*." However, in the end, recruitment deviations were actually tightly constrained with $\sigma_R = 0.2$ ($\sigma_R = 0.6$ is a common assumption in tuna assessments; $\sigma_R = 0.4$ was used in the 2008 Swordfish assessment). This was required because *" ...model runs using a weaker prior revealed a very strong temporal trend in the deviations in recruitment, essentially following the long-term trends in longline CPUE. The penalty was used to mediate this effect in the model.*" It was also noted that there was a very small (unspecified) constraint on how the recruitment was divided between the two regions. The authors judged this to be a satisfactory compromise, e.g. *"Region-specific recruitments appear to be unique and are consistent with the CPUE and size observations in each region.*"

However, the 2013 assessment did not note (and hence the analysts may not have realized), that there was a very strong negative recruitment correlation between regions (Pearson coefficient -0.83 for the reference case, -0.55 for the equivalent sensitivity run with no movement between the western and eastern recruitment time series), and strong auto-correlation within regions (e.g. Figure 2). The 2013 assessment tended to estimate a period of poor recruitment during the early 2000s in the western region, corresponding to the period of highest catches and declining CPUE. The eastern region was estimated to have anomalously high recruitment during this period. This would be an interesting biological phenomenon, but given the limited data which drive the estimates, it is likely that the model is taking advantage of the recruitment spatial freedom to improve the fit to the CPUE trends in a manner that Davies et al. sought to avoid at the aggregate level. We expect that there is more uncertainty than the assessment suggests with respect to the extent that the CPUE decline during the early 2000s is a result of CPUE noise, recruitment patterns, exploitation and migration.

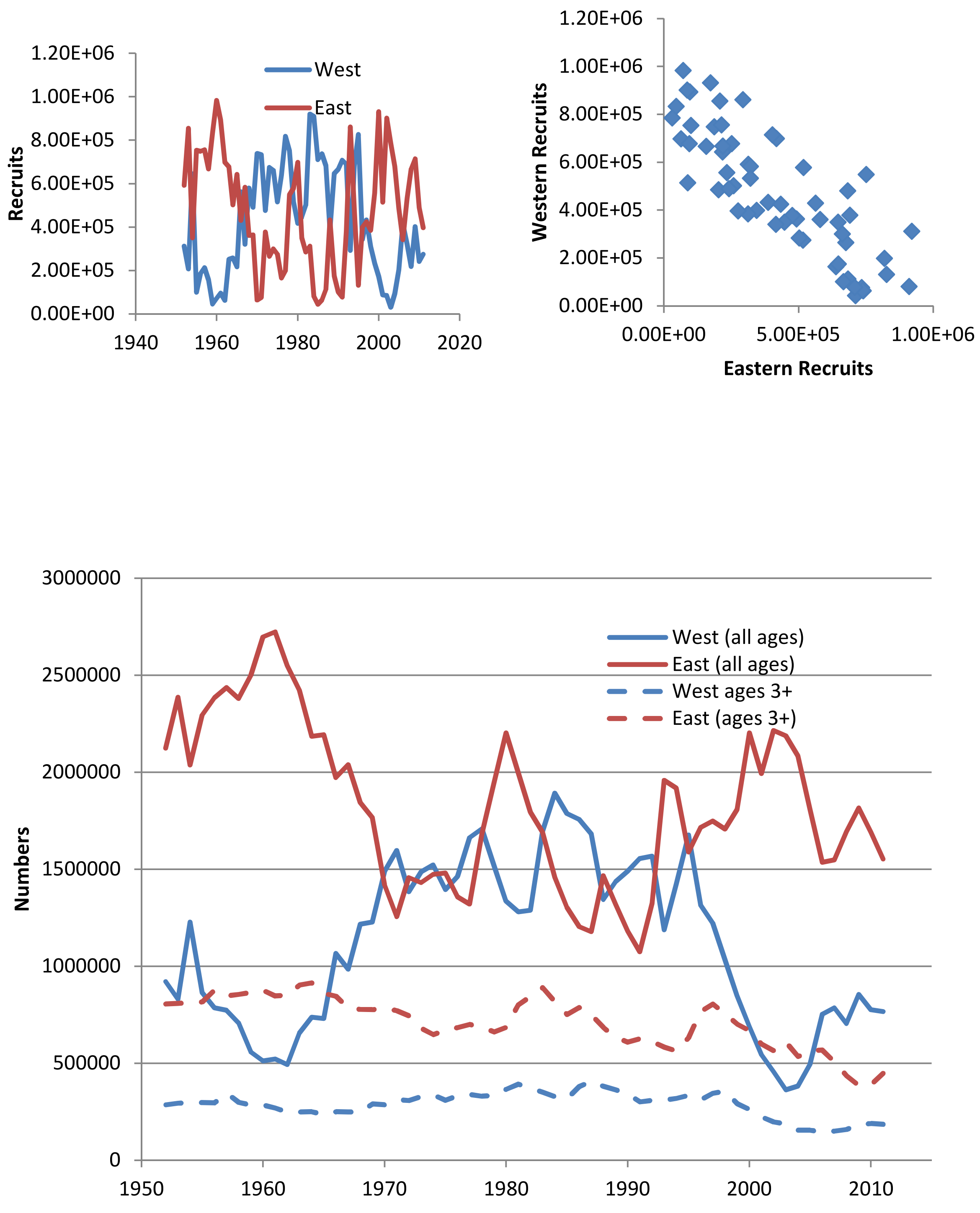


Figure 2. Spatial correlation in recruitment and population numbers in the reference case Swordfish assessment model from Davies et al. (2013).

The assessment models provide reasonable agreement between predictions and observations, including:

- Total catch data – the assessments assume that catch is known essentially without error (though minor catch deviations are estimated, which improve the apparent fit to the CPUE). There is no reason to think these data are particularly problematic, though some discarding of small Swordfish is likely.
- The assessment provides an excellent fit to the core CPUE series (including the Australian and New Zealand fleets, Figure 3). These data are probably over-fit given the difficulties in standardizing commercial longline catch rates.
- The assessment provides a reasonable fit to the general characteristics of the size composition data for some fleets, including the Australian fleet (Figure 4). The fit to the size trend is not very good for some other fleets, which probably reflects a combination of: i) size sampling biases, ii) non-stationary selectivity, due to changes in the spatial distribution and targeting over time, including unknown gear configuration effects, and possibly iii) inability to describe spatial and temporal variability in growth (including sex dimorphism).
- For completeness, tag data were included in the 2013 assessment, but there are so few observations, that their influence is negligible.

Both assessments estimated a high degree of stock status uncertainty. The 2013 assessment estimates a high probability that recent spawning biomass is likely to be above levels that can sustain MSY (Figure 5), but a reasonable probability that over-fishing may be occurring (such that if effort levels remained constant, the spawning biomass would eventually be expected to decline below a level that could sustain MSY). The over-fishing probability was most clearly associated with the (combined) growth, maturity and mortality assumptions (moderated through the interactions with other assumptions). Two sets of assumptions (derived from CSIRO and NMFS age/maturity studies) were used in both assessments. In the 2008 assessment, results were not very sensitive to these assumptions. In 2013, the pessimistic status was associated with the relatively slow growth, late maturity and low natural mortality options. The WCPFC and AFMA have funded a project to reduce the growth and maturity uncertainties, which includes age estimates derived from otoliths rather than fin spines, revisiting the maturity estimates and comparison of methods between the two labs (Farley et al. 2014). The results should be available for the next Swordfish assessment.

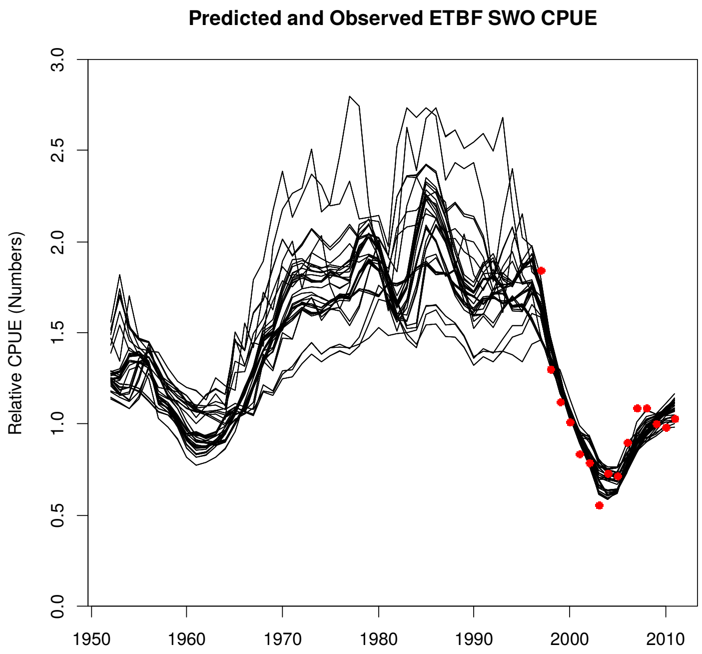


Figure 3. Exploitable ETBF SWO population in numbers (left panel), and predicted (exploitable numbers X selectivity) and observed CPUE (scaled relative to the 1997-2011 mean) (right panel) from a range of assessment models adopted for the reference case operating model. Red points indicate observed, standardized ETBF CPUE.

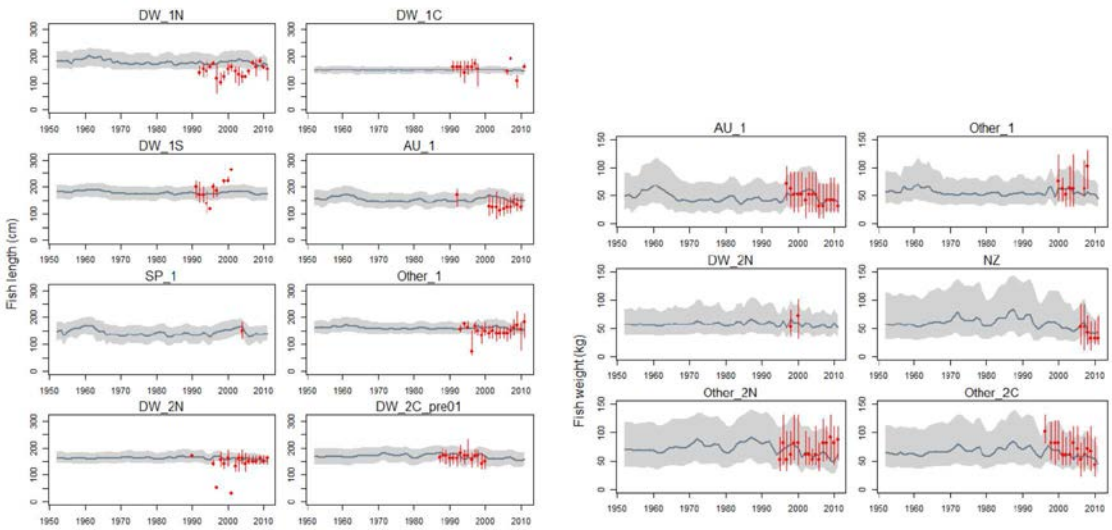


Figure 4. Predicted (red points) and observed (grey lines) Swordfish catch length (left panel) and mass (right panel) from the reference case assessment in Davies et al (2013). AU_1 is the ETBF.

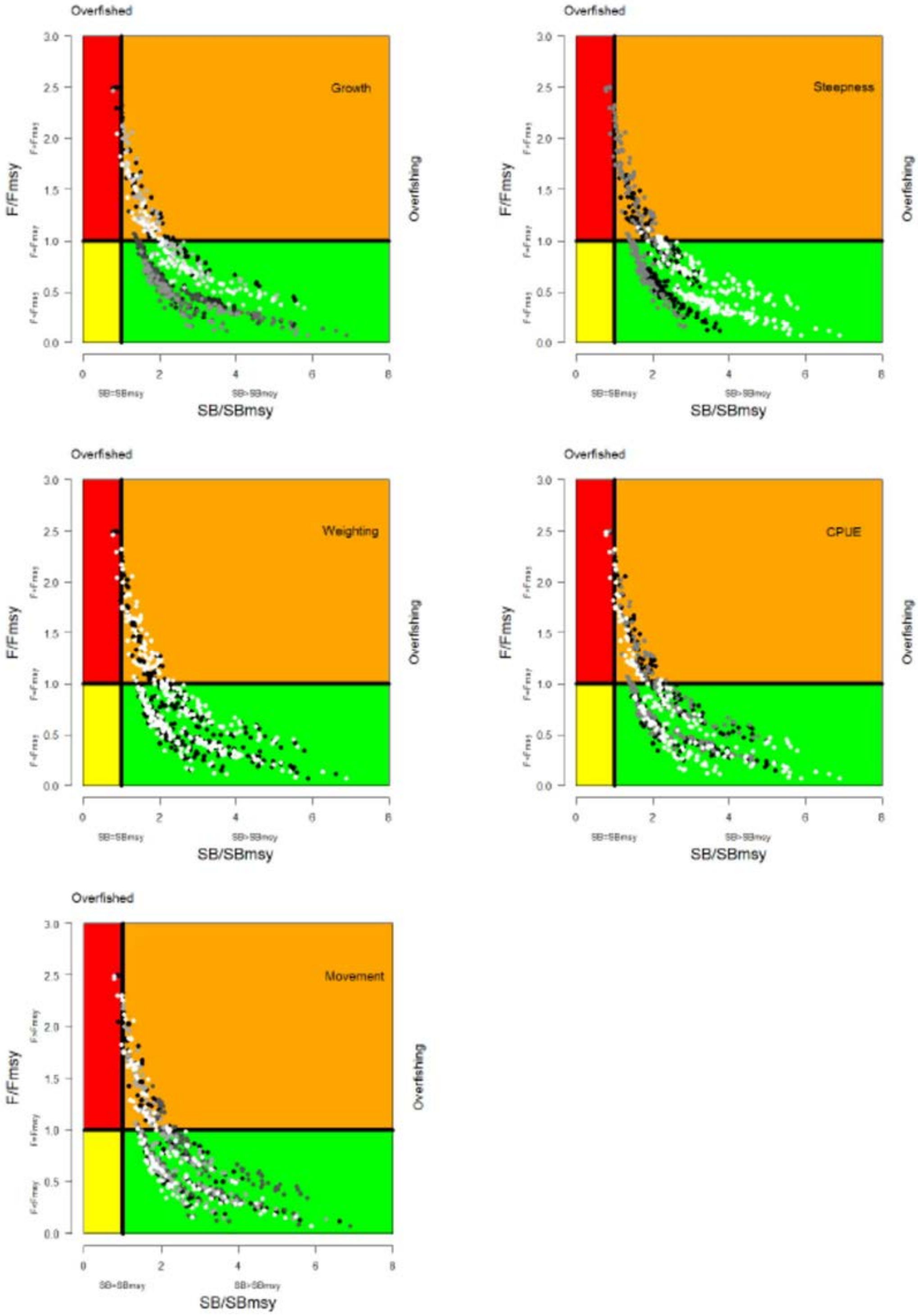


Figure 5. Stock status estimates from the grid of 561 assessment model point estimates presented in Davies et al. (2013), partitioned by assessment model assumptions. Each panel shows the same points, but the grey scale indicates the level of each indicated assumption (e.g. the 3 levels of steepness in the top right panel are indicated by white = 0.95, grey = 0.65 and black = 0.8).

Overall, the 2013 Swordfish stock assessment admits a broad range of alternative plausible assumptions (more thorough than most assessments) and forms a reasonable starting point for testing the HCR. However, it would have been preferable to couple the assessment process to the HS evaluation. Specific concerns that we have about the assessment include:

- Spatial uncertainties:
    - No explicit consideration of a potentially independent stock in the Australian region
    - No explicit consideration that the eastern equatorial region might represent an extension of populations from the north and east Pacific.
- Stock-Recruitment uncertainties:
    - Low variance on the aggregate stock recruit relationship
    - Strong negative correlation in recruitment between areas
    - Strong autocorrelation in recruitment within areas
- Potential over-fitting to the CPUE series.

Swordfish Reference Set Operating Models

The harvest strategy update used the same software as Kolody et al. (2010), with a few minor modifications. The OM assumptions are listed in Table 2, with justifications detailed below. The OMs consist of a mix of explicit conditioning (results adopted from the assessment models) and ad hoc modifications to represent key uncertainties that we do not consider to be adequately represented in the assessment model configurations.

From Figure 5 (and other summary plots shown in Davies et al. 2013), it is evident that the 561 assessment models span a large range of stock status uncertainty, which we want to represent within the reference set operating model. The stock status is most clearly sensitive to the growth/maturity/M, and steepness assumptions (i.e. the different shades of grey associated with each assumption option have the least degree of overlap). The stock status appears to be less sensitive to the data weighting and CPUE options (i.e. selecting either CPUE option results in a suite of models that spans almost the full range of stock status uncertainty). The sensitivity to movement is intermediate between these two groups, but it is a major structural uncertainty that needs special attention in the context of the fishery performance. Accordingly, we chose to represent 3 dimensions of the assessment uncertainty grid in the OM (growth/maturity/M, steepness and movement). Data weighting and CPUE options were fixed at the reference case assessment value (though we recognize that there could be relevant interactions that are lost because of this simplification). This reduces the number of assessment results to 96 (8 growth X 3 steepness X 4 movement) models. The movement and recruitment assumptions in the assessment were not considered to provide an adequate representation of the uncertainties of the system, so some additional ad hoc adjustments were made.

Of the 96 assessment models selected to be operating models, 72 involved non-zero migration linking the western and eastern regions. The population estimates, and migration assumptions from both areas of the assessment were adopted for the operating models in these cases, labeled SWC (South-West-Central). In contrast, for the 24 assessment models where migration was set to zero, an ad hoc adaptation was made to define an operating model population for the western area only (SW). For technical reasons, the SW OM was still parameterized as two regions, but with the population and stock-recruitment dynamics adopted from only the western region of the assessment, and a high migration rate linking the two (effectively a single population on the relevant time-scales).

At the spatially-aggregated level, the recruitment assumptions were the same as those in 2010, i.e.:

$$R_t = \frac{\alpha SSB_t}{\beta + SSB_t}\exp(\tau_t - \tfrac{1}{2}\sigma^2),$$
$$\tau_t = \rho\ \tau_{t-1} + \varpi_t\sqrt{1-\rho^2}$$
$$\varpi \sim \text{IID } Normal(\mu = 0, \sigma)$$

where:

R = total 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,

σ_R = the standard deviation for the recruitment deviates,

and subscript t corresponds to an annual recruitment frequency. Also as in 2010, $\sigma_R = 0.6$ and $\rho = 0.7$, were adopted, which introduces considerably greater recruitment variability than was assumed in the assessment, and a broader challenge for the HS. An additional stochastic process was introduced to partition R_t into western and eastern regions ($R_t = R_{t,west} + R_{t,east}$) in the two region SWC scenarios:

$$R_{t,west} = R_t \mu \exp(\zeta_t)/(\mu_{r=1}\exp(\zeta_t) + (1-\mu)),$$
$$R_{t,east} = R_t - R_{t,west},$$

where:

μ = proportion of total (model-specific) recruitment over the period 1980-2004 estimated to have been distributed to the western region, and

ζ = an auto-correlated random normal deviate (equivalent to τ above).

This ad hoc stochastic process yields quantitatively similar results to the estimates from the reference case 2013 assessment in terms of the spatial and temporal correlations, however, we emphasize that this correlation structure emerged from the stock assessment parameter estimation. It was not imposed through a priori statistical assumptions and may reflect some unrelated systematic problem within the assessment model (e.g. systematic errors in CPUE, selectivity or size composition samples). The values adopted to govern these processes for the two area models were $\sigma_\zeta = 1.4$ and $\rho_\zeta = 0.7$.

CPUE is the most important information in the harvest strategy and assessment (aside from the total catch in mass). The assessment clearly has excellent agreement with the ETBF CPUE observations (Figure 3). All of the models have a Root Mean Squared Error (indicator of agreement between predictions and observations) between 0.10 – 0.17, with most models near the lower end of the range. The fit suggests that the steep CPUE decline from 1997-2001 is consistent with the population dynamics, with very little observation error. This level of agreement is better than we could reasonably expect, so (as in 2010) we imposed a higher CV (σ_{CPUE} = 0.20), with a substantial auto-correlation (ρ_{CPUE} = 0.70), to ensure that the CPUE series was not unrealistically informative.

Selectivity for the ETBF and international fleet was adopted from the assessment model-specific estimates. In the OM, all international fleets were aggregated, and assumed to have the selectivity of the Spanish fleet in the central eastern region. This fleet was selected because it has large recent catches, and some of the best size composition data with which to estimate selectivity. It can be argued that it would be preferable to maintain the disaggregated fleet structure, but some of the selectivity estimates in the assessment are dubious, and selectivity uncertainty has often been found to be not very important in an MSE context (e.g. Butterworth et al. 2014).

Migration is parameterized differently in the assessments and operating models, but the two processes are essentially identical, at least for a two area model with reasonably low migration. The assessments have asymmetrical migration rates between regions, which estimate about 25% of the population in the western region at equilibrium (it is not clear how these quantities were derived in the assessment, but it seems like a reasonable first approximation given the relative size of the two regions). The corresponding parameters for the OM (which match the movement analysis section of the MFCL assessment .rep files) are listed in Table 3.

Table 3. OM migration parameters corresponding to the assessment model scenarios.

		OM Parameter		
Assessment scenario	OM scenario	West equilibrium Proportion	East equilibrium Proportion	Redistribution rate
M1	SW-M00*	0.5	0.5	0.5
M2	SWC-M05	0.25	0.75	0.21
M0 (ref)	SWC-M11	0.25	0.75	0.32
M3	SWC-M25	0.285	0.715	0.41

* The OM consists of only the western sub-population from the assessment for scenario M00 (but is implemented as two highly mixed areas for technical reasons)

Other differences between the 2010 and 2015 OMs included:

- Only one level of RBCC implementation error (σ_{RBCC} = 0.05) was included in 2015 (in the original iteration, implementation error was potentially more important because the management was originally expected to operate on the basis of effort regulation).
- Only the more challenging level of size composition sampling error was adopted in 2015. This was introduced to ensure that the harvest strategy does not have unrealistically informative information about the population age structure. This error is intended to reflect

the net effect of several processes: biased size composition sampling, non-stationary fishery selectivity, and potentially growth/sex composition variability, all with a temporally correlated structure.

Key features of the 96 operating models are illustrated in Figure 6 - Figure 9, illustrating the historical and projected dynamics if all fisheries were to stop in 2011 (HS CC_swo_00). Results are partitioned by the 4 spatial/migration rate assumptions, and aggregated across the other 24 sets of model assumptions (each with 100 stochastic replicates, such that each panel summarizes 2400 simulations). From these figures, we observe that:

- The difference between SW and SWC spatial scenarios are somewhat different, while the differences within the SWC scenarios (migration rates 0.05, 0.11, 0.25) are much smaller.
- Within the 24 SW scenario, median SSB rebuilds to levels observed around 2001 (and 1970), while projected upper and lower 10^{th} percentiles in 2040 span a factor of two, roughly encompassing the estimated historical SSB range prior to the fishery expansion in the mid 1990s (Figure 6). Median projected SSB appears to still be increasing in 2040, though the upper and lower 10^{th} percentiles appear to be stable, with only the most optimistic 10^{th} percentile reaching SSB_0. Within the 72 SWC scenarios, the median projected SSB is closer to the SSB_0 estimates (Figure 6) than the SW scenarios, but also appears to still be increasing in 2040.
- The SW scenarios appear to go through substantial historical recruitment regime shifts (Figure 7) which are not observed in the SWC scenarios (i.e. presumably because the negative spatial correlation averages out at the aggregate level, resulting in relatively low aggregate recruitment variability)
- The SWC scenarios predict that the median (and lower 10^{th} percentiles) of ETBF total biomass will increase to levels that are somewhat lower than pre-1990 levels, while the eastern total biomass is generally predicted to increase to levels that are higher than recent estimates (not seen since the 1960s) (Figure 8). To some extent, this reflects the recruitment spatial distribution returning to the 1980-2008 mean. (This spatial comparison is not meaningful for the SW scenario, because the abundance by region is essentially identical by design).
- The SW and SWC scenarios are pessimistic in terms of the median $CPUE_{prime}$ predictions. Despite the fact that median spawning and total biomass are predicted to increase until 2040 in the absence of fishing, the SW scenarios predict that $CPUE_{prime}$ will stabilize near the CPUE target from 2015-2040, while the SWC medians stabilize somewhat below the target. This suggests that there may be an unacceptable disconnect between $CPUE_{prime}$ and SSB (i.e. because $CPUE_{prime}$ explicitly excludes the larger 25% of catch, which would presumably all be mature). As such, it is not clear that $CPUE_{prime}$ is the best choice for either the decision rule or the reference points.

The results from 2010 were also pessimistic in predicting that, in the absence of fishing, $CPUE_{prime}$ would stabilize near the CPUE target. However, the results are not directly comparable because the targets and size-class definitions have changed.

At this time, we are not confident that the suite of operating models reflects the true uncertainty in the Swordfish fishery (particularly spatial and recruitment dynamics), and we are reluctant to describe the projections as probabilistic statements. However, the scenarios that are represented do span a broad range of dynamics and provide guidance about situations in which the HS can be expected to fall short of performance expectations. We focus on a qualitative description of the performance in relation to i) the SW option and SWC option (with a mixing rate of 0.11), and ii) a range of international effort scenarios. The international effort scenarios were defined to bracket a plausible range of conceivable outcomes, including unlikely increases and decreases at the extremes. The four scenarios assume that international effort will change linearly from 2010 levels to 0.5, 1.0, 2.0 and 4.0 X current during the first 5 years of the HS application, then remain constant. Figure 10 and Figure 11 show the basic performance characteristics of the adopted harvest strategy (HS_SWO_100) for the SW-M00 and SWC-M11 spatial scenarios and 4 levels of international effort, in the absence of stochastic variability (recruitment, CPUE observation error, temporally-variable bias in size composition sampling and TAC implementation error). These figures demonstrate the best performance that could be expected for the harvest strategy given perfect information, and the variability in outcomes that is due to deterministic differences among assessment models (initial population structure, fishery selectivity and life history biology). Key points from these results:

- The adopted HS recommends almost continuous quota cuts out to 2040 for virtually all scenarios, with larger cuts for the SWC scenarios than SW. This is what one would expect if the $CPUE_{prime}$ target is set near or below the level that can be achieved in the absence of fishing. Hence any optimistic RBCC outcomes that arise in the stochastic simulations that follow are due to chance (e.g. a series of above average recruitment or anomalously high CPUE observation error).
- For the SW-M00 scenarios (Figure 10), the HS stabilized median $CPUE_{prime}$ and SSB above the target reference points, regardless of the international effort scenario.
- For the SWC-M11 scenarios (Figure 11), the HS maintained SSB above the SSB limit reference point when international effort remains at current levels, while $CPUE_{prime}$ generally remained below the CPUE target.

Table 4. 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). The harvest strategy was evaluated with 46000 simulated projections (i.e. product of 96 assessment model scenarios, 100 stochastic replicates, 4 spatial-migration rate options, and 4 international effort options).

Source of Uncertainty	Option 1	Option 2	Option 3	Option 4	Number of OM grid elements
Model specifications (96) derived from the Davies et al. (2013) assessment model grid:					
M	These biological parameters were adopted from individual MULTIFAN-CL output files from the WCPFC stock assessment and do not represent a balanced set of independent combinations.				8
Growth					
Maturity					
Steepness	0.65	0.8	0.95		3
Movement (redistribution) per quarter	0 (SW-M00)	0.05 (SWC-M05)	0.11 (SWC-M11)	0.25 (SWC-M25)	4
Selectivity	independent estimates from each assessment model international fleet selectivity was assumed to be equal to the Spanish fleet in the eastern region in all cases				1
N(2011)	independent estimates from each assessment model				1
Specifications adopted on an ad hoc basis, that are not necessarily consistent with the assessment model assumptions:					
Stochastic replicates	100 (errors conserved among models)				100
Recruitment aggregate variation and autocorrelation	W models $\sigma_R = 0.6$; $\rho_R = 0.7$ WE models $\sigma_R = 0.2$;$\rho_R = 0.24$				1
Recruitment spatial variation and autocorrelation	W models $\sigma_\zeta = \rho_\zeta =$ NA WE models $\sigma_\zeta = 1.4$, $\rho_\zeta = 0.7$				1
CPUE variation/ autocorrelation (No Effort creep)	$\sigma_{CPUE} = 0.2$ $\rho_{CPUE} = 0.7$				1
International fishing effort	Linear 5 year decline to remain stable at 0.5 X current	Constant at current levels	Linear 5 year increase to remain stable at 2X current	Linear 5 year increase to remain stable at 4X current	4
CV on N(2011,a=0)	0.5				1
CV on N(2011,a=1)	0.25				1
Size sample / Distortion / autocorrelation	0.7 / 0.2 / 0.7				1
RBC implementation error sd(log))	0.05				1
Data Time Lag	6 months				

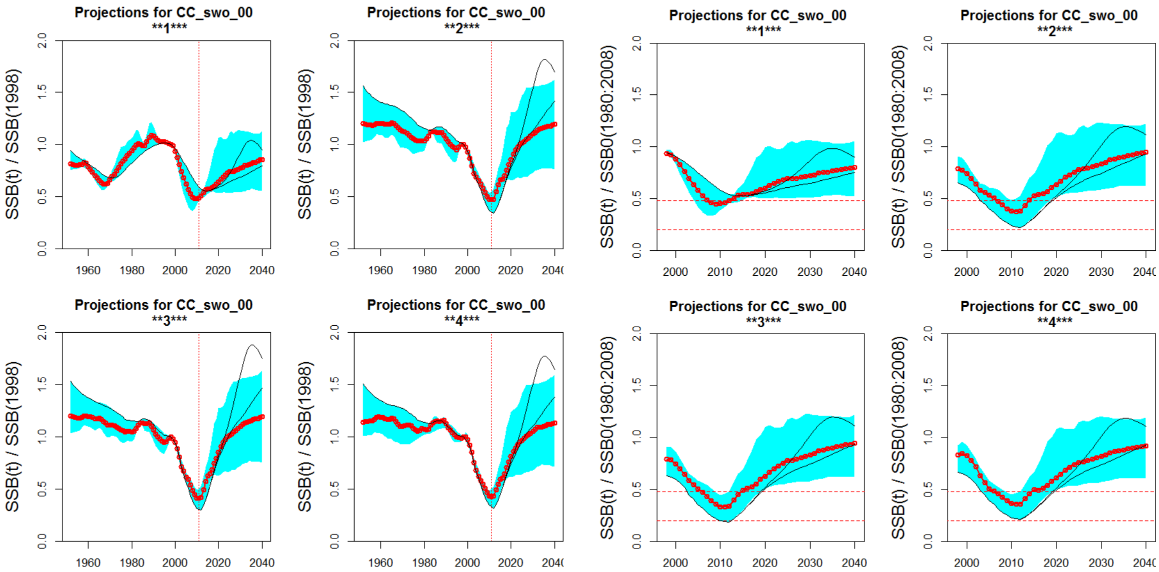


Figure 6. Relative spawning biomass comparison for the 96 SWO operating models, assuming that harvesting stopped for all fisheries in 2011. Results are partitioned by spatial-migration rate assumptions, each consisting of 24 models with 100 stochastic projections. 1= SW-M00, 2=SWC-M05, 3=SWC-M11, 4=SWC-M25. Red circles indicate the median, shaded blue region bounds the upper and lower 80th percentiles, black lines indicate individual realizations, and red broken lines indicate target and limit reference points.

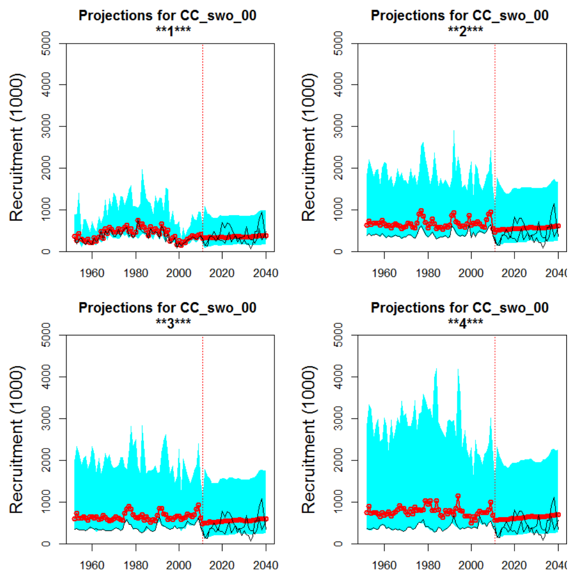


Figure 7. Recruitment time series for the 96 SWO operating models, assuming that harvesting stopped for all fisheries in 2011. Results are partitioned by spatial-migration rate assumptions, each consisting of 24 models with 100 stochastic projections. 1= SW-M00, 2=SWC-M05, 3=SWC-M11, 4=SWC-M25.

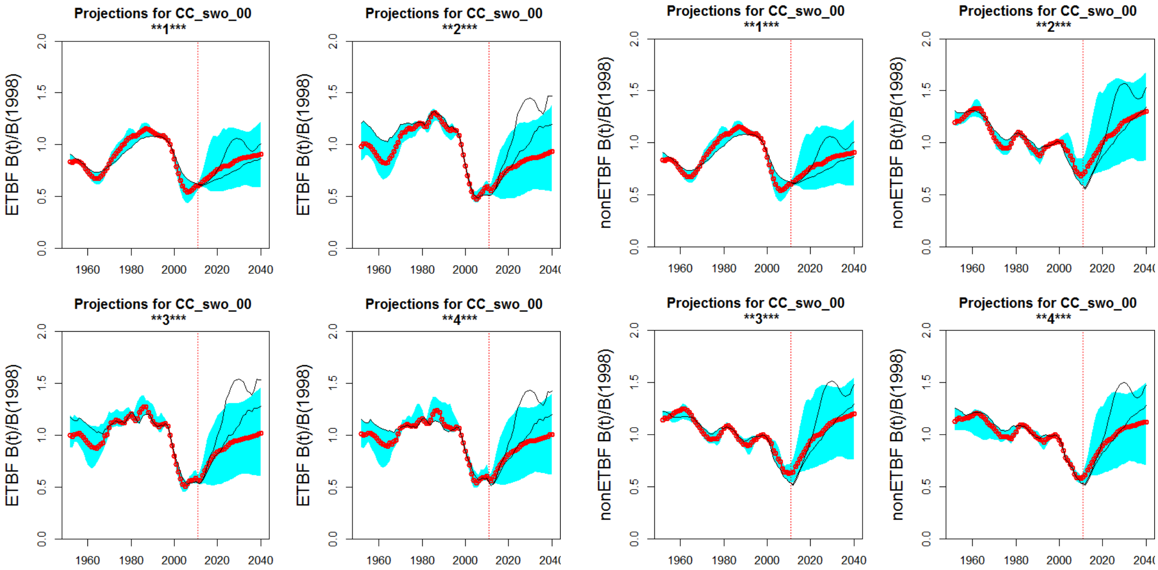


Figure 8. SWO biomass (all ages, relative to 1998) in the western region (left 4 panels) and eastern region (right 4 panels) for the 96 SWO operating models, assuming that harvesting stopped for all fisheries in 2011. Results are partitioned by spatial-migration rate assumptions, each consisting of 24 models with 100 stochastic projections. 1= SW-M00, 2=SWC-M05, 3=SWC-M11, 4=SWC-M25.

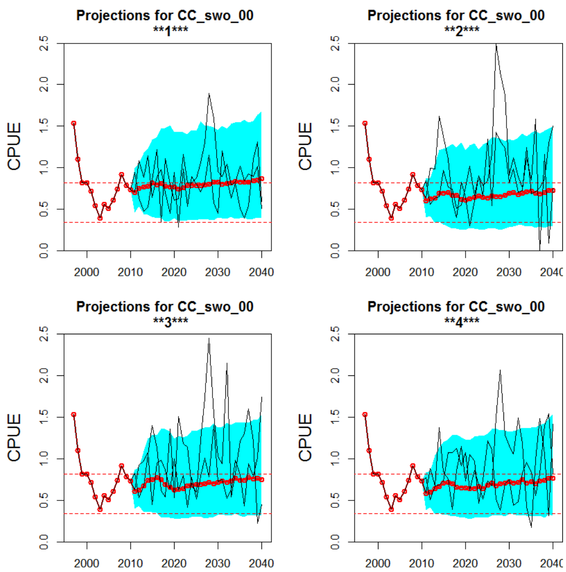


Figure 9. ETBF CPUE$_{prime}$ for the 96 SWO operating models, assuming that harvesting stopped for all fisheries in 2011. Results are partitioned by spatial-migration rate assumptions, each consisting of 24 models with 100 stochastic projections. 1= SW-M00, 2=SWC-M05, 3=SWC-M11, 4=SWC-M25.

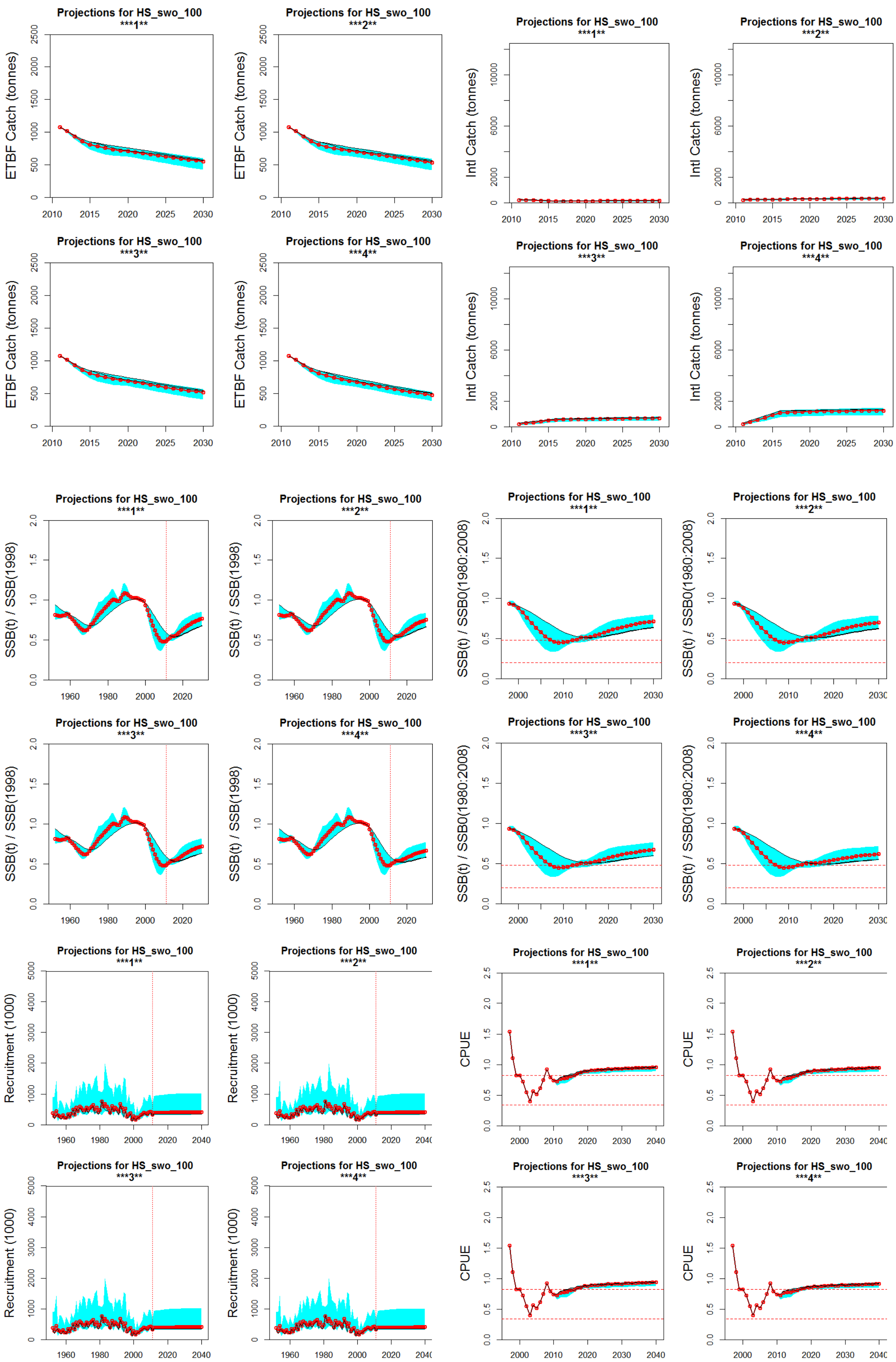


Figure 10. Adopted harvest strategy projections for the suite of 24 SWO operating models (SW-M00) that assume the western population is isolated, with all stochastic process and observation error removed. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

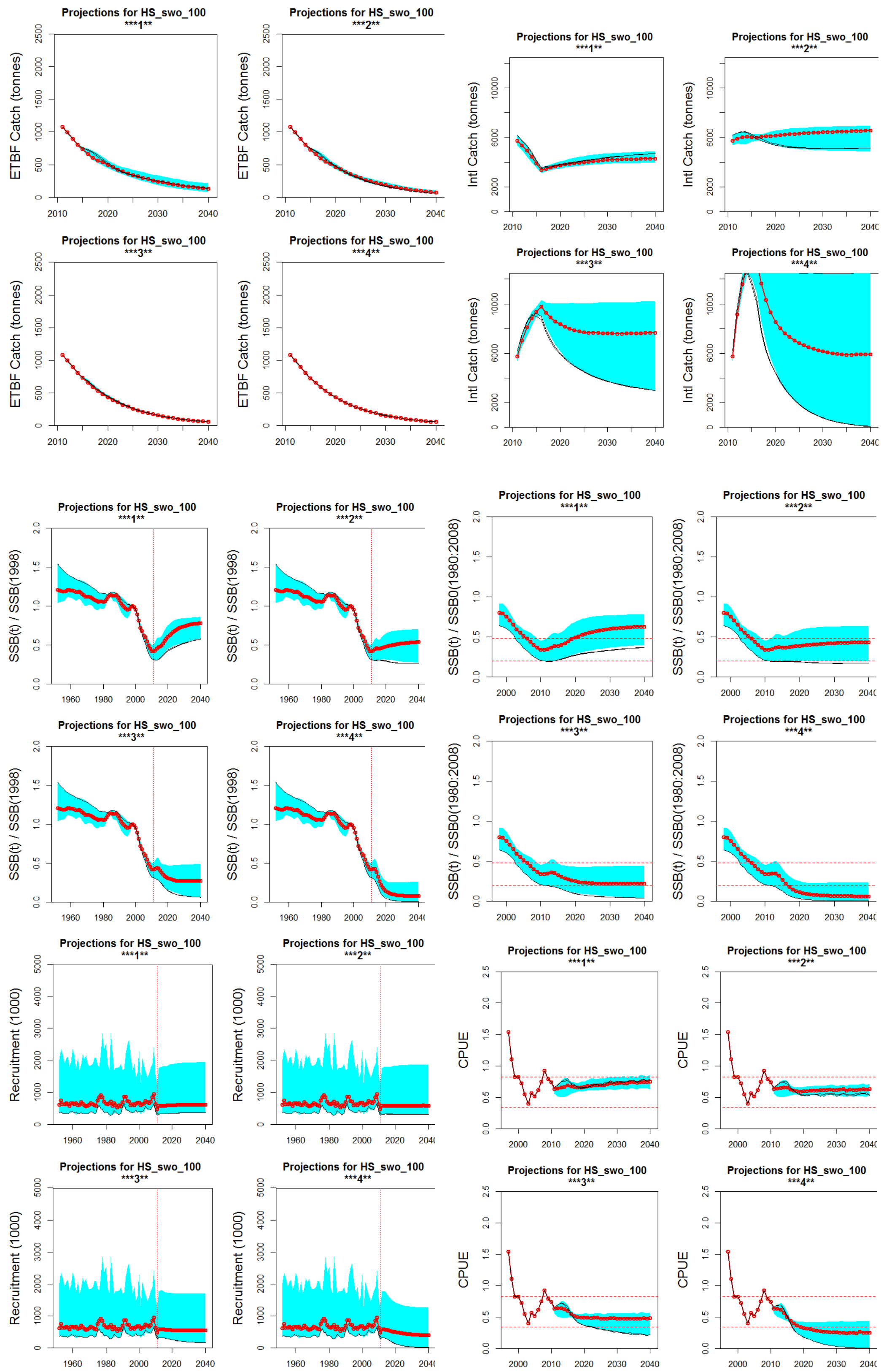


Figure 11. Adopted harvest strategy projections for the suite of 24 SWO operating models (SWC-M11) that assume the western and eastern populations mix with a quarterly migration rate of 0.11 and all stochastic process and observation error removed. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

Swordfish Robustness Set Operating Models

As is evident in Figure 10 and Figure 11, the reference set of operating models is very pessimistic in terms of future ETBF catches. Given our concerns about the representativeness of the reference set, we arbitrarily defined two robustness scenarios, which should provide some contrasting insight into how the HS will perform under more optimistic conditions :

1) SWC-M11-Pr50 - the 24 SWC OMs with migration rate = 0.11 were modified to have an equal west-east equilibrium population split.
2) SWC-M11-Ga40 - the 24 SWC OMs with migration rate = 0.11 were modified to have 1.5X the initial numbers and 1.5X future recruitment (with no change to HS targets or reference points).

The first robustness scenario provides a contrasting example of how spatial complication can affect the choice of a localized CPUE-based target and the performance of the harvest strategy, without altering the productivity of the population. The second scenario provides an indication of how the HS should behave under scenarios that are more productive than the reference set of models.

Swordfish Harvest Strategy Evaluation Results and Discussion

Figure 12 - Figure 15 show the key results of the simulation testing of the reference set of operating models. The adopted HS (HS_SWO_100) predicts very different performance depending on the spatial assumptions. Key points from these figures include:

- The SW-M00 (single spatial area) OM simulations suggest that:
    - Changes in the international effort from 0.5 – 4 X current levels have a relatively minor effect on the HS performance (because international effort is currently very small in the western region).
    - The projections mostly resulted in continuous catch declines without stabilizing by 2040 (Figure 12), with <10% of realizations supporting current catches in 2040.
    - Median CPUE is estimated to increase slowly, reaching the target sometime after 2030 (Figure 13). The lower 10^{th} percentiles never cross the CPUE limit proxy.
    - Median SSB is predicted to increase slowly and continuously to 2040, remaining well above the spawning biomass proxy target, though it may fluctuate substantially due to the high recruitment variability (Figure 14, Figure 15). Greater than 90% of the simulations result in SSB remaining consistently well above the SSB proxy limit reference point.
- The SWC-M11 (two spatial area, migration rate 0.11 per quarter) simulations suggest that:
    - Outcomes are much more sensitive to the international effort scenarios. Doubling international effort is expected to cause a substantial population decline, including a high probability of violating the SSB limit reference point by 2020. Quadrupling international effort has a high probability of causing a population collapse.
    - Median ETBF catches are projected to decline fairly continuously to 2040, regardless of the international effort scenario (Figure 16).
    - Median projected ETBF $CPUE_{prime}$ is projected to stabilize around 2020, with slightly > 10% chance of exceeding the CPUE limit if international effort remains constant, and

~ 50% of projections exceed the CPUE limit if international effort doubles. (Figure 17).

- o Median spawning biomass is predicted to stabilize below the target, if international effort remains stable (Figure 18), with almost 90% of projections remaining above the biomass limit. If international effort doubles, >50% of realizations result in biomass declining below the SSB limit by 2020.

Results from the two spatial area models with higher and lower migration rates (SWC-M05 and SWC-M25) are qualitatively very similar to SWC-M11 (not shown).

Due to the time lags in data availability for the stock assessment, we note that there are up to 4 years (2011-2014) of CPUE, catch and RBCC recommendations for the ETBF that were not included in the assessment model conditioning, and which might be informative about the plausibility of the operating models (Figure 20). The envelope of CPUE projections from OMs SW-M00 (Figure 13) and SWC-M11 (Figure 17) encompass the CPUE observations (though they are near the upper part of the range), but not the high catch and RBCC observations (Figure 12, Figure 16). This supports the notion that that the OMs are unduly pessimistic, however, this comparison is only a rough indicator, because the HCR application was not consistent over time (i.e. changing targets and size composition cut-offs).

Figure 21 - Figure 28 illustrate HS performance against the more optimistic robustness set OMs:

- OMs SWC-M11-Pr50 (migration rates imposed that result in equal unfished equilibrium abundance west and east), result in high predicted catch variability, with median ETBF catch stabilizing above current levels if international effort remains constant (Figure 21), while median $CPUE_{prime}$ stabilizes considerably above the target CPUE (Figure 22), and median SSB stabilizes below the SSB target, but with ~90% of SSB projections above the SSB limit (Figure 23).
- OMs SWC-M11-ga04 (initial numbers and future recruitment increased 50%), also result in high predicted catch variability, with median ETBF catch stabilizing around or slightly below current levels if international effort remains constant (Figure 25), while median $CPUE_{prime}$ tends to remain somewhat above the target level (Figure 26) stabilizes considerably above the target CPUE (Figure 22). Median SSB remains above the target level (and with a doubling of international effort, ~90% of realizations result in SSB above the SSB target (note however that the SSB target was not redined in relation to the increased productivity of the scenario).

Given our lack of confidence in the current suite of operating models, it is difficult to say much about the expected performance of the adopted Swordfish harvest strategy, but we note a few features of the behaviour (some of which were also noted in 2010):

- There can be a substantial mismatch between the $CPUE_{prime}$ and SSB_0 proxy reference points. The mismatch is attributable to:

- $CPUE_{prime}$ was not defined to describe SSB, as it explicitly excludes the larger 25% of the population. Hence it is possible to have a long term increase or decrease in older indivuals with no change in $CPUE_{prime}$
  - the CPUE definition remains constant among OMs, while SSB varies with the biological assumptions (growth, reproductive schedule, M)
  - $CPUE_{prime}$ is based on the ETBF region only, while SSB is summed over both regions
  - The SSB_0 proxy reference points were an approximation
- The HS has limited capacity to stabilize $CPUE_{prime}$ at the CPUE target. This is not surprising given the fact that the slope-to-target responsiveness parameter is fixed, while the population productivity varies among OM scenarios, and ETBF population abundance is affected by the spatial connectivity and international effort, which vary among scenarios.
- The HS generally seems to be biologically conservative, sacrificing domestic catch due to the actions of international effort. However, the capacity for the ETBF to compensate for increasing international effort is limited.
- With respect to the formulation of the Harvest Control Rule, we note that the LOESS smoother applied to the CPUE series in the HCR did not make any obvious difference to the performance of the HS (not shown). It was never really expected to make a big difference for Swordfish and the somewhat arbitrary way in which the CPUE observation errors were implemented in the OM means that this observation might not be representative of the real-world application.

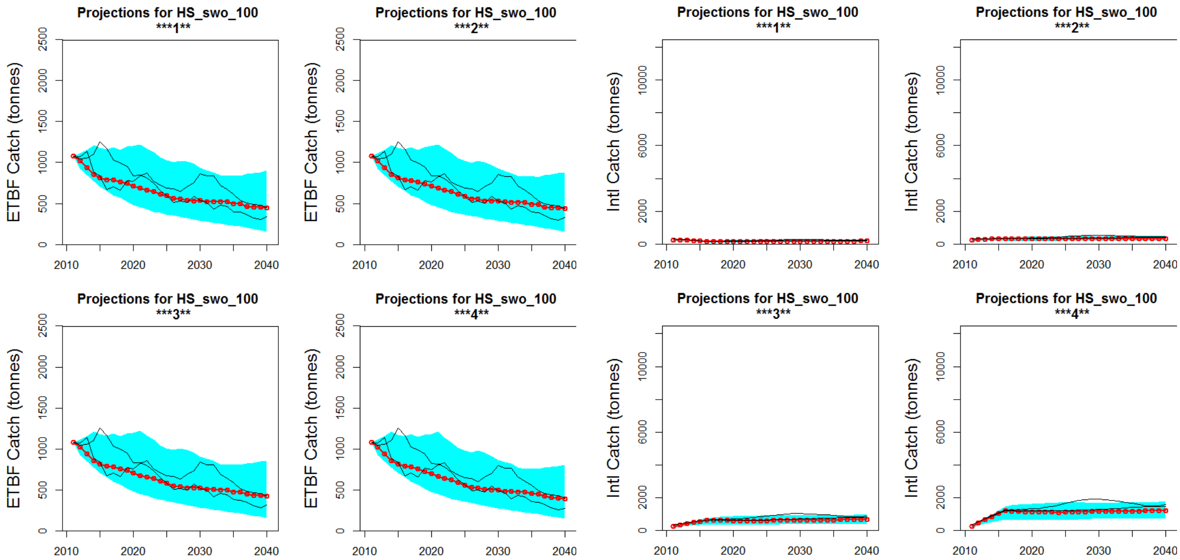


Figure 12. Adopted harvest strategy catch (ETBF left 4 panels, international right 4 panels) projections for the 24 SWO operating models (100 replicates each) that assume the western population is isolated. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

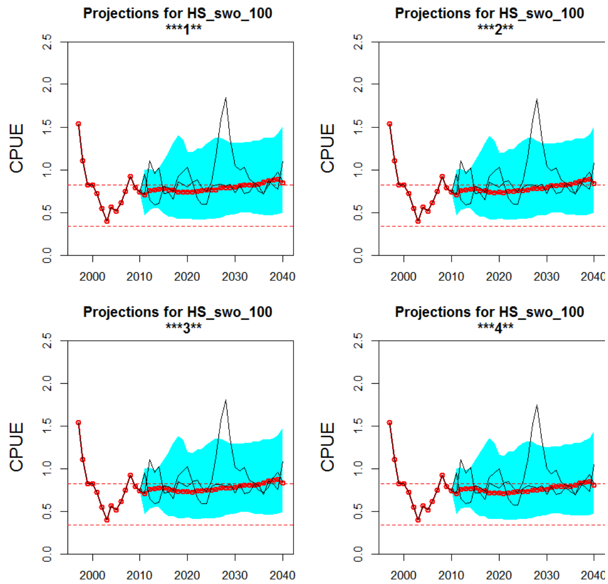


Figure 13. Adopted harvest strategy CPUE for the 24 SWO operating models (100 replicates each) that assume the western population is isolated. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

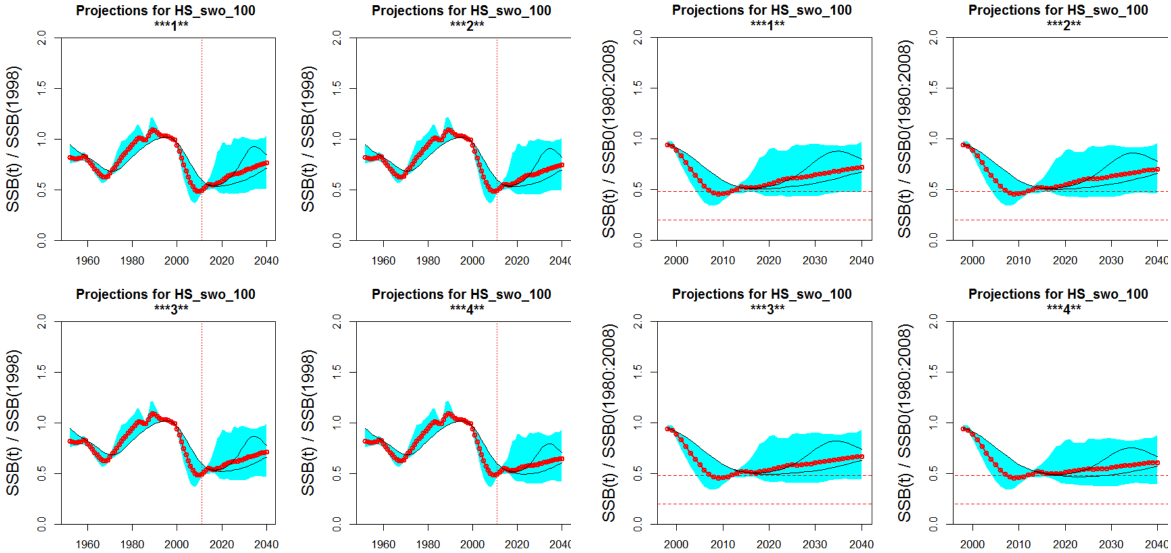


Figure 14. Adopted harvest strategy spawning biomass projections for the 24 SWO operating models (100 replicates each) that assume the western population is isolated. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

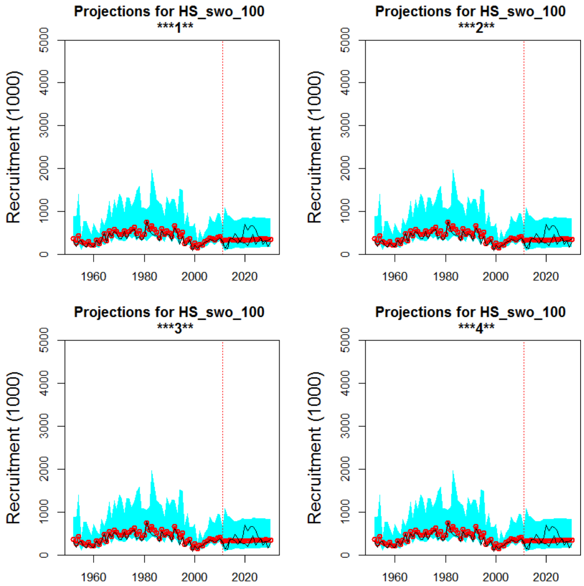


Figure 15. Adopted harvest strategy recruitment for the 24 SWO operating models (100 replicates each) that assume the western population is isolated. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

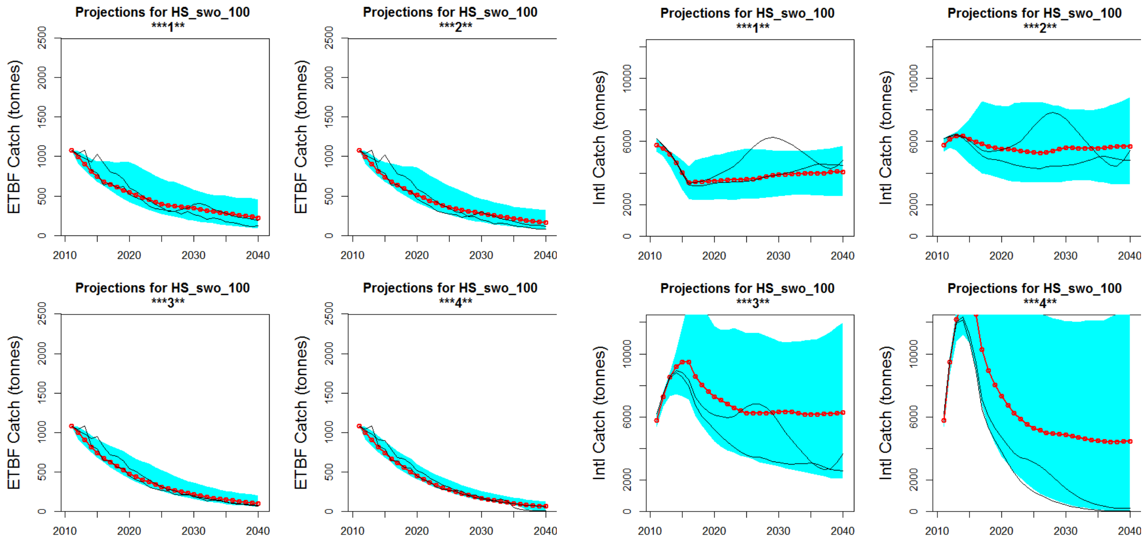


Figure 16. Adopted harvest strategy catch (ETBF left 4 panels, international right 4 panels) projections for the 24 SWO operating models (100 replicates each) that assume the western and eastern populations are linked with a diffusion rate of 0.11/qtr. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

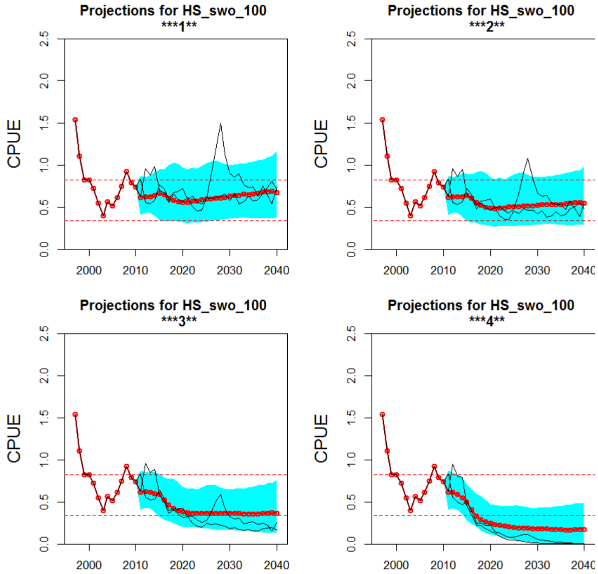


Figure 17. Adopted harvest strategy CPUE for the 24 SWO operating models (100 replicates each) that assume the western and eastern populations are linked with a diffusion rate of 0.11/qtr. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

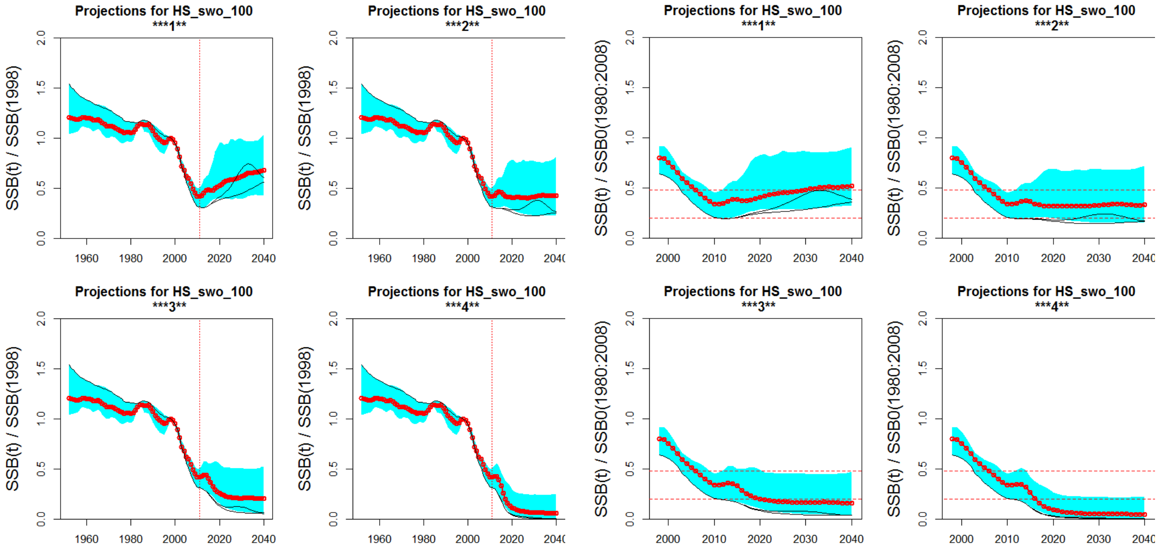


Figure 18. Adopted harvest strategy spawning biomass projections for the 24 SWO operating models (100 replicates each) that assume the western and eastern populations are linked with a diffusion rate of 0.11/qtr. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

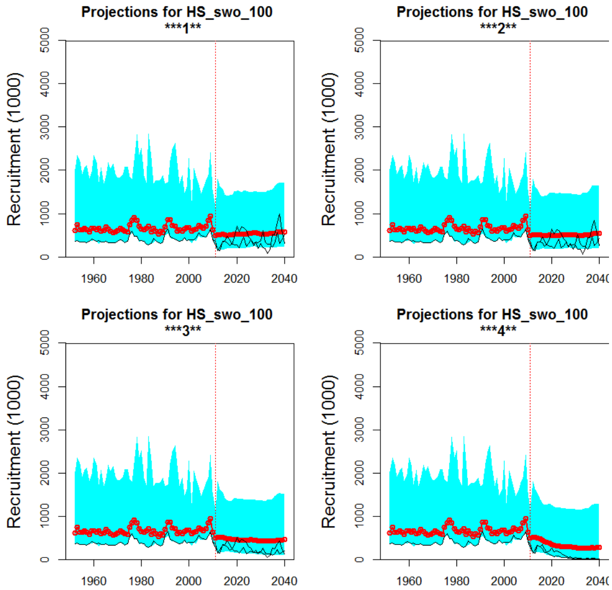
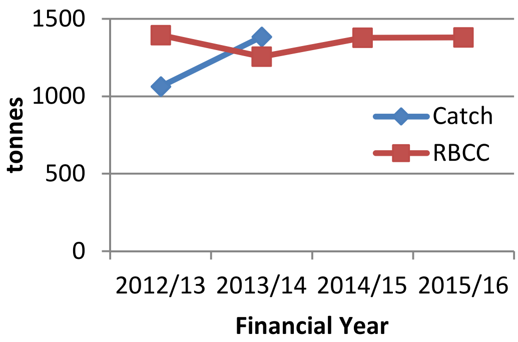


Figure 19. Adopted harvest strategy recruitment for the 24 SWO operating models (100 replicates each) that assume the western and eastern populations are linked with a diffusion rate of 0.11/qtr. Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.



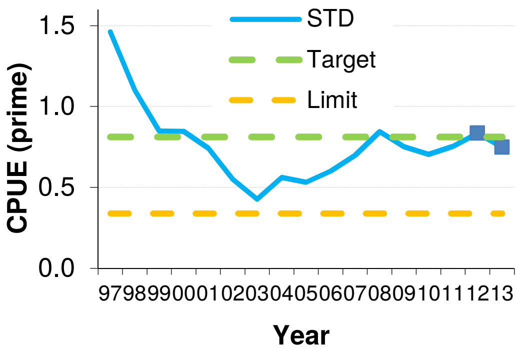


Figure 20. Observed ETBF catch, RBCC and $CPUE_{prime}$ for years which were not included in the OM conditioning.

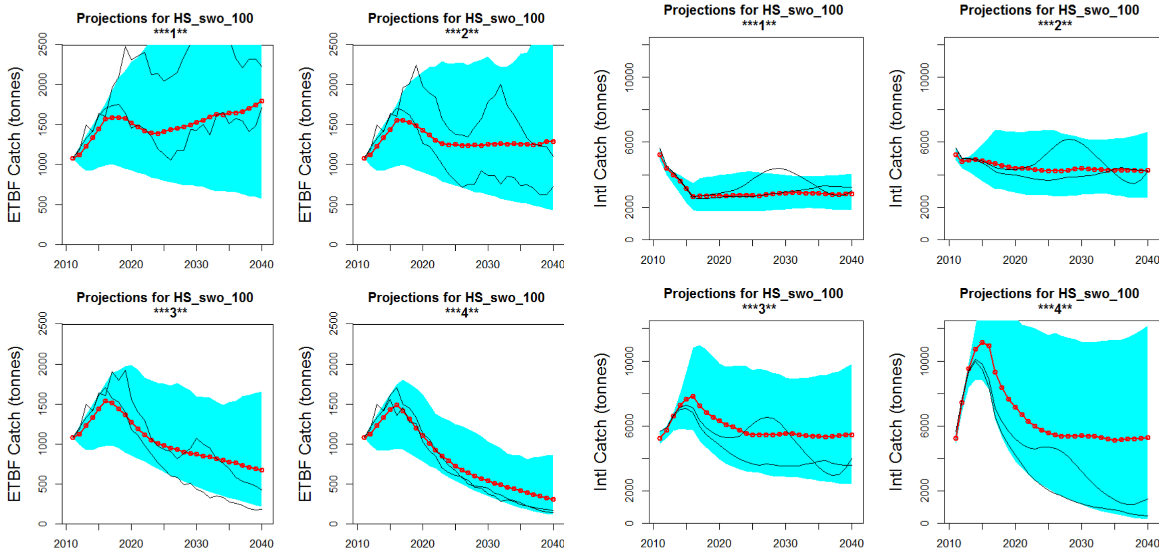


Figure 21. Adopted harvest strategy catch (ETBF left 4 panels, international right 4 panels) projections for the robustness set of OMs SWCPr50 (equilibrium population split 50% west and 50% east) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

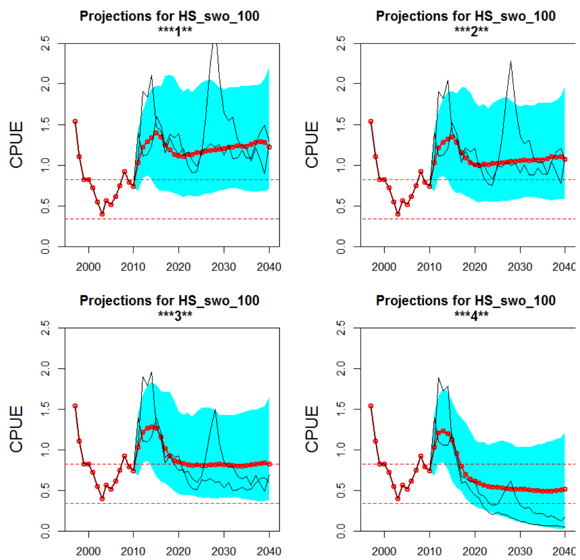


Figure 22. Adopted harvest strategy *CPUE* **$CPUE_{prime}$ (ETBF left 4 panels) projections for the robustness set of OMs SWCPr50 (equilibrium population split 50% west and 50% east) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.**

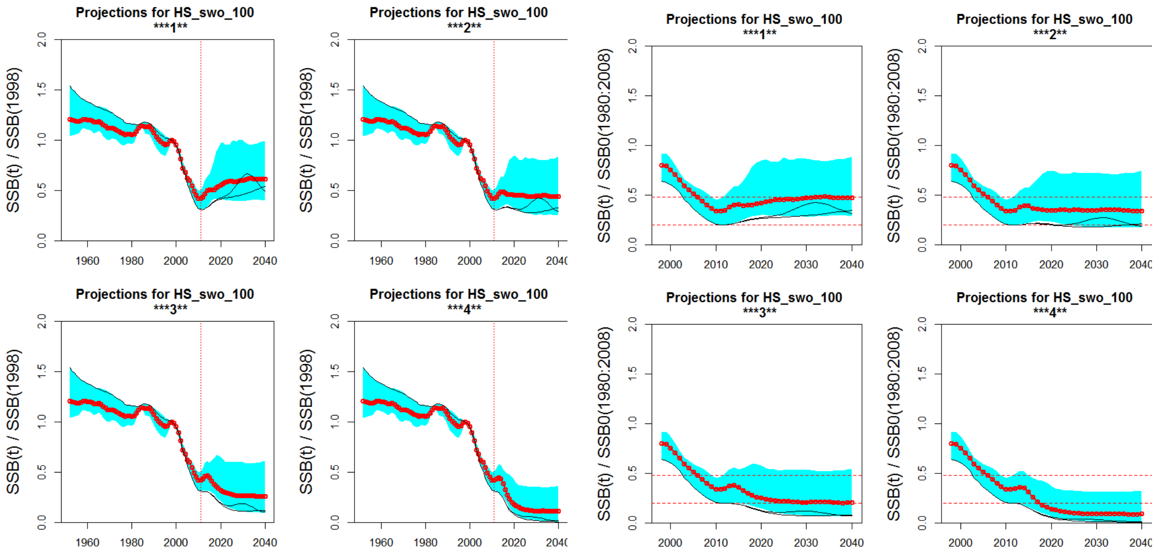


Figure 23. Adopted harvest strategy spawning biomass projections for the robustness set of OMs SWCPr50 (equilibrium population split 50% west and 50% east) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

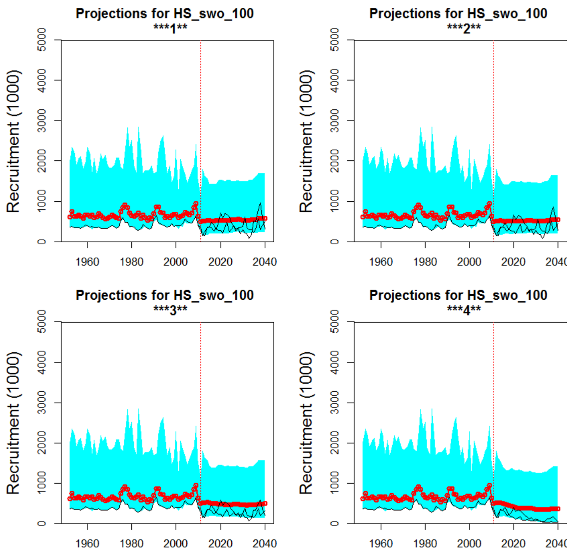


Figure 24. Adopted harvest strategy recruitment projections for the robustness set of OMs SWCPr50 (equilibrium population split 50% west and 50% east) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

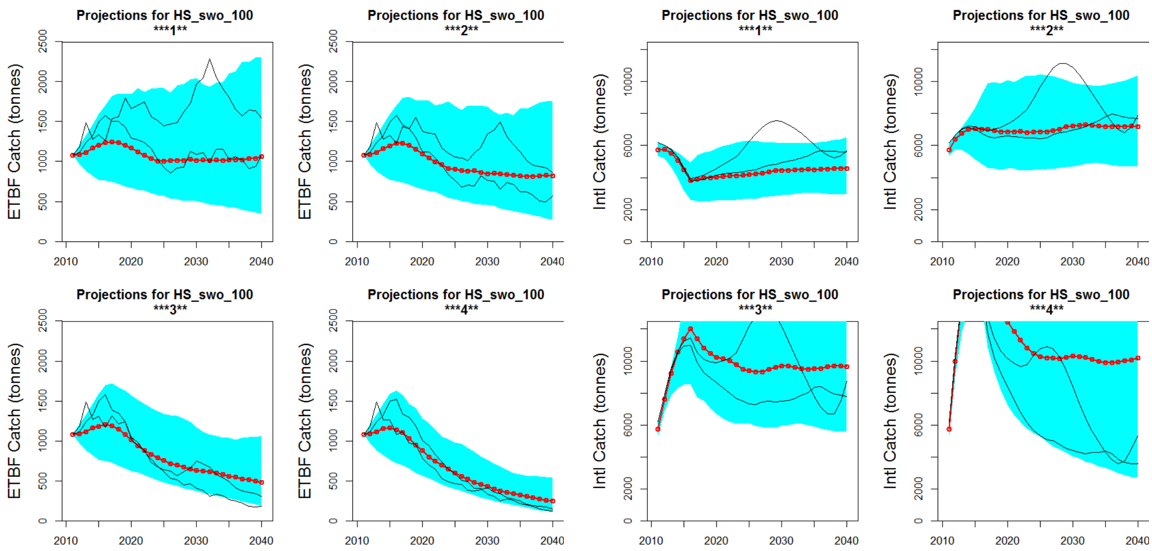


Figure 25. Adopted harvest strategy catch (ETBF left 4 panels, international right 4 panels) projections for the robustness set of OMs SWCGa40 (initial population and recruitment increased by 50%) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

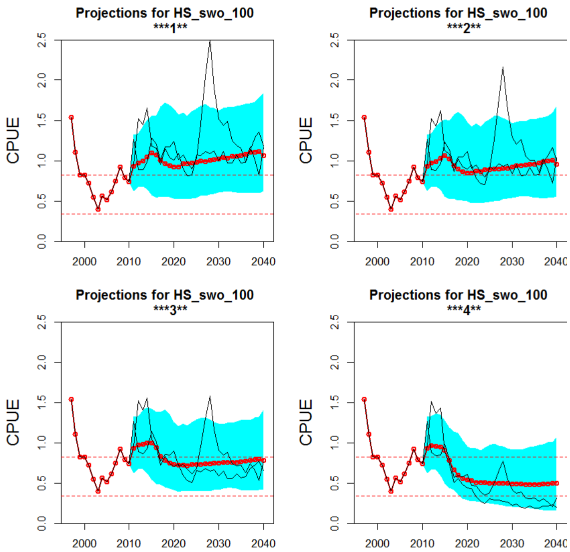


Figure 26. Adopted harvest strategy $CPUE_{prime}$ (ETBF left 4 panels) projections for the robustness set of OMs SWCGa40 (initial population and recruitment increased by 50%) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

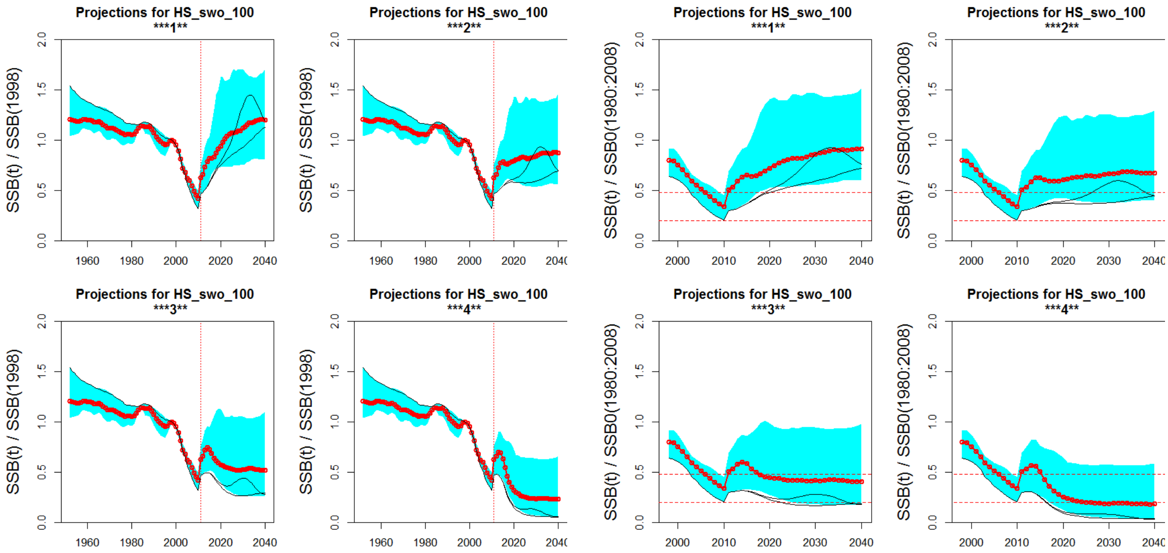


Figure 27. Adopted harvest strategy spawning biomass projections for the robustness set of OMs SWCGa40 (initial population and recruitment increased by 50%) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

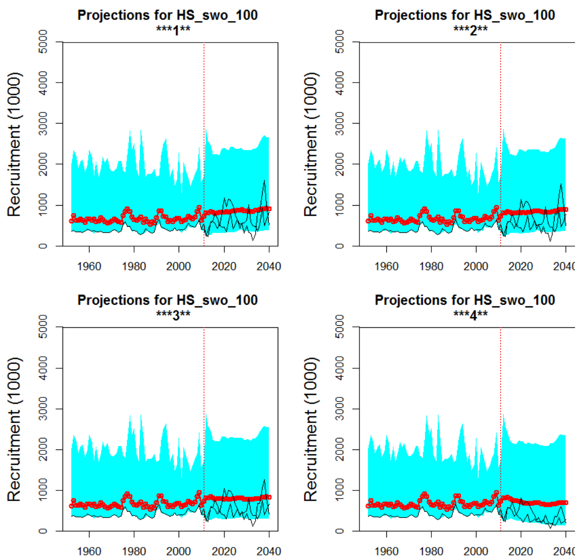


Figure 28. Adopted harvest strategy recruitment projections for the robustness set of OMs SWCGa40 (initial population and recruitment increased by 50%) (100 replicates each). Results are partitioned by panel for the assumed effort in the international fleet, which changes linearly over 5 years from current levels to the scenario-specific level: 1= 0.5, 2=1.0, 3=2.0, 4=4.0 X current.

Conclusions

1. The most recent Swordfish assessment (Davies et al. 2013) has important differences from the previous one (Kolody et al. 2008, which was used in the original harvest strategy testing). The assessment includes 561 alternative sets of model assumptions, which encompass a broad range of stock status uncertainty and the new spatial structure recognizes population connectivity that was not evident in 2008 (i.e. a migration corridor between New Zealand, at least as far as south-eastern French Polynesia). Our biggest concerns about the assessment relate to the representation of spatial and recruitment processes:
    - The new PSAT tag tracks do not provide compelling evidence for a strong link between Australia and New Zealand, and none of the assessment options explicitly describe the possibility of a fully isolated ETBF spawning population. Furthermore, tags released in the north-east Pacific have been observed moving closer to the large equatorial catches reported in the assessment (>7000km from Australia), than any of the south-west tag releases. Thus these equatorial catches might not be associated with the population that spans the New Zealand – southern French Polynesia region.
    - The aggregate recruitment deviates in the new assessment were tightly constrained to the stock recruit relationship, and show a strong negative spatial correlation, and a strong auto-correlation within each spatial region, which estimate that recruitment patterns during the development of the ETBF were far from average. We attempted to approximate these error assumptions in the new operating model, but it is not clear that either the estimates or the ad hoc approximations are realistic.

2. A suite of 96 (of the 561) assessment models were adopted for the reference set of operating models, spanning most of the range of stock status uncertainty from the assessment. These included 8 sets of growth/maturity/mortality assumptions, 3 stock recruit steepness assumptions and 4 spatial/migration rate scenarios (8 X 3 X 4 = 96). These operating models were derived differently depending on the assumed west-east migration rate.
    - The SW (western area only) OMs, were derived from 24 assessment specifications with zero migration. Only the sub-population (and fishery catch) from the western region were included in these scenarios to represent the possibility that the Australian zone might be a largely isolated spawning population with independent dynamics.
    - The SWC (2 spatial region) OMs included 72 models using the full spatial structure, with west–east migration rates of 0.05, 0.11 and 0.25 per quarter. Among the SWC

scenarios, the harvest strategy performance was reasonably insensitive to the migration rate.

3. The reference set OM projections are very pessimistic about future ETBF catches, though they suggest that the HS is likely to prevent a violation to the SSB limit reference point if international effort does not increase too much.

4. The robustness set operating models, which were defined arbitrarily to be optimistic for the ETBF, suggest that the HS will allow the ETBF to sensibly take advantage of higher productivity than the reference set OMs allow, without representing a SSB risk.

5. Given the concerns about the current OM conditioning, we do not provide probabilistic statements about the expected performance of the adopted HS. However, there are some HS behaviour characteristics that are worth noting:
   - The HS appears to provide reasonable feedback-based RBCC recommendations, dropping ETBF catches in pessimistic situations (including high international effort) and raising RBCCs in optimistic scenarios.
   - However, the HS is unlikely to stabilize CPUE at the specified target level (even in the absence of stochastic error),
   - There is an inconsistency between the proxy CPUE and SSB reference point definitions, that potentially has an important effect on the CPUE-based target reference point, and hence the general behaviour of the HS.

Recommendations for future updates:

1) Explicit consideration of different population connectivity assumptions in the assessment model fitting assessment process. At a minimum this should include 3 options:
   a. The whole SWC Pacific is a single population, with variable degrees of diffusive mixing among sub-regions (consistent with the 2013 assessment assumption).
   b. The region from Australia to western French Polynesia represents a single population (as indicated by tags), excluding the equatorial north-east region.
   c. ETBF population represents an essentially independent population including stock-recruitment processes and migration (different degrees of mixing in the fisheries might also be entertained).

2) The CPUE-based index in the “slope-to-target” part of the decision rule, and the CPUE-based proxy reference points should probably be redefined to include the large size-class fish (as these are probably more indicative of spawning biomass than the prime-sized fish.

3) Improved consistency among assessment model and operating model recruitment processes (in terms of stock structure, aggregate annual variability, spatial partitioning and the associated reference point calculations).

4) The 2013 assessment suggests that troublesome source-sink dynamics are plausible, and the HS might need to use additional information from international fleets to account for it. If

there really is a strong inverse relationship in recruitment between west and east, its also possible that there could be large interannual variation in migration east and west as well.

5) The stock structure connectivity issue might be resolved by employing next generation genomics tools, as are currently being applied to some tuna populations.

References

Abecassis, M., Dewar, H., Hawn, D., Polovina,J., 2012. Modeling Swordfish daytime vertical habitat in the North Pacific Ocean from pop-up archival tags. Mar. Ecol. Prog. Ser. 452: 219-236.

Butterworth, D.S., Rademeyer,R.A., Brandão, A., Geromont, H.F., Johnston, S.J., 2014. Does selectivity matter? A fisheries management perspective. Fish. Res. 158: 194–204.

Campbell, R., 2013. Identifying Target CPUE values for Broadbill Swordfish and Striped Marlin in the ETBF. Information paper to Tropical Tuna RAG – July 2013.

Campbell, R., 2014. Aggregate and size-based standardised CPUE indices for longline target species caught within the ETBF - 2014 Update. Working Paper to Tropical Tuna RAG, June 2014.

Davies, N., Pilling, G. Harley, S., Hampton, J., 2013. Stock assessment of Swordfish (*Xiphias gladius*) in the southwest Pacific Ocean. WCPFC-SC9-2013/SA-WP-05

Evans, K., D. Kolody, F. Abascal, J. Holdsworth, P. Maru and T. Sippel. 2012. Spatial dynamics of Swordfish in the south Pacific Ocean inferred from tagging data. WCPFC Working Paper: WCPFC-SC8-2012/SA-IP-05.

Farley, J., Clear, N., Kolody, D., Hillary, R., Young, J., 2014. Determination of southwest Pacific Swordfish growth and maturity. WCPFC-SC10-2014/ SA-IP-17.

Kolody, D., and N. Davies. 2008. Revisiting the south Pacific Swordfish stock assessment spatial structure: evidence from PSAT and conventional tags, genetic studies, larval surveys and fisheries demographics. Working paper for the South Pacific Swordfish assessment workshop 15-18 April 2008, Secretariat of the Pacific Community, Noumea, New Caledonia.

Kolody, D.S., A.L. Preece, C.R. Davies, J.R. Hartog, N.A. Dowling. 2010. Integrated evaluation of management strategies for tropical multi-species long-line fisheries. Final report for FRDC project 2007/017. 213p.

Peltier 2009. LOESS smoothing in excel. Available from (as of Jan 2014): http://peltiertech.com/loess-smoothing-in-excel/

TTRAG 2013 or 14...

Appendix 2: Striped Marlin Management Strategy Evaluation of the ETBF Harvest Strategy

Striped Marlin - Management Strategy Evaluation of the ETBF Harvest Strategy

Table of Contents

Acknowledgments

Nick Davies and Shelton Harley from the Secretariat of the Pacific Community Oceanic Fisheries Program, for extracting and providing the stock assessment output files from the 2012 Striped Marlin stock assessment models for use in the operating models used here to evaluate harvest strategies.

Robert Campbell, CSIRO, for provision of CPUE and size data from the ETBF fishery.

Tropical Tuna RAG members for their feedback and advice.

1 Introduction

Striped Marlin (*Kajikia audax*) is one of 5 key species commercially caught in the Eastern Tuna and Billfish Fishery (ETBF). The Striped Marlin catches in the ETBF are managed via a Harvest Strategy control rule which is used to recommend the annual Total Allowable Commercial Catch (TACC). Full management strategy evaluation of a variety of harvest strategies was completed in 2009, and the adopted harvest strategy implemented in 2011. In the report of the management strategy evaluation (MSE) of the Striped Marlin harvest strategy (Kolody et al, 2010), it was noted that: 1) the Western and Central Pacific Fisheries Commission (WCPFC) Striped Marlin stock assessment, which was used to condition the operating models, was out of date and new biological data were available to inform the stock assessment models, and 2) that the evaluation indicated that the harvest strategy may have a higher risk of breaching the limit reference point than outlined in the Commonwealth Harvest Strategy Policy guidelines. This updated management strategy evaluation of the harvest strategy for Striped Marlin deals with both of these issues; it is based on an updated stock assessment (Davies et al, 2012) and provides a re-evaluation of performance in general and performance relative to the limit reference point in particular.

2 Background

This project builds upon earlier work completed in 2009 (Kolody et al, 2010) on Management Strategy Evaluation (MSE) of a range of harvest strategies from which the Resource Assessment Group (RAG) selected the adopted harvest strategy.

The Striped Marlin MSE in 2009 was based on data from the 2006 stock assessment. A generic operating model, developed as part of the 2009 project, uses the outputs from stock assessments to condition the model. In the case of Striped Marlin the stock assessment was out of date, and new biological information had become available for use in the stock assessment.

In the 2009 evaluation of the harvest strategy for setting the TACC for Striped Marlin, it was identified that the harvest strategy could potentially increase the risk to the stock. It has subsequently been a high priority for the RAG and Management Advisory Committee (MAC) to undertake an updated MSE of the harvest strategy using the most up to date data, and an updated stock assessment.

In 2009 the ETBF RAG and MAC adopted the harvest strategy used to set the TACC for Striped Marlin. In 2010 the harvest strategy was implemented to set the Striped Marlin TACC for 2011, and has been used each year since. In 2013 the method for calculating the Catch Per Unit Effort (CPUE) series used in the harvest strategy and the target reference point were changed and therefore the 2014 TACC was set using a harvest strategy that is untested.

In 2012 the Western and Central Fisheries Commission (WCPFC), scheduled an updated stock assessment for Striped Marlin (Davies et al, 2012), which included new biological information. The software developed for the 2009 management strategy evaluation work has been reused here, with the models updated with outputs from the most recent stock assessment.

3 The Striped Marlin 2012 stock assessment

The Secretariat of the Pacific Community's Oceanic Fisheries Program Scientists provide stock assessments for the WCPFC scientific committee meeting. The most recent Striped Marlin stock assessment was presented in 2012 (Davies et al, 2012), and considerably updates the 2006 stock assessment (Langley et al, 2006).

There were several major changes in the 2012 assessment compared with 2006:

- The Japanese catches between 1952-2011 were revised to be approximately 50% smaller than those used in 2006, because of a data collation error in 2006 (i.e. two data sets for the Japanese catch and effort data were provided, for different spatial aggregations, and both were accidentally used in the 2006 stock assessment rather than just one).
- The CPUE series were revised and updated, and the Australian recreational catch size data were included.
- New biological estimates for growth, length-weight and maturity at age (Kopf 2011) were included.
- The assessment included a broader uncertainty analysis than the 2006 work and presented results across 11 sensitivity models (based on the reference case model), and for a grid of 229 models which covered the cross-combination of uncertainties (e.g. alternative values for natural mortality crossed with alternative values for steepness). In contrast, in the 2009 MSE project only a single stock assessment model was available for conditioning the MSE operating model.
- Recent catch data since the last assessment (which only included data up to 2004) indicates that the Australian longline catches are less than 10% of the total catch in the SW Pacific, and are no longer the major catches in any of the assessment regions. Catches by non-Japanese and non-Australian fleets are now dominating.

Some items in the 2012 assessment remained the same as in 2006:

- The stock assessment considers the SW Pacific stock to be separate from the Northern Pacific and southern Eastern Pacific Ocean stocks.
- The spatial structure in the model remained the same as in 2006 – with a single spatially mixed stock, with a regional component used only to specify selectivity for the different fisheries and gears (Figure 1 from Davies et al 2012).
- The largest historical catches were taken out of the ETBF area by the Japanese fleet (Figure 2).
- Tag data were not included in the models.
- There is still large uncertainty in stock status associated with assumptions regarding CPUE and selectivity, natural mortality and steepness.
- The decline in recruitment observed in the 2006 stock assessment is also observed in the 2012 stock assessment.

The SPC advice to the WCPFC in 2012 on Striped Marlin was:

- Current catches are below MSY but are approaching MSY
- Overfishing is not occurring in the Striped Marlin stock
- Striped Marlin is approaching an over-fished state

The current conservation management method adopted by the WCPFC with respect to the SW Pacific Striped Marlin stock is a vessel limit. The limit is equivalent to the maximum number of vessels fishing for Striped Marlin in any one year within the period 2000 – 2004 (CMM 2006-04).

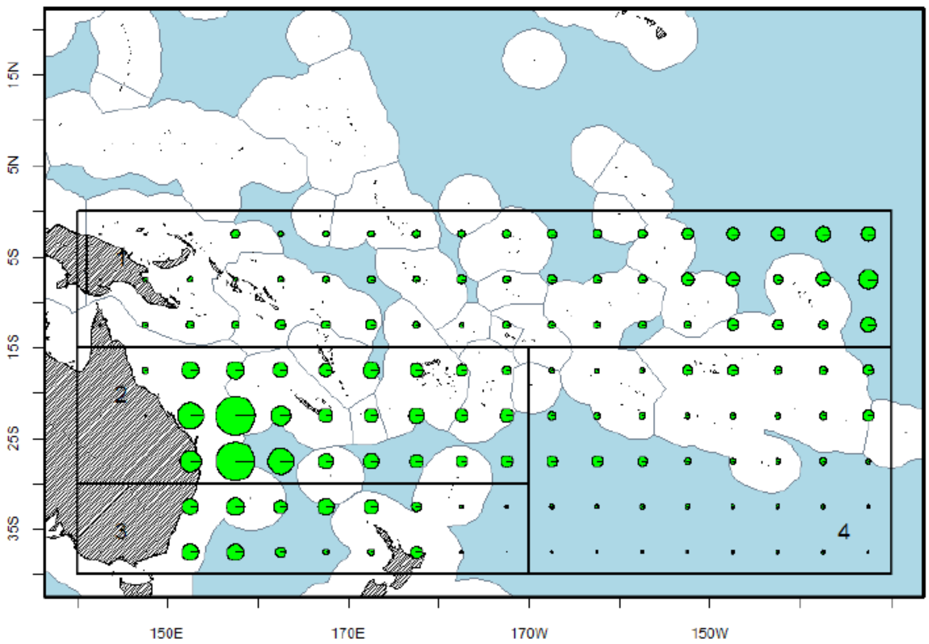


Figure 1 The spatial structure of the stock assessment indicating catches over the history of the fishery: Note there is one population with fisheries defined in 4 regions (from Davies et al, 2012)

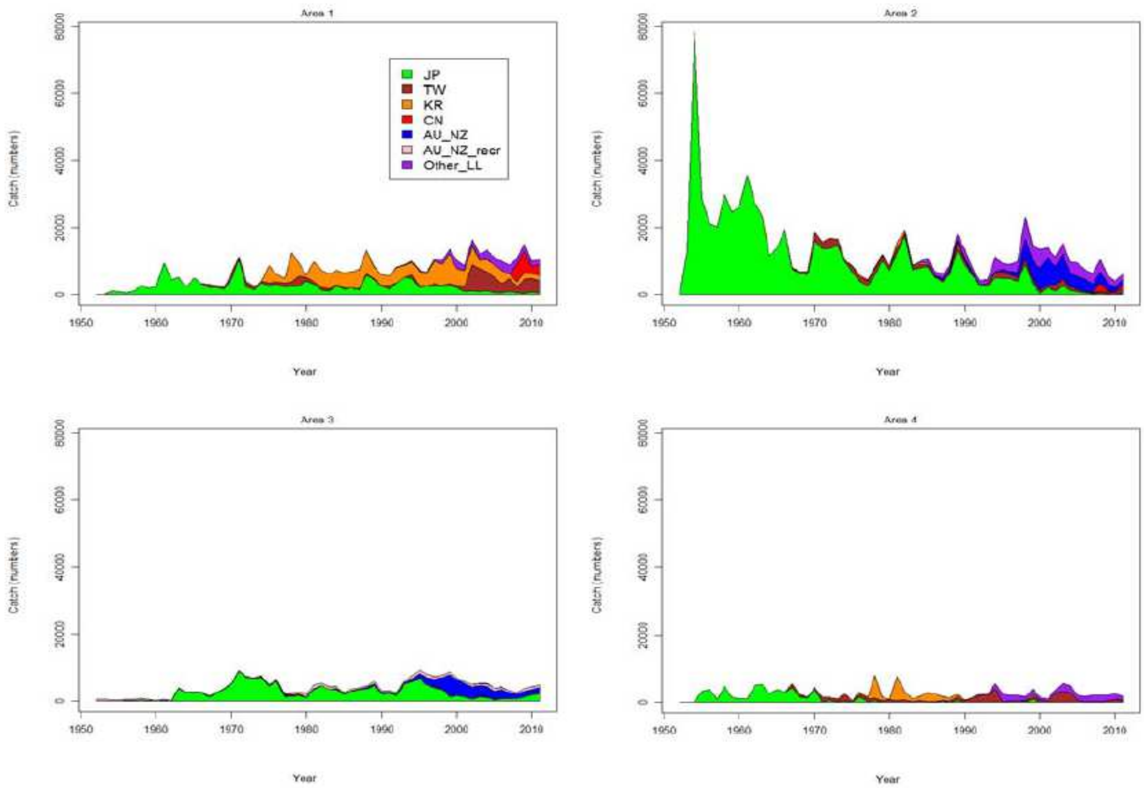


Figure 2 Total estimated catch of Striped Marlin (in numbers) by region and vessel flag (from Davies et al, 2012)

4 The ETBF Harvest Strategy

The ETBF harvest strategy (HS) adopted in March 2009, is based on a tree structure designed by the ETBF HS working group and described in Davies et al (2008), and Kolody et al (2010). The input data to the HS are the CPUE series for 3 size classes of fish (juvenile, Prime, Old), and the proportion of old fish in the catch. The first and major component of the decision rule structure for adjusting the TACC is the first stage which determines what adjustment is needed to reach the target CPUE level (can be an increase or decrease in catch). The recent CPUE trend for Prime sized fish splits the decision rule into the first set of branches. The second set of branching in the decision rule tree structure is determined by the CPUE trend for Old fish, and the relative proportion of old fish in the catch. The final stage of branching in the tree structure is based on trends in the CPUE of juvenile fish. It is at the ends of these different branches that the TACC can be further adjusted downward, by different amounts depending upon the branch, from the initial calculation of the TACC at stage one. In adopting the HS the RAG and MAC agreed that a maximum TAC change of 10% would be allowed, and the performance of this was tested in the MSEs completed in 2009.

The tested and adopted HS has been used to set the TACC in the ETBF in 2011-2013, however, changes to the input data used in the HS were introduced in 2013 (Campbell, 2013a) and the target reference point was revised downwards (Campbell, 2013b). This new HS was used to set the TACC in 2014 and these changes are currently untested, in terms of performance of the harvest strategy using MSE. The changes involve smoothing of the CPUE series before use in the HS. This has the potential to reduce the highs and lows that are normally seen in CPUE series, but may also have the effect of slowing the responsiveness of the HS or damping TAC fluctuations, and the effects on performance are unknown.

The original target that the ETBF HS aimed to reach is the average CPUE in the years 1998-2002. The rationale was that this level of CPUE was considered economically optimal (Davies et al, 2008). The target CPUE level was reviewed in 2013 (Campbell, 2013b) and changed by the Tropical Tuna RAG (Anon 2013) to a lower target of 0.86 of the average 1998-2002. The review examined the biomass trend in the 2012 stock assessment over the same period (1998-2002) relative to the initial biomass. This was used as a comparison with the Commonwealth HS policy target of MEY which can be estimated via a proxy related to MSY and is assumed to be equivalent to 0.48 of the initial biomass (B0). The comparison was limited to the reference case model, and did not examine all the models in the full structural uncertainty grid. A limit reference point was also introduced at 0.2 B0 which in this case is assumed to equate to 0.36 of the standardized CPUE prime. The new reference points are shown in the CPUE performance figures.

4.1 HS input data requirements

The ETBF HS input data requirements are the ETBF CPUE series for 3 size groups (juvenile, prime and old), and the proportion of the old size group in the ETBF catch. Around 70% of the fish caught are measured as part of the size data monitoring program. Logbook and observer data are used in the CPUE calculations. These inputs are unchanged from the 2009 MSE work, except that the CPUE series are now smoothed using a lowess function. The data inputs and methods are described in Campbell (2013a), and the data inputs and methods are not reviewed here.

5 MSE steps and operating model conditioning

5.1 MSE steps

The operating models used for MSE are conditioned on the data outputs from the Striped Marlin stock assessment models. The estimates from individual stock assessment models of the numbers at age in each year, selectivity of the different fisheries, and natural mortality, steepness and growth rates are used to define the values of the variables and parameters in the individual operating models. The population numbers are then projected into the future, using these population dynamics parameters. In the projections, for each annual loop, the HS decision rule is used to set the TACC in the ETBF area, and data for the next HS decision are simulated. The performance of the HS, relative to the Commonwealth HS Policy and guidelines performance objectives, is then evaluated.

5.2 Operating model conditioning

The assessment model spatial structure is defined as a single area. For the operating models, the spatial structure involves an ETBF and non-ETBF area, with hypotheses for connectivity between them. The HS only operates in the ETBF area. Therefore some assumptions must be made to re-partition the population into a suitable spatial framework in the OM.

- The operating model (OM) is a two area model representing the ETBF and non-ETBF areas. The data from the stock assessment (estimates of numbers at age in each year 1950-2011) are partitioned into the two areas based on the geographical surface area of the ETBF in the assessment region (36% was used as the ETBF area in the first MSE OM's, and re-used here).
- A single selectivity vector (by age) is used in each of the OMs 2 areas. The stock assessment areas 2 and 3 (Figure 1) cover the ETBF but also extend further east into the south-west Pacific Ocean. The Australian longline and recreational fisheries selectivities are estimated for the 2 assessment areas and are quite different above and below 30S (the line between areas 2 and 3 in the stock assessment) (Figure 3). These selectivities are used in the OMs for the ETBF area. For the non-ETBF area in the OM, the Japanese longline 2 fishery selectivity ('LL2' as defined in the stock assessment) is used. This fishery has taken the largest catches over the history of the fishery, but in recent years the catches in areas 1 and 4 by non-Japanese fleets have increased substantially (Figure 2).
- The stock assessment model assumes that there is a single well mixed population, and single spawning population. Similarly, the OM assumes that there is a single spawning population (the combination of mature fish from both the ETBF and Non-ETBF areas) and has fixed parameters for distribution of recruits to the 2 areas in the OM.
- The OM allows for migration between the ETBF and non-ETBF areas, and different rates of migration are explored, related to different connectivity hypotheses.
- Of the 229 stock assessment models examined in the full analysis of the grid of uncertainties, only a subset of these are selected to cover the range of uncertainties in population size and

dynamics in the OMs. The set of 229 stock assessment models is a subset of the all the stock assessment models run, because 21% were considered not plausible or failed converge.

The operating model is not re-conditioned to fit the historical data to the new spatial structure or assumptions regarding selectivity, recruitment distribution and migration.

In the projections of the population into the future, the catch in the ETBF is determined by using the HS decision rules that is being tested, and alternative scenarios for fixed non-ETBF effort are examined.

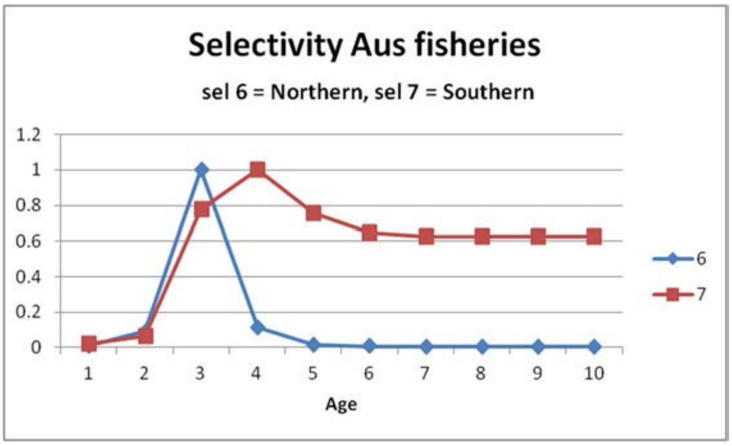


Figure 3 Selectivity estimated in the reference case stock assessment model for the Australian longline fisheries in area 2 (north of 30S) and area 3 (south of 30S)

5.2.1 Options and impacts of conditioning the OM using the stock assessment outputs

The 2009 MSE work identified an inconsistency in the operating model data and the size composition data from the ETBF. We have explored the consistency of the OM estimates of CPUE and proportions for the 3 size classes used in the ETBF HS with the observed data over the years where the data overlap (1999-2009). There are options in defining the OMs that can affect the consistency between modeled and observed data, and three of these options are discussed below. Inconsistencies remain, however it was not in the scope of this project to consider reconditioning the operating models.

1) The CPUE series used in the stock assessment

One of the changes in the 2012 stock assessment models, compared with 2006, is that different models used different CPUE series data, and conflicting CPUE series are no longer combined in the one stock assessment model. There are 9 CPUE indices available for use in the stock assessment, but only 5 are used in the grid analysis of structural uncertainty, in 4 combinations. Australian longline CPUE indices were provided for the stock assessment for areas 2 and 3 by Campbell (2012), and an Australian recreational fishery CPUE Series in area 3 was provided by Ghosn et al (2012).

The stock assessment structural uncertainty grid includes 4 options for the CPUE used: 1) the Japanese ‘LL1’ fishery CPUE series, 2) the Japanese ‘LL2’ CPUE series, 3) the Japanese ‘LL3’ CPUE series or 4) the Japanese ‘LL2’ CPUE series and the Australian Longline CPUE in areas 2 and 3. The stock assessment reference case uses the Japanese LL2 CPUE series only. This means that in the structural uncertainty grid of models, only a subset of models use the Australian CPUE indices. The choice of CPUE used in the stock assessment can affect the estimates for the selectivities in areas 2 and 3 for the Australian longline fishery (selectivities are discussed further below), and stock structure may be affected because the stock assessment estimates of absolute abundance are sensitive to the CPUE series used. These effects therefore also occur in the OMs. The CPUE factor in the structural uncertainty grid contributes to the large uncertainty in stock status estimates.

2) Which selectivity from the stock assessment to use in the OM

The structural uncertainty grid in the stock assessment has 2 options for selectivity function shapes, and selectivities are estimated for 12 longline and 2 recreational fisheries in each stock assessment model. The shapes options are: 1) splines for all longline fisheries, 2) logistic function for Japanese 'LL3' and Australian 'LL3'. In the OM we have chosen a single selectivity to represent the non-ETBF fisheries, and one to represent the whole of the ETBF area. The choice of which longline fishery selectivity to use has impacts on the model estimates of the ETBF size and CPUE data, and how well these match with the observed size and CPUE data from the ETBF. The selectivities are also dependent on the stock assessment model, and which CPUE series is fit within that model.

3) Differences in the conversion factors used in the ETBF data processing and in the stock assessment model.

The operating model estimate of the proportion of the catch in each size class is dependent on the cut-off sizes used. The cut-off weights are defined in the ETBF data processing and are processed weight values. The stock assessment models and hence the operating models use whole weight, and therefore the processed weights must be converted to whole weights. Regardless of the conversion factors the observed ETBF proportions by size group would not change, but the modeled proportions will be dependent upon whole weight cut-off values used. We have used the stock assessment conversion factors to determine the whole weight cut-off values for use in the operating model catch sampling algorithms. In the stock assessment, the authors use the following processed weight to whole weight conversion and argue that these are the most appropriate values currently available. They are derived from Japanese observer data collected in the 1990s. It's acknowledged that this factor is uncertain and will remain so until a conversion factor is calculated from data collected on Australian longliners. The stock assessment conversion factors are described in Davies et al, 2012 as:

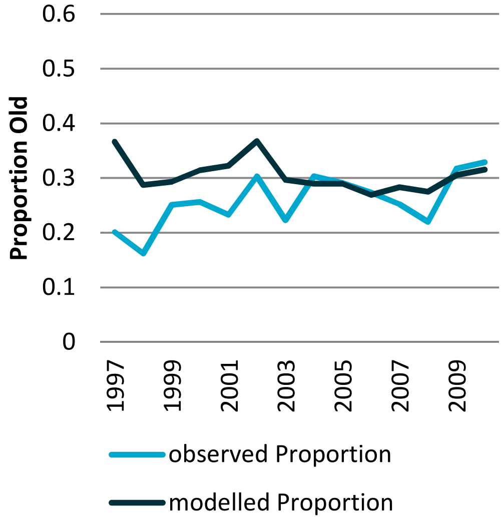
Whole weight (kg) = 1.1788 x gilled-gutted weight (kg)$^{0.9984}$.

The cut-off weights used, in combination with the selectivity curve, can affect the allocation of the numbers of fish in the catch between the 3 size classes used in the ETBF HS. The steep selectivity curves for the Australian longline fishery (especially the area 2 Australian longline selectivity), in combination with a slight mismatch in conversion rates from processed weigh to whole weight can make a difference to the partitioning of the catch into each of the size classes in the OM.

5.2.2 Fit to the observed data in the ETBF

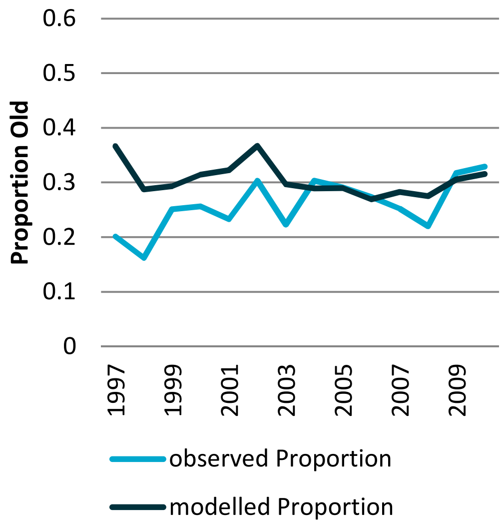
We have explored the 3 main options in defining the OM to examine the impact on consistency between observed and modeled CPUE and proportions in each size class.

The observed Australian longline CPUE series appears to track reasonably well with the modelled estimate CPUE series for the available years of overlap for the operating model based on the stock



assessment reference case (

Figure 4) where only the Japanese longline 2 CPUE is used and for model 004 which also uses the Australian longline CPUE for areas 2 and 3 (Figure 5, Figure 6). This is a positive outcome given that the Australian CPUE series is not used in the reference case stock assessment model.



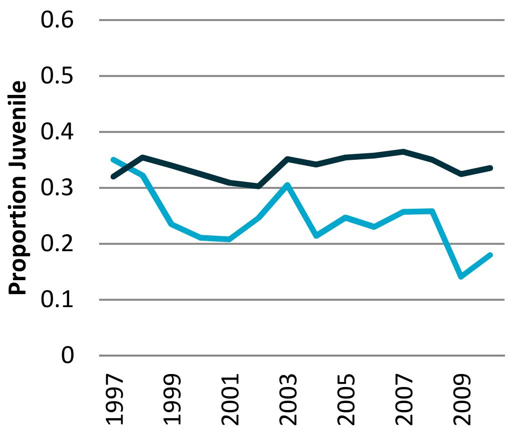
For the reference case and model 004 (

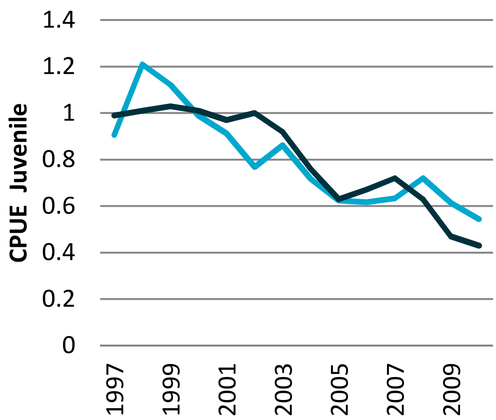
Figure 4 and Figure 6), when the Australian longline 3 selectivity is used, the match for the proportion old size class (which is used in the HS) is good. However, for the other size groups, the observed and modeled data show some inconsistencies. When selectivity Australian longline 2 is used with model 004 (Figure 5) and the reference case (not shown, but very similar to model 004 results) all the proportions by size class show inconsistencies between observed and modeled data. For the prime sized fish the trends in observed and modeled data appear similar, but the proportions are different, for the available years of overlap. When using Australian longline 2 or 3 selectivities, the proportions of juvenile Striped Marlin in the ETBF area are too high compared with the catch at size data observed in the ETBF. When the Australian lonline 2 selectivity is used, the proportion old is too low (Figure 5).

The Australian longline 2 selectivity for area 2 is very steep and centers around 1 age class (Figure 7), and OMs using this selectivity show an inconsistency with proportion old size class. The Australian longline 3 selectivity appears to be more representative of the ETBF catches, but changes depending on the stock assessment model. The inconsistency in the juvenile and prime proportions remain unresolved, however these proportions are not used in the HS, and the CPUE series appear to be unaffected by this inconsistency.

In addition to these three main options in defining the OMs and the impact on consistency with observed data, the size composition can also be affected within the OMs from a variety of reasons, described below:

- The distribution of the numbers at age from the stock assessment to the operating model does not represent the underlying spatial complexity of the stock by age or size
- Choosing a single selectivity for the ETBF and non-ETBF regions in the operating model, does not account for the effects on stock structure created by the other fisheries in the stock assessment models (in particular the recent increased fishing effort in areas 1 and 4, some of which is targeting smaller fish).
- The cutoff sizes for the 3 size classes are not correct when applied in the OM: We explored the weight-to- length and processed- weight to whole-weight conversions and could find no reasonable alternative methods or inconsistencies that would resolve the problem.
- Lack of fit in the assessments to the Australian Length or weight data: The diagnostic plots from the reference case stock assessment model don't indicate any lack of fit to the Australian length and weight data used in the stock assessments.





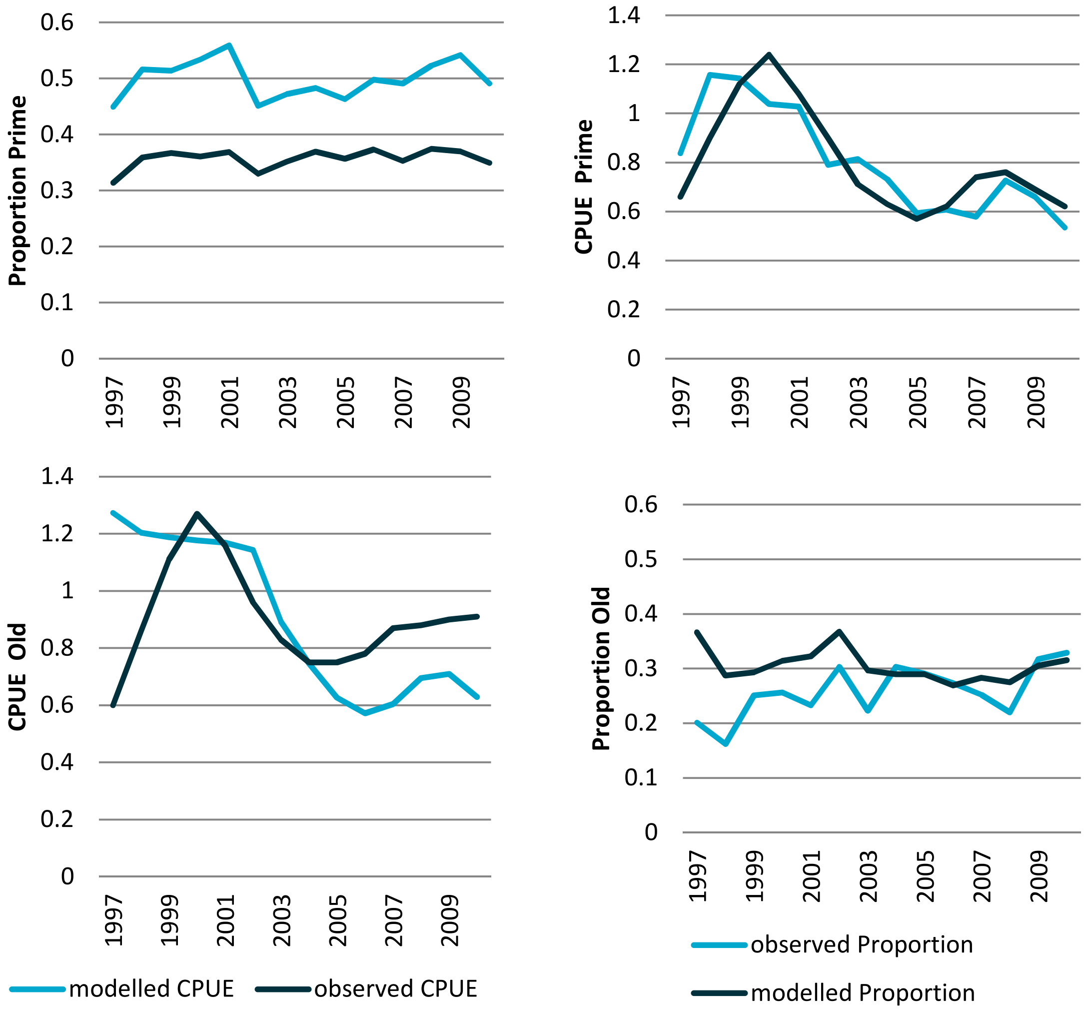
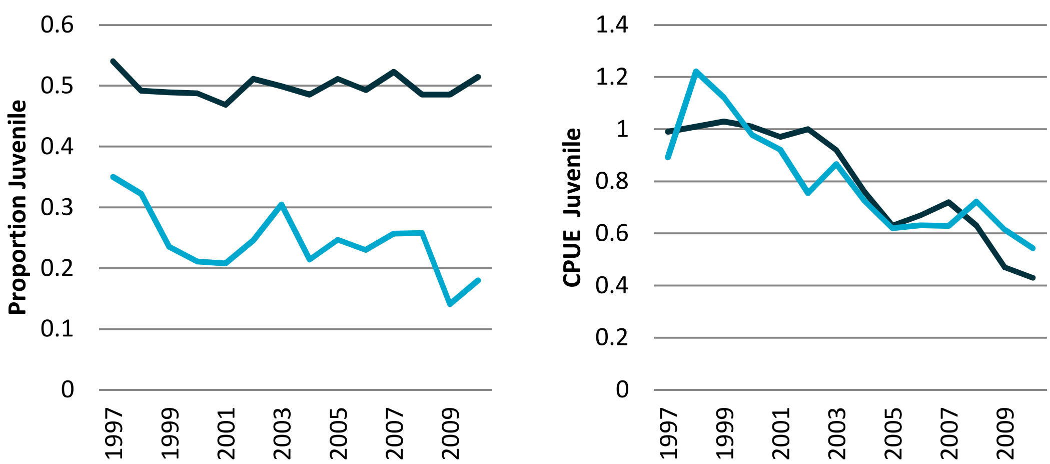


Figure 4 Observed and Modelled proportions and CPUE by size group, from the reference case stock assessment used in the OM. Operating Model: Aus CPUE fitted (in stock assessment: model 004), OM selectivity: Aus area 3 (southern ETBF).



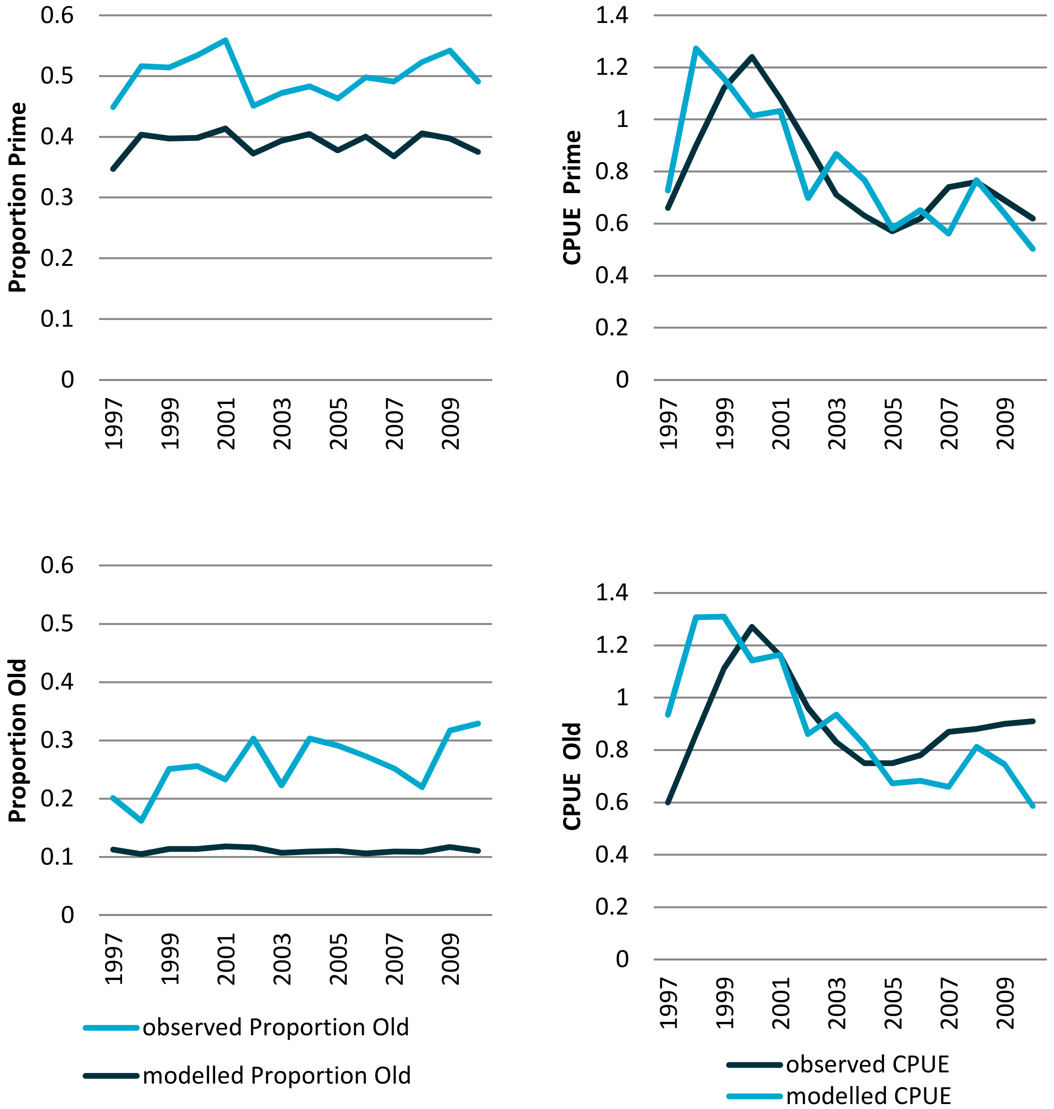
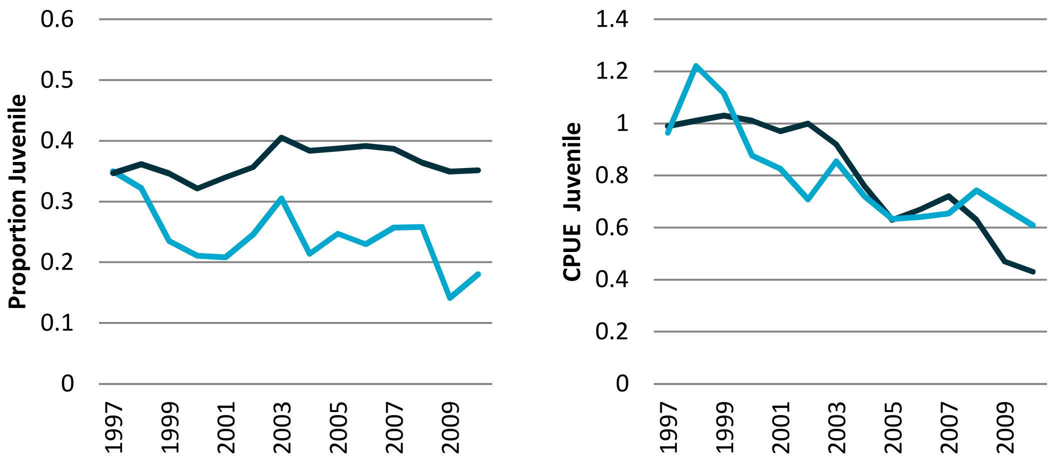


Figure 5 Observed and modelled proportions and CPUE by size class for the OM where Australian longline CPUE series are included, and estimated selectivity from area 2 (northern) is used in catch estimates in the ETBF.



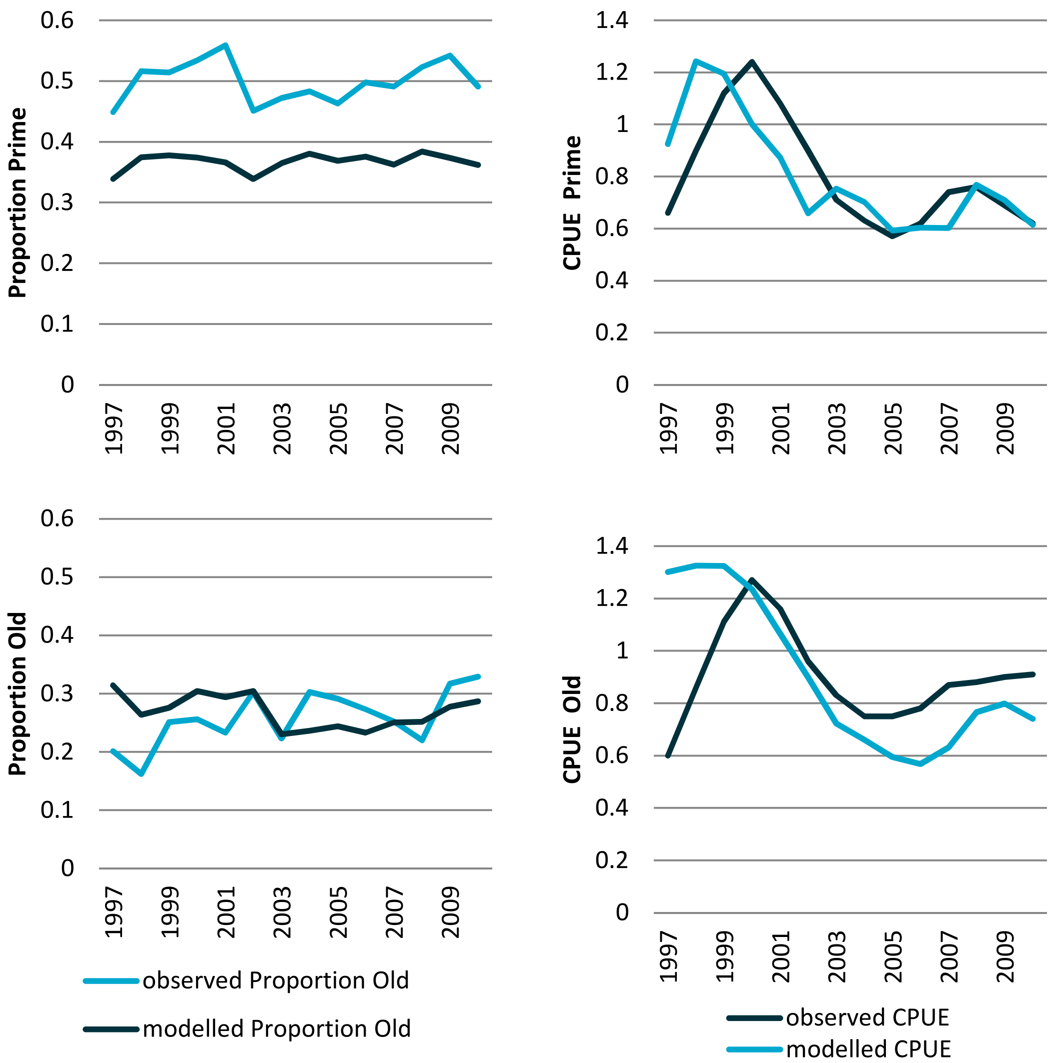
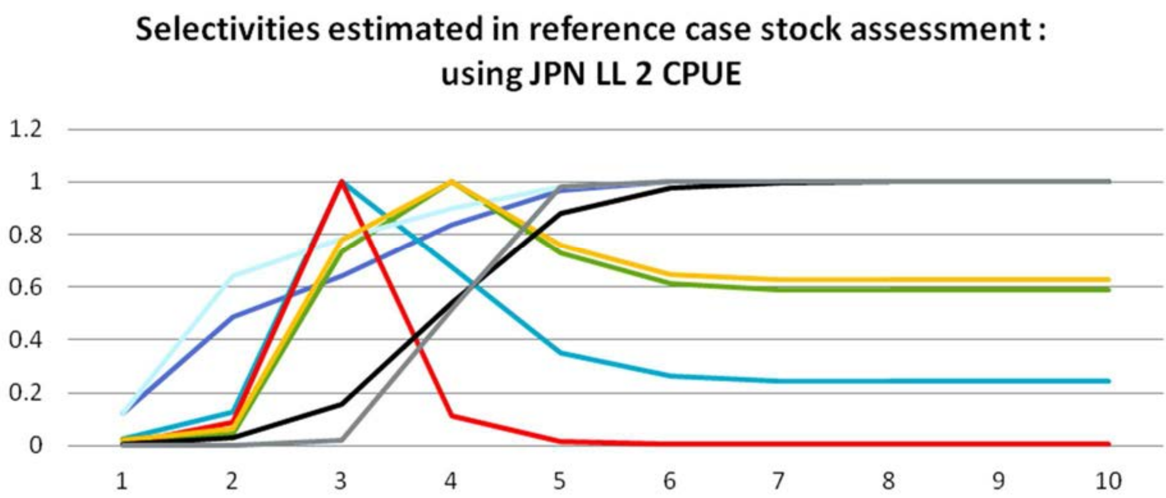


Figure 6 Observed and modelled proportions and CPUE by size group, for the stock assessment using the Japanese longline 2 CPUE. Selectivity in OM is area 3, southern ETBF.



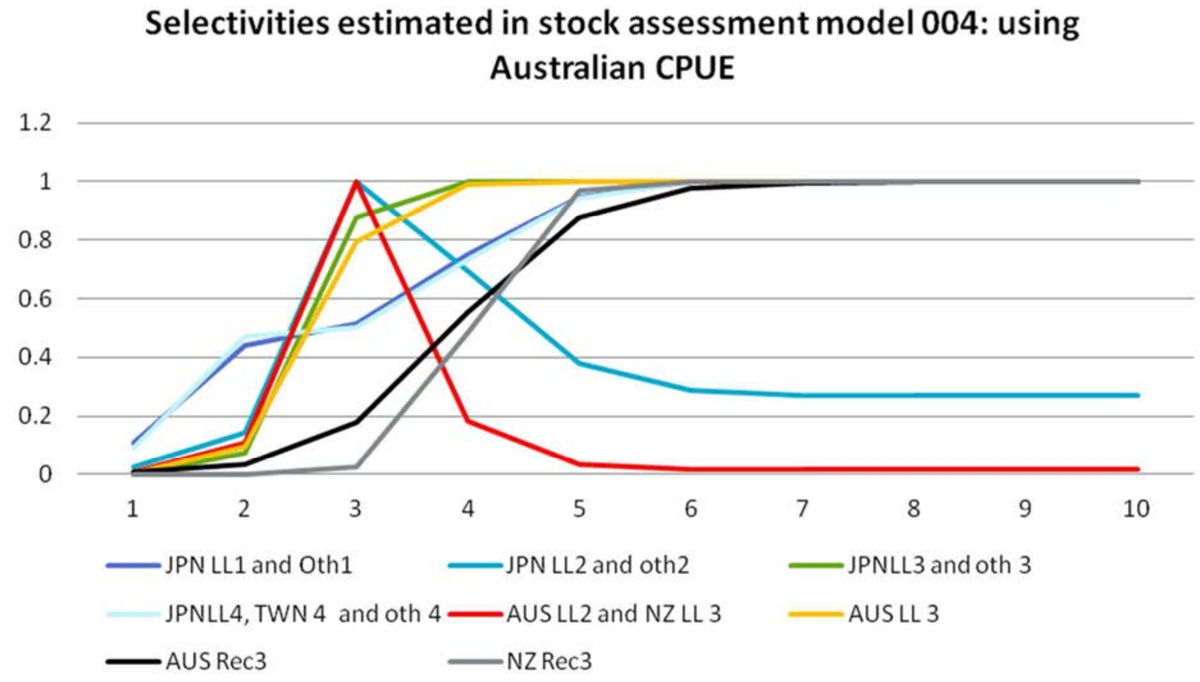


Figure 7 Selectivities estimated in the reference case stock assessment model (top) and for the equivalent model (004) using the Australian CPUE data (Bottom). Note the Australian longline3 (AUS LL3) selectivities (yellow) are quite different for these 2 model runs. For the reference case model selectivity for AUS LL3 peaks at age 4 and then drops for age 5 and is steady from age 6 onwards. In model 004 when the Australian CPUE data are used, the selectivity is a logistic shape with selectivity near 1 for ages 4-10

5.2.3 Effects of inconsistencies

The inconsistency between the observed and modelled size data can have several impacts on the HS evaluation. If the population becomes depleted and skewed in some age classes, then there could be impacts on the CPUE series by age class. From the model runs examined in close detail, there doesn't appear to be evidence of this in the evaluation simulations. Since the AusLL3 selectivity gives reasonable consistency between proportion old observed and modelled, we use this selectivity for the ETBF area in the OMs, and this component of the HS should operate as anticipated.

6 MSE reference set

From the structural uncertainty grid of 229 stock assessment models, 14 were selected as a representative set that covered the range of stock status results from the stock assessment, via inclusion of models which varied by CPUE series, steepness and natural mortality parameter values. The growth and weighting of the size data factors in the stock assessment didn't have a large impact on the range of stock status results, so these weren't considered necessary to include as a factor.

The Reference Set of OM and the projections have the following assumptions based on the reference set used in 2009:

- 14 Maximum Posterior Density(MPD) estimates from the uncertainty grid of stock assessment models (in 2009 only 1 estimate was available)
- Spatial split of the historical estimates of numbers at age: 36 % in ETBF and 64% in non-ETBF.
- Migration options: 20% and 1% per quarter
- Recruitment from a single spawning biomass – recruits are distributed 36% to ETBF and 64% to non-ETBF
- Non-ETBF effort assumed to stay constant at most recent levels
- Selectivity in the non-ETBF area uses the JPN LL 2 selectivity estimated from the stock assessment model.
- Selectivity in the ETBF uses Australian longline area 3 (AUS LL3) selectivity estimated in the stock assessment models.
- Recruitment variability: sd (log)=0.6 autocorrelation rho=0.7, plus additional stochastic error on the 2 youngest cohorts in the first year of projections: age0 sd(log)=0.5, age 1 sd(log)=0.25
- Size composition sampling errors: 1) 70% sampling, magnitude distortion 0 and autocorrelation 0, and 2) 70% sampling, magnitude distortion 0.2 and autocorrelation 0.7.
- CPUE observation error low sd(log)=0.2 rho 0.7
- Implementation error: 0 and 0.2

The reference set comprised: 14 MPD estimates, x 2 migration rates x 2 size composition sampling errors x 2 implementation errors x 10 stochastic realizations per scenario = 1120 projections models.

Since the catches of Striped Marlin in the ETBF have been less than the Total Allowable Commercial Catch since implementation of the HS, the implementation error 0.2 is not included in a reduced subset of the reference set (i.e. implementation error =0 only).

7 Results and Discussion

Results are examined to address the key issues of interest to the TTRAG on the Striped Marlin HS: 1) performance of the harvest strategy relative to the target and limit reference points, 2) impacts of the new data inputs, 3) impacts of connectivity uncertainty on performance of the HS. A process for managing any future changes to the harvest strategy is also discussed.

7.1 Performance of the adopted HS

The performance of the current ETBF HS is examined using the same stock indicators and status measures examined in detail in 2009 (Kolody et al, 2010), which include trends in Spawning Stock Biomass (SSB), CPUE for the Prime size fish, and Catch in the ETBF and non-ETBF area. The figures show the 80th percentile confidence interval of the operating model historical trajectories and future projections estimates, from the full suite of models that were run (i.e. 1120 projections in the reference set). The dotted points are the median of these trajectories, and the single thin black line shows a randomly selected single trajectory. The vertical line indicates where the projections begin. In addition to projections where the ETBF HS sets catches in the ETBF area, a constant zero catch in the ETBF scenario is run, to provide a comparison of the impacts of the ETBF HS on the status and indicator measures.

Under a constant zero catch in the ETBF scenario, with fishing in the non-ETBF area continuing at recent effort levels, the Spawning Stock Biomass trajectories show a wide range of future results, with the lower percentile of the range of trajectories higher than recent SSB levels in the operating models, and the median SSB greater than the 1998 levels (Figure 8). This indicates that SSB would increase under a zero catch in the ETBF scenario. We compare this against the adopted ETBF HS performance for which median SSB also increases to approximately the 1998 level. The SSB in 1998 is used as a simple relative measure because in the original development of the HS these conditions for the fishery were seen as optimal.

In Figure 9, the range of Prime CPUE indicator trajectories are shown for the reference set and the reduced reference set (the reduced set does not include implementation error). In both cases the median of the prime CPUE trajectories increases towards the new target reference point. The lower percentile of the reference set of models rarely falls below the limit reference point in the reduced reference set.

The median of the trajectories hides the variation in CPUE trends over the projection period, as shown in the single trajectory “worm” (thin black line). The wide range of stochasticity and uncertainty built into the reference set also affects the range of trajectories, so subsets of the reference set of models are further explored. In the reduced set where the TAC implementation error is not included (because ETBF catches are below the HS TACC) the mean CPUE recovery trajectory reaches and goes above the target reference point, on average. The risk to the stock is within the terms set in the harvest strategy policy definition of the being above the limit reference point 90% of the time. Performance relative to this risk criterion can be influenced by the range of uncertainties included in the reference set of models. The performance for the reference set and reduced reference set relative to this risk measure resolves the key concern in the previous MSE of performance of the HS.

In Figure 10, the trajectories for the HS catches in the ETBF and corresponding catches in the non-ETBF area (based on continuation of current effort) are shown for the reduced reference set (i.e. with no implementation error). The median of the trajectories in the ETBF indicates a slight long-term decline, however the confidence intervals indicate that the HS will allow for higher catches when conditions allow. This indicates that the feedback mechanism in the HS for Striped Marlin is working. The non-ETBF area catches increase when the ETBF is managed under the HS and assuming that there is a continuation of current levels of effort in the non-ETBF area. Catches of Striped Marlin in the stock assessment area (ETBF and non-ETBF) have declined in recent years.

In summary, the HS evaluation using the reference set demonstrates that the ETBF HS for Striped Marlin can respond to feedback from the stock conditions to set the TACC in the ETBF that will increase catch rates near to the target levels. The modifications to the data inputs do not affect the performance of the HS. The issue of the HS increasing the risk to the stock has been resolved and risk under the reduced reference set examined here is within the guidelines of the Commonwealth Harvest strategy Policy.

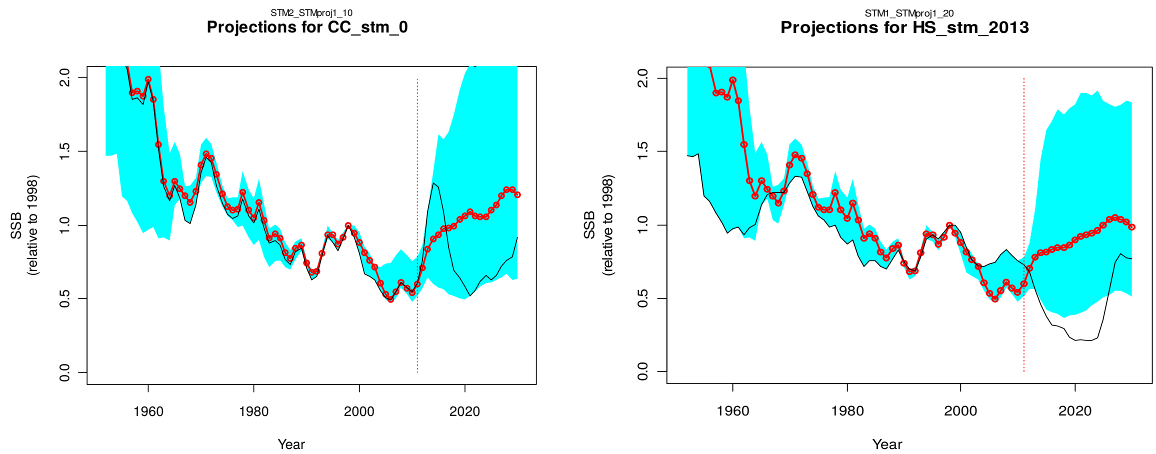


Figure 8. SSB trajectories from the reference set of projection models for the zero constant catch scenario in the ETBF area CC_stm_0 (left), and the adopted ETBF HS Striped Marlin_2013 (right). Red circles indicate median projections, shaded blue region represents the 10th-90th percentiles of the distribution, and the thin black line represents a random trajectory.

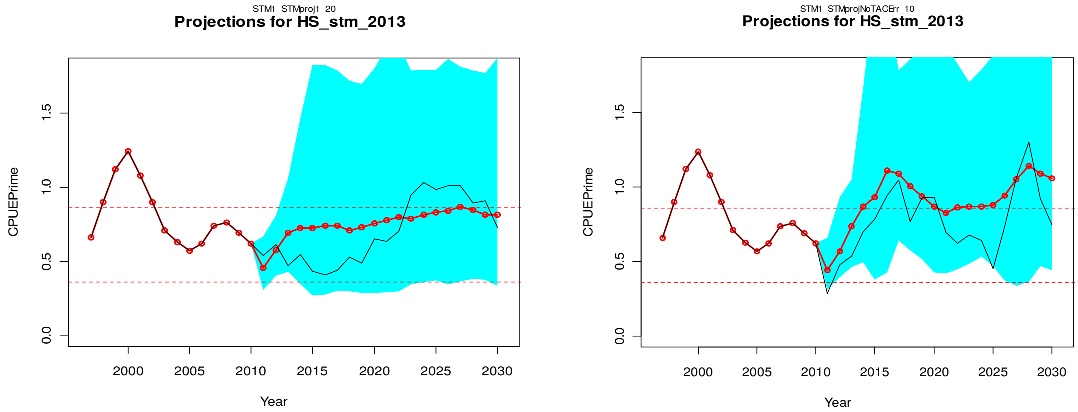


Figure 9. Examination of HS performance relative to the target in CPUE Prime for the reference set (left) and for the reduced reference set with no TAC implementation error (right). Red circles indicate median projections, shaded blue region represents the 10th-90th percentiles of the distribution, and the thin black line represents a random trajectory.

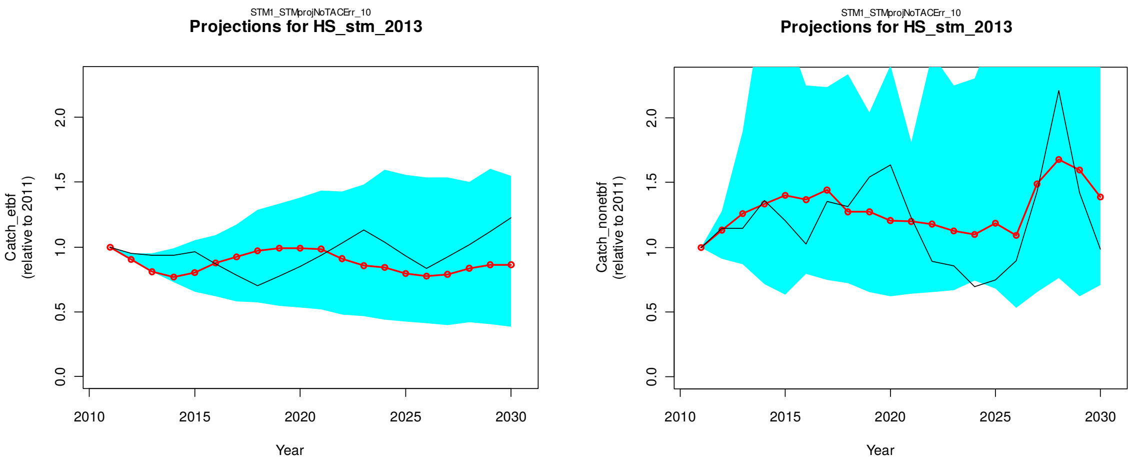


Figure 10. The HS catch trajectories in the ETBF (left) and Non-ETBF area (right) for the reduced reference set (no implementation error). Red circles indicate median projections, shaded blue region represents the 10th-90th percentiles of the distribution, and the thin black line represents a random trajectory.

7.2 Connectivity uncertainty

Stock structure and connectivity are unresolved uncertainties for Striped Marlin, and to account for this the reference set of simulation models includes two migration rates. Figure 11 shows CPUE catch rate trajectories in the ETBF and non-ETBF areas for these 2 migration rates (high 0.2, or low 0.01 percentage migration per quarter). Under these simulation conditions, the low migration rate scenarios (i.e. low connectivity to the non-ETBF area) indicate higher catch rates in the ETBF. In the high migration rate scenarios (i.e. high connectivity between the ETBF and non-ETBF), catch rates are lower.

The Tropical Tuna RAG has also been interested in threshold levels of catch in the non-ETBF area at which the HS recommends TACC that impose economic restriction in the ETBF but have no positive conservation effect. This is a difficult question to answer because of the lack of knowledge in population structure and connectivity between the ETBF and non-ETBF areas.

The HS has previously been tested for robustness to the uncertainties in effort outside of the ETBF (Kolody et al, 2010). Tests of the impacts of higher effort in the non-ETBF area are examined in Figure 12, where the non-ETBF effort has been increased to a very high level of four times the current level of effort. Under this rather extreme scenario, the Spawning stock biomass declines, Catches in the ETBF are heavily reduced and catches in the non-ETBF are higher but constrained by low catch rates. This extreme scenario demonstrates that the HS will respond to negative conditions and cut catches to maintain or increase catch rates.

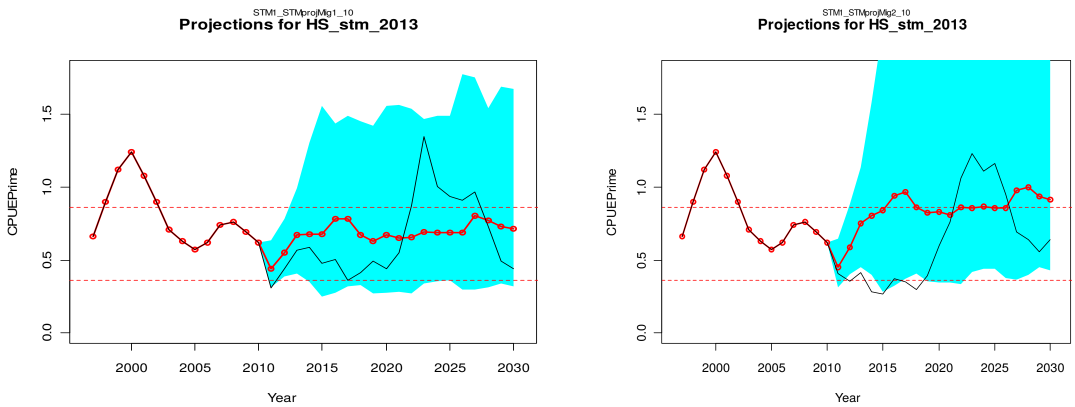


Figure 11. CPUE performance of the HS for the reference set of models for High migration rate between the ETBF and Non-ETBF area (left) and low migration (right). Red circles indicate median projections, shaded blue region represents the 10th-90th percentiles of the distribution, and the thin black line represents a random trajectory.

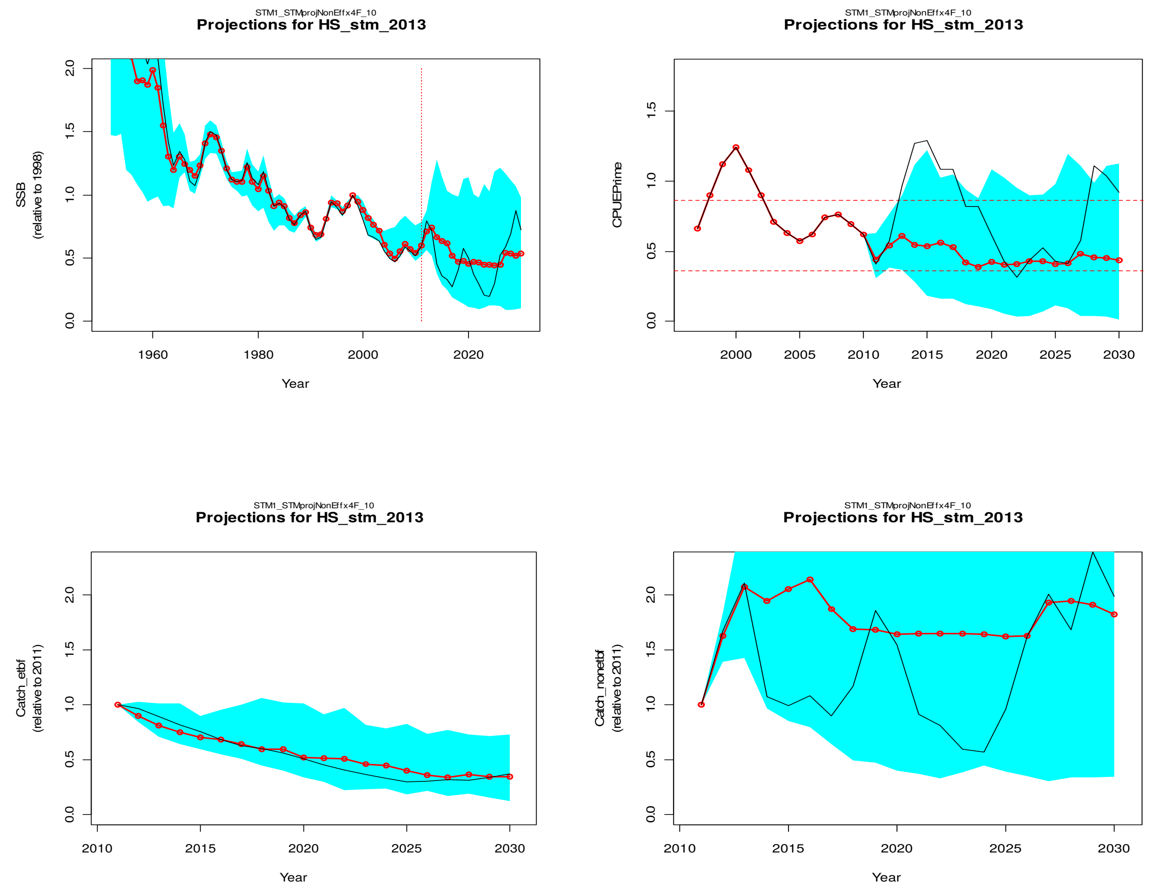


Figure 12. MSE results under the extreme scenario of four times the current effort in the non-ETBF area. SSB trajectory (top left), CPUE Prime (top right), catch in the ETBF (bottom left) and catch in the non-ETBF (bottom right). Red circles indicate median projections, shaded blue region represents the 10th-90th percentiles of the distribution, and the thin black line represents a random trajectory.

7.3 Future changes to the Harvest Strategy

In some fisheries, a management procedure is defined which includes components on data collection, specification of data processing, the specification of the HS decision rule, and rules to follow if there are exceptional circumstances related to management or the stock indicators. As part of this package, the frequency of review of the HS is specified. One of the aims of the specification of a review period is that the HS is not “tinkered with” in the mean-time. The RAG and MAC could consider fixing the HS for some period, setting exceptional circumstances that will occur in the event of indications of stock collapse or incongruent management actions (international or domestic), and set a review period, within which alternatives for the HS might be explored, but not implemented unless MSE tested.

8 Conclusions

This work focuses on an updated management strategy evaluation of the current ETBF harvest strategy for Striped Marlin. The operating models for the management strategy evaluation have been updated using outputs from the most recent stock assessment of Striped Marlin in the WCPFC (Davies et al, 2012) which included new biological information, updated catch data, CPUE series including the Australian CPUE and size data from the Australian recreational fishery. Full reconditioning of operating models was not considered in the scope of the project. The harvest strategy has been re-evaluated relative to new target and limit reference points and other performance measures.

Key results:

- The management strategy evaluation demonstrates that the feedback mechanism in the harvest strategy is working. The HS can respond to improving or worsening conditions by adjusting catches to increase catch rates.
- An issue, identified in the original MSE work, of the HS increasing the risk to the stock has been resolved and risk under the reduced reference set used here is within the guidelines of the Commonwealth Harvest strategy Policy.
- An evaluation of the implications for the harvest strategy performance of different assumptions regarding the connectivity of the stock between the ETBF and non-ETBF areas was conducted. Results showed that if there is low connectivity then higher catch rates could be achieved in the ETBF, than if there is high connectivity.
- The cut-off value of non-ETBF effort, at which the ETBF HS would cut catches for no conservation effect on the stock or catch rate increases, was examined but would require information on the connectivity with the broader SW Pacific stock. Catches in the non-ETBF area have declined in recent years.
- The changes to the harvest strategy input data and reference points have been used in this management strategy evaluation and do not appear to have any impact on performance relative to the previous MSE work (Kolody et al, 2010). A process for incorporating future changes is discussed.

References

Anon. 2013. Minutes of the Seventh Meeting of the Tropical Tuna and Billfish Resource Assessment Group (TTRAG 7). Mooloolaba 24-25 July 2013.

Campbell, R. 2012. Abundance indices for Striped Marlin and broadbill Swordfish in the south-west Pacific based on standardised CPUE from the Australian longline fleet. WCPFC-SC8-SA-IP-13.

Campbell, R. 2013a. Aggregate and size-based standardised CPUE indices for longline target species caught within the ETBF. Working paper presented to the 5th meeting of the Tropical Tuna RAG, held 24-25 July 2013, Mooloolaba

Campbell, R. 2013b. Identifying Target CPUE values for Broadbill Swordfish and Striped Marlin in the ETBF: Information Paper to Tropical Tuna RAG - July 2013. CSIRO Marine and Atmospheric Research, July 2013.

Davies, C. R., J. Prince, N. Dowling, D. Kolody, M. Basson, K. McLoughlin, P. Ward, I Freeman and A. Bodsworth. 2008. Development and Preliminary Testing of the Harvest Strategy Framework for the Eastern and Western Tuna and Billfish Fisheries. Final Report to AFMA, Canberra.

Davies, N., Hoyle, S., Hampton, J. 2012. Stock assessment of Striped Marlin (*Kajikia audax*) in the southwest Pacific Ocean. WCPFC-SC8-2012/SA-WP-05

Ghosn, D., Collins, D., Baiada, C., and Steffe, A. 2012. Catch per unit effort and size composition of Striped Marlin caught by recreational fisheries in southeast Australian waters. NSW Department of Primary Industries. WCPFC-SC8-SA-IP-07.

Kolody, D.S., A.L. Preece, C.R. Davies, J.R. Hartog and N.A. Dowling. 2010. Integrated evaluation of management strategies for tropical multi-species long-line fisheries. FRDC project: 2007/017

Kopf, R. K., Davie, P.S., Bromhead, D., and Pepperell, J. 2011. Age and growth of Striped Marlin (*Kajikia audax*) in the Southwest Pacific Ocean. ICES Journal of Marine Science; doi:10.1093/icesjms/fsr110

Langley, A., Molony, B., Bromhead, D., Yokawa, K, and Wise, B. 2006. Stock assessment of Striped Marlin (Tetrapturus audax) in the southwest Pacific Ocean. WCPFC-SC2-2006/SA WP-6.

Appendix 3: Tropical Tuna MSE and Cost-Benefit Work

Feasibility of "local" assessments for Eastern tropical tuna resources and the costs and benefits of reducing current uncertainties

Currently, the tropical tuna species in the ETBF - Yellowfin Tuna and Bigeye Tuna - are assessed as being part of a wider population and fishery covering the whole Western and Central Pacific Ocean (WCPO). Fishery data (catch composition, total catch and effort), mark-recapture data (where available and usable), and biological data (maturity, growth etc.) are combined together in spatially explicit, highly complex integrated stock assessments (Davies *et al.*, 2014), run by the Secretariat of the Pacific Community (SPC) on behalf of the Western and Cental Pacific Fisheries Commission (WCPFC).

Although the exact spatial stratifications have changed over time, the spatial areas defined in these assessments are driven almost exclusively by specific fishery locations. As such, the ETBF fishery is contained within one (or now two) of these regions along with the non-ETBF long-line fishery. One issue that has existed for both species for some time is that the vast majority of the catch and informative data on abundance is found in the equatorial regions. The MULTIFAN-CL model structures explicitly model catchability commonality (with total area scalings) across the main Japanese long-line fishery across the WCPO - the dominant information source on abundance and trend over time. This means that "local" estimates of tropical tuna abundance in the ETBF are heavily influenced by those from other regions.

Recent stock structure work for Yellowfin Tuna has cast extreme doubt on the current assessment assumption of a single pan-WCPO Yellowfin Tuna spawning population (Grewe *et al.*, 2015; Aquila *et al.*, 2015). Similar issues may exist for Bigeye Tuna, and a recently developed FRDC project proposal will hopefully discover the extent of the structure in all the ETBF main target species within the wider WCPO. At this stage, the ETBF Yellowfin Tuna population is genetically distinct from the closest adjoining population in the equatorial region in and around Tokolau. Indeed, existing tagging data also support low levels of connectivity between the ETBF and the equatorial regions (see connectivity review in this report).

Even with the current assessment predictions for the size and trend in the abundance of both Yellowfin Tuna and Bigeye Tuna, the issue of the impact of the ETBF fleet on those populations has been a major reason for not implementing the current harvest strategy (HS) for those species. With little impact on the population, there is little to no feedback through the HS, and so changing TACs within the ETBF has little to no impact on the population - irrespective of the trend therein. The worst-case scenario would be a continually reducing ETBF catch, driven by a declining trend in the stock abundance, that has nothing at all to do with the ETBF (or perhaps any fleet's) catch levels.

There is, in theory, enough data and connectivity information to attempt to assess the tropical tuna populations within the ETBF in isolation to the wider WCPO. The national benefits would be a better more locally driven idea of the size of these populations and the subsequent increase in understanding of ETBF impact (or lack of it) on the stock. This would then feed into decisions as to whether to maintain the principle of not implementing the ETBF HS for the tropical tuna or not. Additionally we also perform a cost-benefit analysis of exisiting plausible methods for reducing the current uncertainty in both stock connectivity and population size and status in the ETBF region.

Undertaking "local" assessments for tropical tuna

Current WCPO assessments for the tropical tuna have the following general structure:

- Age and length structured population models with a quarterly time-step
- A "box"-type spatial stratification with estimated quarterly movement rates
- Recruitment is estimated for each region and for each quarter, with total recruitment a function of the overall spawning biomass
- Each fishery has its own selectivity function and set of catch composition data (by length and/or weight)
- Data used in the estimation of parameters include: total catch, effort, CPUE, catch composition, mark-recapture data

Obviously, for ETBF-specific assessments we remove the spatial element of the models and we also reduce the complexity of some elements of the model, which reduces the number of estimated parameters and does very little to reduce overall information content. For the ETBF assessments we have the following:

- Age and length structured population models with a quarterly time-step
- Recruitment is estimated for each time-step as a function of the spawning biomass
- Assumed rates of natural mortality., maturity and growth are the same as those used in the WCPO assessments
- CPUE from the ETBF and non-ETBF fleets are both used as abundance indices (i.e. constant but estimated catchability)

- Catch composition by length and weight is converted into age composition data and then used in the model, not converted within the model as growth is assumed constant and known
- Mark-recapture data for both species is not used given known mixing issues
- The spatial extent of the data is a rectangle stretching from 10–40°S in latitude and 150–170°E in longitude.

What is obtained are estimates of spawning stock biomass (SSB), recruitment, and fishing mortality (and impact) for both the ETBF and non-ETBF fisheries. The main aim was to include the salient and informative structures and data used in the WCPO assessments, while reducing what we would consider to be the extraneous complexities therein that add little information for the very high number of additional parameters required. One major difference is that we assume that both the ETBF and non-ETBF long-line fleets are potentially abundance indices - in the WCPO assessments this is *not* the case, as ETBF catchability is assumed to vary over time (Davies *et al.*, 2014). The main reason for this is that, if the ETBF catches *do* significantly impact the stocks in question, and a HS is to be explored, assuming the ETBF CPUE not to be an index of abundance invalidates the HS right from the beginning. There is no information that suggests one CPUE series is any better than the other in terms of being an abundance index, and one could argue the ETBF series has more scrutiny than its counterpart, so we feel this assumption is *a priori* plausible. Although we do point out that the series is only used from 1997 onwards, as the analyses of these data appear to suggest that the assumption of a continuous time-series prior to this year would be unwarranted.

Yellowfin Tuna results

Figures 1 and 2 summarise the fits to the CPUE abundance indices and the catch composition data, respectively, for Yellowfin Tuna and with the "local" ETBF assessment model. For the composition data, a multinomial distribution was assumed (as with the WCPO assessments); for the CPUE data an annual observation error is also imposed with a time-independent additional process error also estimated. Weightings of these data sets were done according to the currently accepted best practices outlined in Francis (2011).

Fits to the CPUE data (left of Figure 1) are very noisy for both series. The general trend of both series is captured, but large process errors are estimated for both also - especially the non-ETBF long-line series (a process error CV close to 0.4). The fits obtained in the "local" assessment are of the same quality as those obtained for the WCPO assessments (Davies *et*

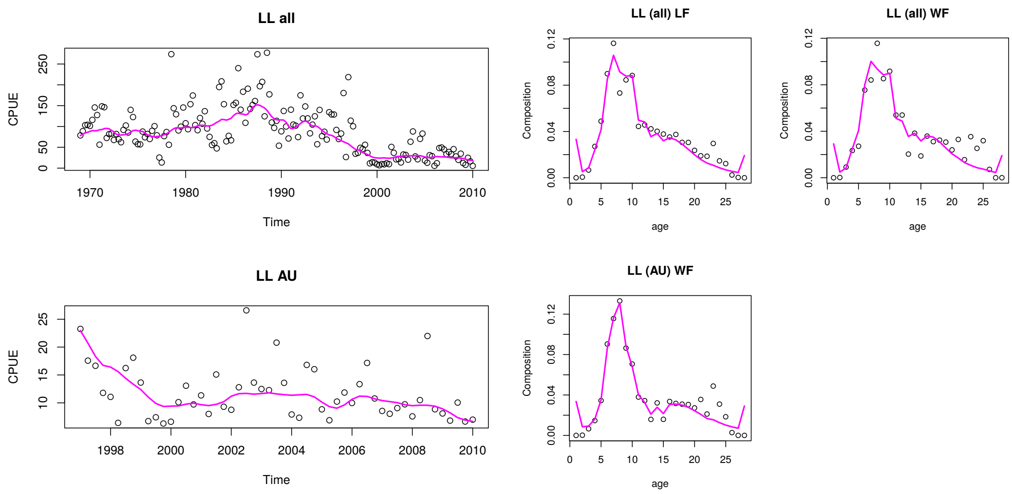


Figure 1: *Fits to the ETBF (LL AU, bottom left) and non-ETBF (LL all, top left) standardised CPUE series and inferred age composition for the non-ETBF length (LL all LF; right, top left) and weight (LL all WF; right, top right) frequency data, and the ETBF (LL AU WF; right, bottom right) weight frequency data. The black circles are the data and the magenta line the model-prediction at the maximum likelihood estimate.*

al., 2014), with respect to the non-ETBF series. Standardised CPUE is noisy across the whole WCPO - even for those series assumed to be proportional to abundance - and this emphasises this issue when we consider that this is the only information available in this region, once we disconnect from the equatorial highly informative zones.

Fits to the composition data (right of Figure 1), weighted by catch and summarised across all time periods for clarity, are generally fine, albeit with some apparent misfit at the youngest and oldest ages where the least fish are caught. They are very comparable to the WCPO assessment fits (Davies *et al.*, 2014), as with the CPUE data, and we assumed a flexible age-specific selecitivity model - free up to age 20 - to avoid overly constraining the model.

Figure 2 shows the historical estimates of the key population and fishery variables: SSB (tonnes), recruitment (in thousands), and *fishery impact*. Fishery impact is define as follows:

1. Calculate the SSB-per-recruit at zero (SPR_0) and annual ($SPR_{\xi_{f,y}}$) estimates of exploitation rate ($\xi_{f,y}$) for each fishery, f

2. For each fishery, calculate $\phi_{f,y} = 1 - SPR_0/SPR_{\xi_{f,y}}$

3. This defines the fishery impact for each fishery

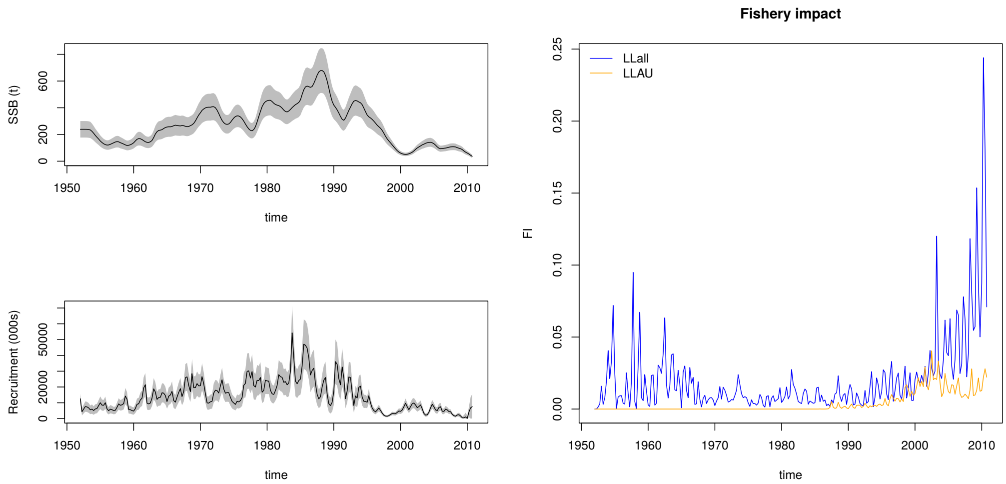


Figure 2: *Historical SSB (top left, tonnes) and recruitment (bottom left, thousands) with maximum likelihood estimate the black line and the grey envelope the approximate 95% CI. On the right is the fishery impact variable for the ETBF (LLAU) and non-ETBF (LLall) long-line fleets, respectively.*

This notion of fishery-specific impact essentially calculates the proportional reduction in the possible spawning stock biomass obtainable from one recruit over its lifetime by each fishery. Values of zero obviously mean no impact; values close to one imply the fishery is taking pretty much everything. The measure ignores the impact of the stock-recruit relationship, but is an easy way too understand relative impact of each fishery on the spawning stock over time.

Clearly from Figure 2 there has been a large change in SSB over time (increase then decline) from 1950 to the present. The recruitment trend is similar, though with an appearance of a lag in the SSB change, relative to the SSB. This, coupled with low fishery impact estimates, is strongly suggestive of regime-driven recruitment and abundance variation with little connection to fishing effort - at least historically. To formalise this look at the plot on the left of Figure 3, showing the correlation between recruitment and SSB (not the other way around) with increasing lag effect on the SSB. If there is a strong stock-recruit relationship this should peak at zero, and decrease afterwards. What we see is in fact a peak at a lag of around 10 quarters (2.5 years) coincident with the point at which the fish begin to hit 50–100% maturity. This clearly shows that recruitment is driving the SSB trends and *not* the other way around.

This fundamentally changes any reading of stock status from Figure 2. Clearly, equilibrium SSB with no fishing, B_0, is *not* stationary, and the $B_0 = B_{\text{initial}}$ type interpretation deeply flawed. In this case we would be close to the limit reference level of 0.2 if we chose to follow

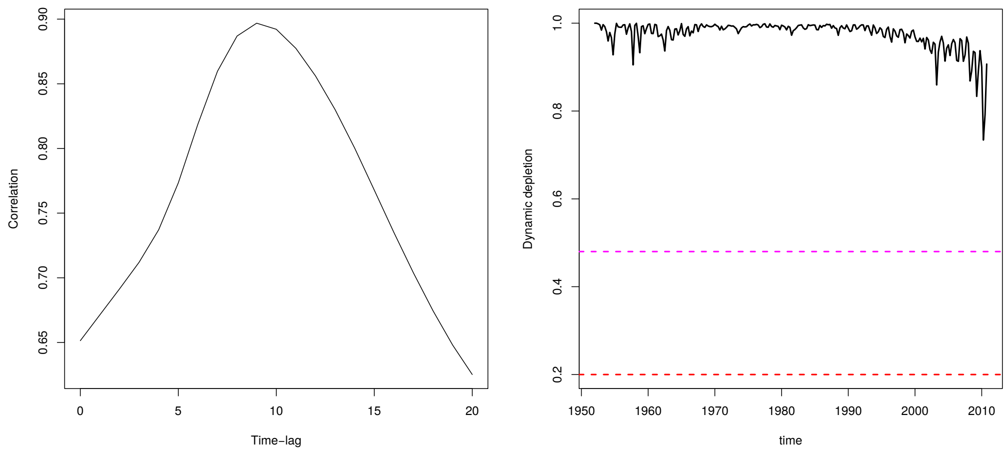


Figure 3: *On the left, the correlation between recruitment and SSB with a given lag applied to SSB, and the lag is in quarters not years. On the left, SSB depletion under the dynamic B_0 paradigm, relative to the target (0.48, dotted magenta line) and limit (0.2, dotted red line) levels of the current HSP.*

that path. The correct interpretation is via the concept of dynamic B_0: the SSB we would expect for the given estimate of current recruitment at zero fishing mortality. The right-hand side of Figure 3 shows the dynamic interpretation of stock status, relative to the current HSP target (0.48) and limit (0.2) levels and gives a very different picture. The depletion level has stayed close to 1 historically and, only recently, as mean recruitment entered its lowest regime observed, has depletion come down to around 0.75 given the increased level of fishery impact, mostly from the non-ETBF fleet.

In summary, there is some information in the "local" fishery data with which to try and estimate population size and status. However, it should be noted that the information is highly uncertain, and alternative model formulations that could be considered plausible if not as "best practice" as this one, gave answers between 50–300% different to this one in terms of absolutes (though not depletion levels). With what we have at present, there is little evidence that the local population exploited by the ETBF is very large or depleted even close to the target levels of the HSP, and that the ETBF has *minimal* impact on the stock. A final point that should be mentioned is that *any* current inferences on the state of the local population are strongly dependent on the assumption that the non-ETBF CPUE is effectively standardised. Given the very large targeting and time-area shifts this fishery has undergone over time, it is always worth taking the results with a measure of uncertainty and potentially bias well in excess of any confidence intervals shown.

Bigeye Tuna results

The same general model structure, *mutatis mutandis* in terms of life-history variables etc., was applied to the Bigeye Tuna data on the same spatial and temporal scales. Figure 4 shows the standardised Bigeye Tuna CPUE for the ETBF (LL (AU)) and non-ETBF (LL (all)) long-line fleets in this region. For the main index, the non-ETBF LL (all) fleet, the series is *very* noisy - more so than for the Yellowfin Tuna - with a general decline in CPUE of around 50–70% from 1969 to the present. For the much shorter ETBF series, while less noisy than its counterpart, it is equally non-informative - a barely perceptible decrease over the 15 or so years of its existence.

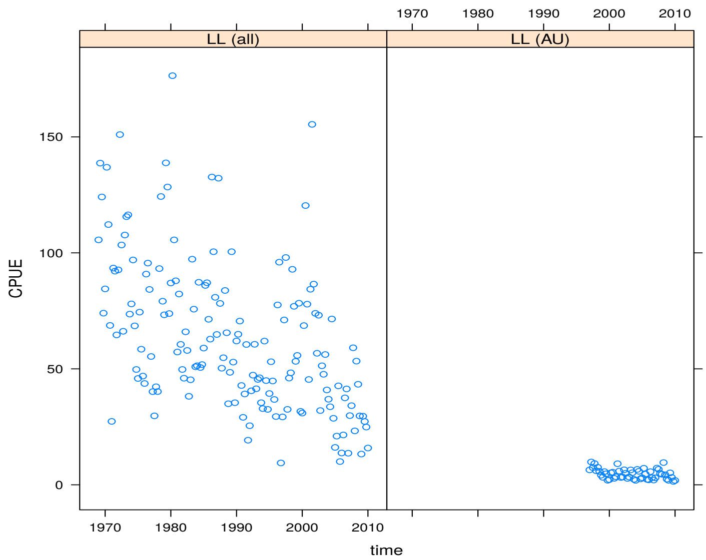


Figure 4: *Bigeye Tuna standardised CPUE for the non-ETBF (LL (all)) and ETBF (LL (AU)) fleets.*

Efforts to obtain a sensible model fit to the Bigeye Tuna data failed. The general problem can be summarised as follows:

- The CPUE data are not very informative, but seem to prefer *very* low stock sizes, with extremely high exploitation rates
- The catch frequency (length and weight) data, uncertain and in some cases showing

notable changes in characteristics over time, generally prefer *very* high stock sizes that are simply not credible

- A range of plausible structures, catchability models (e.g. variable over time for ETBF), data-weighting scenarios simply cause the model to "flip" between one of these two constrasting scenarios

Given the poor mixing characteristics of the tagging data in this region they are also unsuited to providing us with usable abundance information. So, the overall conclusion is that - at present - the available data are either lacking in the requisite information, or contradict each other in their information, making it very difficult to perform a "local" assessment for this species.

Costs and benefits of reducing current uncertainties

At the start of the project, this is issue seemed to refer really to connectivity. As the project developed it really became about three things: (i) connectivity, (ii) population structure, and (iii) abundance. Issues (i) and (ii) both relate to spatial processes, but are very different in terms of the tools available to study them, and sometimes in how the processes themselves occur. One point to make is the relative importance of these issues with respect to stock assessment and management. Often, it is abundance that is far more important than either structure or connectivity when it comes to stock assessment, but the issues around where the fish spend their time and reproduce are *very* important in a management sense.

Connectivity

The project has undertaken an extensive review of what the currently available data say with respect to connectivity for all the major species and we will not reiterate the main conclusions here. What we do focus on is either new data sources, or new methods using of existing data streams, that might be useful in reducing the current level of uncertainty.

With respect to connectivity of highly mobile and migratory pelagic species such as those in the ETBF, the major player is tagging data, though one could include other approaches such as hard-parts micro-chemistry as well. There is a reasonable amount of existing tagging data (conventional, archival, satellite) and it has informed the current state of understanding - see the connectivity review chapter. It is the question one is fundamentally asking that really informs the costs and benefits of particular tagging platforms.

Generally speaking, conventional tags are useful only in a qualitative sense when it comes to movement. Restricted release locations and timings, together with highly heterogeneous fishery effort over both space and time (biasing recapture interpretation). There is a school of thought that simply including all this information in the assessments and then estimating movement internally can avoid this trap, but simulation studies have shown this to be simply asking far too much of the data. What conventional tags have told us to date are that some fish do move between regions, and sometimes large distances, but a lot of them don't seem to do so.

Electronic forms of tagging data have been the most informative, as one might expect, given we do not need to infer the dynamics between release and recapture; we have a full history, albeit with errors and potential biases that need accounting for. Archival data have the potential to be the most informative simply because of the number of things they can measure and how long they can measure them for. Satellite tags struggle in this regard as they really give information on location (and maybe local conditions) and are difficult to keep running for multiple years. On the other hand, archival tags require fishery recapture in general, so one needs enough of them to ensure enough are recaptured to be informative; with satellite tags this is not the case.

Taking the simplest case of asking if fish from area A and area B ever mix into regions other than those they were released into. At the most basic statistical level, if the hypothesis was no mixing, then for each region one would want to have 20 tags that demonstrated no mixing - so 40 in total. Simple releasing 20 in one zone and, in the result of no mixing being seen, declaring that the regions do not mix totally misses the point that there could be total mixing from the unobserved region. So 40 tags in total would give us the usual p-value of 0.05 in terms of rejecting the null hypothesis of mixing. For satellite/pop-up tags this is easy to achieve. For archival tags we have to release enough so that the expectation is we will receive 40 returns. Taking the Yellowfin Tuna levels of fishing mortality and assuming very good reporting rates that would take 500–1000 archival tags! Financially, and even logistically, satellite tags win out every time *if* this is the question we are asking. If the question was movement over longer time frames we then run into issues around diminishing returns for releasing more and more satellite tags given their often more limited lifetimes.

Population structure

Outside of specific situations whereby archival tags could measure key biological triggers of spawning behaviour, or where satellite tags could be linked with fishery surveys to validate spawning activity, tagging data cannot generally tell us anything directly about stock structure. Although promising much historically, it is only recently that genetic techniques have progressed to the kind of level required to undertake detailed, and informative, stock structure analyses on the kinds of scale international fisheries occur at.

Structure and connectivity are coexistent processes in species like tuna and other scombrids. One can have no structure with a high degree of asymmetric connectivity (i.e. where movement parameters across regions are relatively unconstrained and estimated as currently assumed for all the WCPO assessments), or the opposite. Both are very important but really structure has the added importance of relating to what the management units should be. At the RFMO level maintaining the fishing mortality at or below F_{msy} and the spawning population at or above B_{msy} is what drives management efforts, but stock structure (i.e. multiple spawning populations within the designated "stock" being managed) complicates how this works and - crucially - who is supposed to make it happen. One of the main questions of this project is really about this wider issue: how do national and international management processes work for trans-boundary fish populations?

The population of Yellowfin Tuna harvested by the ETBF has recently been thrown into this situation by the clear detection of stock structure between the ETBF region in the Western Pacific and around Tokolau in the Central Pacific (as well as with a control population in the Eastern Pacific around Baja) (Grewe *et al.*, 2015). Current assessments and attempts at management action assume that the WCPO is a single spawning population for Yellowfin Tuna (for all tropical species in fact; temperate stocks are assumed to be split at the equator). If future analyses reveal this structure across the WCPO, which seems likely, this essentially means that totally new assessment structures are required and further complicate an already fraught management landscape. Population structure, by its very nature and given the management requirements of tuna RFMOs, will mean spatial management of the Yellowfin Tuna will become the default approach for the WCPFC simply because adjusting total WCPO catch, effort or capacity levels conditional on current assessments has no sound basis from which we would expect it to every actually work.

To give an example of the likely costs involved in undertaking a wider stock structure project let's use the Yellowfin Tuna example. There are five **major** regions (and more sub-regions to deal with tag release issues) in the current assessment structures. Now in reality, there may be more or less regions when one deals with this stratification in terms of hypothesised population structures - see the connectivity review. But let us take five for now. To be able say anything statistically significant we need a minimum of 50 fish per region, and current costs sit at around $40-50 per fish (taking 50 as the maxmimum). For a one-time sampling strategy that would be 5 x 50 x 50 = $12,500 to genotype all the samples. Sample collection and post-genotyping analyses have additional costs attached that vary by location and research provider so we focus on the genotyping costs here.

This is easily scalable in terms of additional regions and species of interest, but it is clear that obtaining the kind of detailed genetic information from which to accurately categorise stock structure is now quite cheap - and will get cheaper over time. We would argue this type of study is an effective no-brainer given (a) the costs relative to large-scale tagging programs (that cannot generally elucidate stock structure); (b) the fact that there is a current major gap in the knowledge around stock structure in the WCPO for all species; and (c) that, at least for Yellowfin Tuna, when looking for structure it appears to be there and with attendant major assessment and management implications.

Abundance

One of the key outcomes of the tropical tuna related work in this project is actually how weak the abundance information is, once it is uncoupled from the equatorial regions in the WCPO assessments. Given the apparent lack of precise information for Yellowfin Tuna, or any real consistent information for Bigeye Tuna, some form of tagging seems the only only likely workable option.

The three main candidates are:

- Conventional mark-recapture (CMR): as with previous spaghetti tag-type programs in not just the WCPO but all the various tuna tagging programs
- Genetic mark-recapture (GMR): similar to conventional mark-recapture, but using a biopsy sample before release, and subsequent DNA scanning of fish in the future catch, as the mark and recapture process.
- Close-kin mark-recapture (CKMR): a novel approach that uses DNA matches between closely related animals (e.g. parent-offspring) to estimate the size (and survival rate) of the adult population

Conventional mark-recapture

The advantages of this approach are twofold: (i) it has a long and fairly successful history in pelagic applications, often yielding informative data on mortality rates and/or abundance, and (ii) the models required to use the data are also well established. The main disadvantages of conventional mark-recapture are its high release costs, and the problem of both recovering tags from the fisheries and estimating the reporting rates thereof.

In a simplistic sense, in terms of costs, we need to separate into fixed and variable costs: hiring the boat is a fixed cost, with tag purchase and labour time associated with releasing them a variable one. The fixed costs usually dominiate - it is very expensive to charter a boat and staff it whether you are releasing 100 or 10,000 tags. But there is a variable cost involved also as it takes time for well trained taggers to capture, tag and release animals. The follow on costs are twofold: (i) establishing a tag return fund to pay for the returned tags from the fishery, and (ii) establishing a tag-seeding or other detection program (like PIT tags) in the various fisheries to estimate the reporting rates.

Genetic mark-recapture

The main advantages of CMR are also shared by GMR - it might not have a long history in marine applications but it is the same data as CMR released form the same type of platform. The additional advantage of GMR over CMR is the lack of a need for reporting rates or any tag loss over time. For the same release numbers, *pro rata*, one will always get more recaptures from GMR just because (a) if we find a tagged fish and test it we will never miss it, and (b) the tag itself (DNA) is never lost by the fish.

The main disadvantage of GMR is that one has to also initiate the recapture sampling process - the fishery can never see a tagged fish and know it to be tagged - so additional sampling is in order to find them again. This comes with additional costs, albeit far lower than for releasing them.

The obvious control variable for any such program is the expected CV in the target population variable - abundance or fishing mortality. The fundamental comparison is then, for a given CV, which approach comes in cheapest? In the head-to-head comparison between CMR and GMR this really is decided by the following trade-off: is the rate of information (tag) loss from CMR arising from tag shedding and lack of reporting of tags enough when compared to the higher costs of the DNA and recapture sampling required for GMR?

Close-kin mark-repcapture

CKMR is a novel approach, whereby the detection of closely related individuals can give us information on the absolute abundance (and other variables) for the reproductive part of the stock (Bravington *et al.*, 2014). The first example, done for Southern Bluefin Tuna, used the detection of parent-offspring pairs (POPs), given the sampling possibilities available for both the juvenile and adult parts of the stock. Another approach, recently applied to Great White sharks in Eastern Australia, uses the detection of half-sibling pairs (HSPs), to estimate adult abundance and survival rates (Bravington *et al.*, 2016).

We focus on the HSP approach for ETBF applications because: (i) we cannot guarantee to be able to sample adult spawning fish, and (ii) the range of animals we do see - for example between 1 and 3 years old for Yellowfin Tuna - makes the HSP approach more sensible as we can guarantee recent estimates of abundance and survival. The theory is moderately simple:

- Consider two juveniles i and j
- The further apart their respective birth years (cohorts), c_i and c_j, the less likely they are to be HSPs (parents less likely to still be alive)
- The bigger the adult abundance in the latest birth year, the less likely they are to be HSPs (less likely to randomly find a half-sibling from a bigger pool of putative parents)
- A positive/negative growth rate in the adult population *between* their birth years makes it less/more likely they will be HSPs (relates to previous point)

We can, in fact, formalise this into a probability of juveniles i and j being HSPs, and we assume a constant adult population size N and total mortality rate Z for simplicity:

$$p_{\text{hsp}} = \frac{4\exp(-Z * \tau)}{N},$$

where $\tau = |c_i - c_j|$ is the number of years between the respective births of the two samples. For teleosts, we would wish to avoid within-cohort comparisons (one gets over-representation of HSPs and we also have to deal with full-sibling pairs too then). So, for a one-off sampling approach, it is most efficient to sample $\mathcal{M}$ fish from one cohort and $\mathcal{M}$ fish from another - one younger fish this length-range is well defined and is, in principle, feasible. Modern genetics is now at the stage where we can definitively find HSPs, so we can just assume this part of the process, and say we found R HSPs in this sample of $2\mathcal{M}$ fish - more correctly in the $\mathcal{M}^2$ comparisons between the fish. Our estimate of population size, $\widehat{N}$, is then given by

$$\widehat{N} = \frac{4\mathcal{M}^2\exp(-Z * \tau)}{R},$$

with a CV close to $R^{-1/2}$. In practice we can, and should, include more of the life-history (and relative contribution of each age-class) in the calculations. However, the simple model above will suffice in gauging roughly what sample sizes would be required.

Comparing across methods

It is difficult to include CMR at this stage because we have no *a priori* idea what tag loss and reporting would be. We can compare GMR and CKMR though, and discuss scenarios for which CMR is likely to be (a) feasible, and (b) comparable in cost to GMR. Using the most recent estimates of Yellowfin Tuna abundance from the ETBF assessment model describer herein, we look to obtain abundance estimates with a target CV of 25% for both approaches.

For GMR, the logistics of tagging tuna require us to tag from schools of very small fish - note we ignore the potential mixing issues that go along with this process for now. That means that we must tag *enough* fish for there to still be a large enough number in the exploitable population as they move through the age-classes that dominate the main ETBF catches. With current estimates of M and F (and ETBF-exploitable abundance) we would require 16,000 releases and 6,000 repeat biopsy samples to get an estimate of current exploitable abundance at the target CV - so 22,000 samples in total. For CKMR, assuming we can target cohorts that are - at most - two years apart, then we would require $\mathcal{M} = 4,000$ samples of each cohort, so 8,000 in total, to get an estimate of adult abundance at the target CV.

When it comes to relative genotyping costs, GMR is approximately \$10 per fish; CKMR using HSPs is around \$25 per fish. As more fish are required to be genotyped for GMR because of the high attrition rate and need to tag very small fish, even for much lower genetic costs it still costs \$220,000 versus \$200,000 for CKMR. For GMR we also have to include the costs of chartering the tagging boat and paying labour costs for taggers. So it is clear, for this example, that CKMR would be the best option relative to GMR.

Given tag loss and reporting issues, we would clearly have to tag a lot more fish for CMR relative to the GMR numbers detailed here. This would very likely include additional chartering and labour costs - both of which are high. Also, we would need to instigate a tag seeding program and fund a tag awareness and return program for CMR, which both cost money. As to whether these would offset the lack of a need to genotype samples, this is difficult to say without a lot of detailed costings. One thing we can see is that previous CMR projects across the tuna world have rarely fully delivered on their initial goals, and often come with sometimes unassailable problems.

The last, and perhaps best argument for CKMR outside of costs, is exactly *what* it estimates, relative to both CMR and GMR. At the international level, management of tuna stocks generally interprets some form of the Kobe-type paradigm: (i) stocks should not be in an over-fished state ($SSB \geq B_{\text{msy}}$); and (ii) stocks should not be experiencing overfishing ($F \leq F_{\text{msy}}$). At the national level the Commonwealth Harvest Strategy Policy dictates that the level of SSB depletion (relative to the unfished state), where a robust estimate of MEY and MSY are not available, should have a target level of 0.48 and a limit level of 0.2. In either of these management paradigms, the spawning population forms one (Kobe) or is the primary (Commonwealth HSP) management index. Both CMR and GMR estimate *exploitable* abundance not spawning abundance; the latter must be inferred from the former using the available life-history and assessment model structure. With CKMR we are able to estimate what we are really interested in, namely the reproductive part of the population.

Discussion & Conclusions

In this chapter we have explored two key issues relating to the implementation (or otherwise) of the ETBF harvest strategy for the tropical tuna species:

1. In the light of recent results suggesting a "local" population of Yellowfin Tuna, are the current data informative enough to assess the size and status of the populations, and the ETBF's impact thereon

2. What are the pros, cons, costs and benefits of various approaches with respect to reducing the current levels of uncertainty in not just connectivity with the wider WCPO, but stock structure and local abundance

In terms of the feasibility of "local" assessments for the tropical tuna species:

For the Yellowfin Tuna, the information content in the standardised long-line CPUE (both ETBF and non-ETBF) and the catch composition data is not very strong, with the absolute (not the relative) abundance highly dependent on which type of data weighting scheme on follows. That being said, the estimated dynamics suggest that recruitment fluctuation, not fishing effort, appears to the historically dominant cause of abundance variation, with low impact from the non-ETBF fleet and little impact from the ETBF. For the Bigeye Tuna the data are even more noisy, and the CPUE and catch composition say totally different things to the degree that one cannot attain any kind of stable and sensible estimates of absolute abundance In relation to reducing current uncertainties around connectivity and structure, there is little hope that conventional tagging programs will increase the current state of understanding along with their more direct use in stock assessments. Satellite tagging, via pop-up tags for example, is still a more cost-effective platform relative to archival tags *if* the focus is on getting decent sample sizes for shorter term (i.e. up to about 1 year) movement patterns. Still the biggest remaining uncertainty is in relation to stock structure, in terms of spawning populations and for all the major target species. Recent work has shown that structure already exists between two close regions within the WCPO for Yellowfin Tuna (Grewe *et al.*, 2015), yet a contiguous spawning population is currently assumed for all assessments and species. Current genetics, in terms of both costs and accuracy, is the clear winner in terms of a platform likely to answer these questions at the lowest cost, and we detailed some simple genotyping costing scenarios for the various species throughout the WCPO region. If further analyses show that the smaller scale structure seen for Yellowfin Tuna does indeed exist (and for other species too) the implications for the wider management of the fisheries resources in the WCPO are immense. From both a research-for-management and costing position, the future analysis of the genetic structure across both the region and the main species should be a high priority.

For yellowin tuna at least, given the apparent spawning isolation of the stock the ETBF harvests, we can no-longer really rely on the current estimates of abundance from the WCPO assessments. As demonstrated herein, the fishery data is not informative enough to allow "local" assessments, so we explored what alternative data sources might be applicable, and what they cost relative to each other. We explored three types of mark-recapture: conventional (CMR), genetic (GMR), and close-kin (CKMR). Both CMR and GMR are largely comparable in terms of release costs - CMR needs more releases due to tag loss and reporting issues and requires tag reward/seeding projects for collection, but GMR costs more per-tag because of genotyping of releases and recaptures. It is much easier to directly compare the costs for GMR versus CKMR and, in this regard, the half-sibling pair approach to CKMR (Bravington *et al.*, 2016) was a clear winner for the Yellowfin Tuna example detailed. While the costs for the genotyping of fish is higher for CKMR, the high loss of fish gene-tagged at a necessarily very young age are such that they outweigh the costs of the CKMR approach. For GMR you have to tag so many more fish to get the same number of recaptures at the older ages in the fishery, relative to the CKMR approach, that it ends up costing more. We note, however, that this is *very* much dependent on this particular example. The CCSBT is currently undertaking a GMR program for estimating juvenile tuna abundance and here the issues that affect the tropical tuna case do not apply: (i) there is no need to tag very small fish and wait a number of years to recover them again; (ii) the recapture platform (the tuna farms) is ideally for undertaking a large-scale resampling program; and (iii) the costs of GMR relative to the current aerial survey are effectively the same, but we obtain absolute - not relative - abundance.

Summing up, of all the remaining uncertainties pertaining to the main target species in the ETBF, stock structure within the WCPO (and potentially beyond) and reliable data for estimating abundance are the two most prominent ones. In relation to stock structure, we have outlined some general approaches (and actual $ amounts) for the costing of the genotyping of fish and how that should be structured across putative stock "units" to obtain informative data. Relative to the costs of large-scale tagging programs, these costs are now much lower thanks to advances in recent genotyping technology. In terms of abundance, using the Yellowfin Tuna example of a local stock, we demonstrated that genetic mark-recapture is preferable to conventional mark-recapture, and that close-kin mark-recapture is cheaper than genetic mark-recapture in terms of obtaining abundance estimates with a pre-specified precision. While it would take more work, we suspect this is true across all the target species in the ETBF. If the stock structure work is completed in the near future, and we have a better idea of the reproductive structure in the WCPO (and beyond), we suggest that close-kin mark-recapture approaches will be a very informative source of abundance and survival data for the key reproductive part of the population age-structure.

References

Aquila, R. D., Perez, S. K. L., Catacutan, B. J. N., Lopez, G. V., Barut, N. C., and Santos, M. D. 2015. Distinct Yellowfin Tuna (*Thunnus albacares*) stocks detected in Western and Central Pacific Ocean (WCPO) using DNA microsatellites. PLoS ONE. **10**(9): e0138292

Bravington, M. V., Grewe, P. G., and Davies, C. R. (2014) Fishery-independent estimate of spawning biomass of Southern bluefin tuna through identification of close-kin using genetic markers. FRDC-2007/034, Canberra, Australia.

Bravington, M. V., Skaug, H. J., and Anderson, E. C. (2016) Close-kin mark-recapture. Stat. Sci. (in press)

Francis, R. I. C. C. 2011. Data weighting in statistical fisheries stock assessment models Can. J. Fish. Aquat. Sci. **68**: 1124–1138.

P.M. Grewe, P. Feutry, P. L. Hill, R. M. Gunasekera, K.M. Schaefer, D. G. Itano, D.W. Fuller, S. D. Foster and C. R. Davies. 2015. Evidence of discrete Yellowfin Tuna (*Thunnus albacares*) populations demands rethink of management for this globally important resource. Nat. Sci. Rep. **5**: 16916.

Davies, N., Harley, S., Hampton, J., and McKechnie, S. Stock assessment of Yellowfin Tuna in the Western and Central Pacific Ocean. WCPFC-SC10-2014/SA-WP-04.

Appendix 4: Stock structure and connectivity of the principal target species of the Eastern Tuna and Billfish Fishery: a review of research conducted and current understanding.

Stock structure and connectivity of the principal target species of the Eastern Tuna and Billfish Fishery: a review of research conducted and current understanding.

1. Introduction

Commercial fisheries within Australia target a number of pelagic species that have broad distributions at the scale of ocean basins. Fisheries targeting these species comprise multiple fleets from a number of nations, which fish both within and outside country Exclusive Economic Zones (EEZ) across the range of these species. Because of the extensive distributions of pelagic species harvested and the associated distribution of the fleets that target them, management of these species often occur at both the national and regional level. Within Australia, there are five fisheries associated with pelagic species that are managed at multiple scales; these include the Southern Bluefin Tuna Fishery, Eastern Tuna and Billfish Fishery (ETBF), Western Tuna and Billfish Fishery (WTBF), the Eastern Skipjack Tuna Fishery (ESTF) and the Western Skipjack Tuna Fishery (WSTF). Management of these fisheries occurs at the national level within the Commonwealth Harvest Strategy framework (with the exception of southern bluefin tuna which is managed under the Southern Bluefin Tuna Fishery Management Plan) and also at the international level by Regional Fisheries Management Organisations (RFMOs).

The largest fishery (by value) targeting pelagic species within Australian waters is the ETBF, which operates along the east coast of Australia. The fishery primarily targets Yellowfin Tuna (*Thunnus albacares*), Bigeye Tuna (*Thunnus obesus*), Albacore (*Thunnus alalunga*), Swordfish (*Xiphias gladius*) and Striped Marlin (*Kajikia audax*). A number of other species are caught as byproduct and bycatch (see Larcombe et al. 2011; Patterson et al. 2013) by the fishery. Populations of the main target species are known to extend well beyond the Australian EEZ and those individuals occurring within Australia's EEZ are currently considered to form either part of a wider western and central Pacific Ocean population or a Southern Hemisphere component of a western and central Pacific Ocean population (Davies et al. 2011; Langley et al. 2011; Davies et al. 2012; Davies et al. 2013; Hoyle et al. 2012). At the international level, populations in the western and central Pacific Ocean are managed under the auspices of the Western and Central Pacific Fisheries Commission (WCPFC), to which Australia is a member and regularly contributes. Stock assessments for individual species are conducted under the framework of the Commission and advice from stock assessments is considered in the formulation of suitable Conservation Management Measures (CMMs) such as limits on spatial operations, capacity restrictions, or catch levels for member states.

Although species in the western and central Pacific Ocean are considered to comprise either one stock or two within each hemisphere under current regional management regimes, the degree of connectivity across the regions at which they are assessed is still a major source of uncertainty (Gunn et al. 2002; Gunn et al. 2005; Itano et al. 2008; Evans et al. 2013; Nikolic and Bourjea 2013). Genetic studies conducted to date on the five species have primarily focused on determining the level of genetic structure at the global level, focusing on potential structure between ocean basins (Alvarado Bremer et al. 1998; Graves and McDowell 2003; Viñas et al. 2004; Montes et al. 2012). Those that have investigated potential structure within the Pacific Ocean basin have been inconclusive and generally limited by small sample sizes (Scoles and Graves 1993; Ward et al. 1994; Rosel and Block 1996; Grewe and Hampton 1998; Reeb et al. 2000; Appleyard et al. 2001; Chiang et al. 2006).

There is growing evidence from catch and tagging data that there is some degree of structure within populations of some species in the Pacific Ocean (Evans et al. 2008; Evans et al. 2011; Evans et al. 2013; Hoyle et al. 2013; Kolody and Hoyle 2013) and that this structure may occur at levels higher than previously thought. This has implications for any management measures put in place at both domestic and regional scales. Without some knowledge of the degree to which populations are connected management measures such as total allowable commercial catches (TACC) set under domestic structures may not match regional management measures and may unintended economic impacts on the domestic fishery if carried out independent of regional management (DAFF 2013).

Domestic harvest strategies for Commonwealth fisheries, including the ETBF, have been developed and implemented by the Australian Fishery Management Authority (AFMA) under the Commonwealth Harvest Strategy Policy and Guidelines developed by the Department of Agriculture, fisheries and Forestry (DAFF; DAFF 2007). The harvest strategy developed for the ETBF aims to provide a means by which assessments of each of the five principal species (Albacore, Bigeye and Yellowfin Tunas, Swordfish and Striped Marlin) can be produced and a Recommended Biological Commercial Catch (RBCC) determined. The RBCC is then used to set a TACC for each of the species. In doing so, the harvest strategy aims to provide for rebuilding of overfished stocks, enable sustainable development of emerging fisheries and reduce inter-annual variability in TACCs, thereby providing stability to the fishing industry. There are however, a number of situations relevant to the ETBF which complicate the implementation of harvest strategies for the key five species targeted by this fishery: (1) prescription of management arrangements for highly migratory/straddling or joint authority fisheries stocks; (2) maintenance of all species within multi-species fisheries at target reference points; (3) uncertainty and variability in reference point definitions; and (4) quantification of uncertainty and risk and associated setting of thresholds (DAFF 2007; Kolody et al. 2010).

An initial harvest strategy framework capable of being applied to for the five main target species was finalised in 2006 (Figure 1.1; Davies et al. 2008) and was subsequently used to inform the setting of total allowable effort for the 2009-11 fishing season in the ETBF. Following the development of the framework, comprehensive evaluation in order to produce fully specified harvest strategies using a detailed management strategy evaluation (MSE) framework was undertaken (Kolody et al. 2010). Across all five species, the harvest strategy framework demonstrated sensitivity to population connectivity, the effects of the non ETBF fleet (the wider western and central Pacific Ocean fleet) on the overall population and lack of agreement between catch per unit effort time series for domestic fleets with that used in broader stock assessments (Kolody et al. 2010). In the case of Bigeye and Yellowfin Tunas, it was concluded that the ETBF is likely to have little effect on both species populations, resulting in the harvest strategy being disconnected from the basic feedback principle on which it was developed (Kolody et al. 2010). The preliminary nature of regional stock assessments for both Albacore and Striped Marlin, which were used in the harvest strategy, also resulted in substantive uncertainty in harvest strategy outputs. As a result of the sensitivities of the harvest strategy framework and resulting unsuitability for use on the three tuna species, the framework is currently only being used to set TACCs for Swordfish and Striped Marlin. Total allowable catches for the three tuna species are instead, at present, based on historical catch levels.

A number of unresolved issues and associated recommendations were highlighted as a result of the evaluation of the harvest strategy framework. These included: (1) better representation of the fishery dynamics of the ETBF through the disaggregation of fisheries data to represent plausible localised populations and evaluation of the characteristics of the ETBF data; (2) resolution of the spatial connectivity of species populations between the ETBF and the broader western and central Pacific Ocean; (3) updating of the MSE with more recent stock assessments for each of the species and incorporation of the associated identified uncertainties in parameters and outputs; (4) thorough testing of harvest strategies in order to identify sensitivities and ensuring these are accounted for in a robust manner (Kolody et al. 2010).

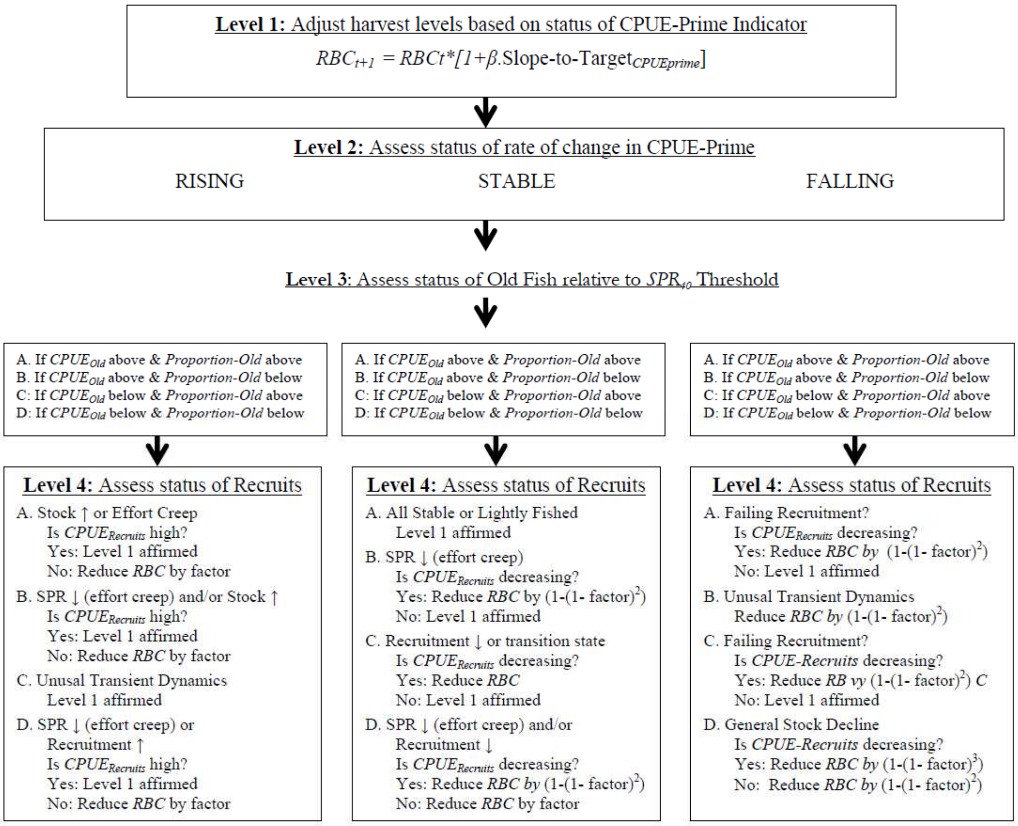


Figure 1.1. The decision tree which forms the basis of the harvest strategy for the ETBF. Taken from Davies et al. (2007).

A recent review of the Commonwealth Fisheries Harvest Strategy Policy has also questioned the relevance of harvest strategies for internationally managed multi-species fisheries such as the ETBF. At present, the policy states that relevant management bodies will be negotiated with to ensure sustainable management of fisheries. This will be done by ‘advocating this policy as an example of best practice in setting sustainable catch levels’ with the context of any negotiations to be in line with the government’s domestic legislation. In the case where catches or fisheries issues are not decided by the relevant regional or international management body, ‘DAFF and AFMA will consult on the management arrangements that will apply and AFMA will implement those arrangements’. The pathway for which negotiation positions for setting international management arrangements and then domestic catches are not entirely clear as they are currently presented in the Policy. As a result, there has been confusion associated with how and when a domestic harvest strategy should be applied to shared internationally managed multi-species fisheries and what process this should entail (DAFF 2013). Due to the lack of comprehensive understanding of the degree of connectivity of fish caught in the ETBF to those in the wider Pacific Ocean there is also some ambiguity over the effect of domestic catches on regional/international stocks and therefore the relevance of catch level decisions made at the regional/international level to those made domestically (DAFF 2012; DAFF 2013).

Within the context of an assessment of the suitability of harvest strategies for the main species within the ETBF, there is a need to assess what information might be available and what current understanding of the connectivity of species caught within the ETBF with the broader western and central Pacific Ocean might be. This chapter outlines the current understanding of the stock structure and degree of connectivity of the five main species caught within the ETBF based on assessments of their population dynamics, genetics, movement and commercial catches throughout the western and central Pacific Ocean (WCPO). The chapter provides summaries of:

1) Current understanding of the connectivity and stock structure of each species within the western and central Pacific Ocean;
2) Knowledge gaps relating to the connectivity of each species in the western and central Pacific Ocean;
3) Research and monitoring required addressing these priority knowledge gaps.

2. Current understanding of species connectivity and stock structure

2.1. Albacore (ALB)

2.1.1. The fishery

With the development of worldwide longline fisheries in the 1950s, catches of Albacore throughout the south Pacific Ocean increased rapidly over the following decade, stabilising at around 30,000 mt during the 1960s to 1980s (Miyake et al. 2004; Langley 2006). Troll and driftnet fisheries throughout the region began in the 1980s resulting in further increases, with catches peaking at 50,000 mt in 1990 (Miyake et al. 2004). As drift net fishing decreased in the early 1990s, catches stabilised at around 40,000 mt in the late 1990’s before climbing again to approximately 50,000 mt in 2001 with the development of small-scale domestic longline fisheries throughout the region (Langley et al. 2006). Catches have continued to increase with recent catches in the order of 80,000 mt (Figure 2.1; Hoyle et al. 2012)

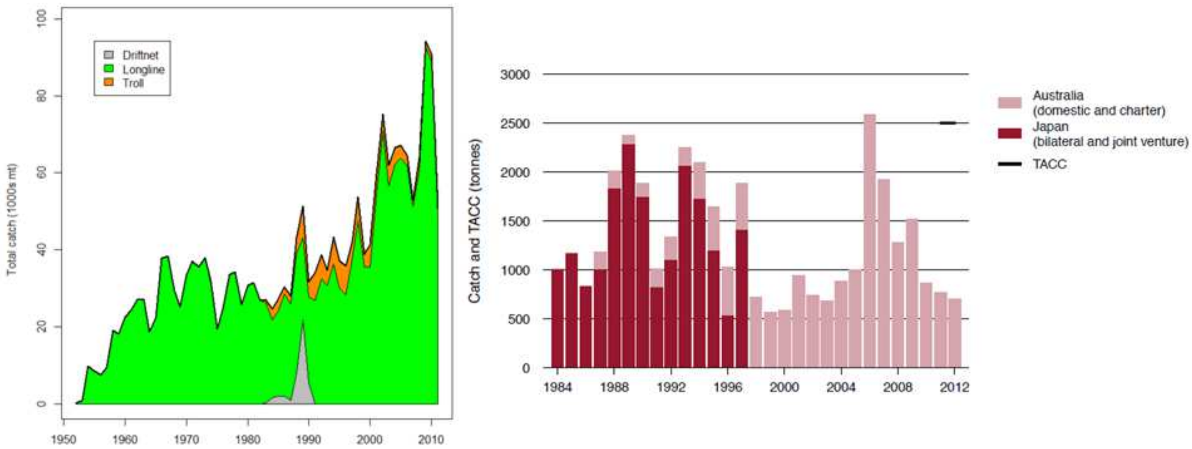


Figure2.1. Annual catches of Albacore in the south Pacific Ocean 1952 – 2011 (left) and the East Australian Billfish Fishery1984 – 2012 (right). Reproduced from Hoyle et al. (2012) and Larcombe and New (2013). TACC: total allowable commercial catch.

Albacore were initially caught off the east coast of Australia as byproduct by Japanese and domestic longline vessels targeting Yellowfin and Bigeye Tunas (Ward 2007). During the 1980s and 1990s, catches of Albacore by the Japanese fleet fluctuated between 1,000 - 2,000 mt, with domestic fleets catching approximately 600 mt per year (Figure 2.1). With the departure of bilateral and joint venture Japanese fleets in 1997, catches reduced to less than 1,000 mt. Catches remained at this level until 2006, when in response to reduced Swordfish availability, high operating costs and market demand for Albacore, a number of longline vessels started to specifically target Albacore (Ward 2007). Catches increased in response to over 2,500 mt, but have declined steadily since, as a result of longline vessels targeting other species mainly due to market forces, management measures which closed the main fishing area for Albacore to new entrants and a reduction in the fleet under the 2006 ‘Securing our Fishing Future’ structural adjustment package implemented by the Australian Fishing Management Authority (Sands et al. 2009; Larcombe et al. 2011).

The most recent stock assessment for Albacore in the WCPO suggests that there is low risk that the stock is currently being overfished and that there is no evidence that catches are causing recruitment overfishing (Hoyle et al. 2012). Stock status indicators are highly sensitive to the growth curve used in the model however, and growth variation observed throughout the WCPO (Williams et al. 2012) introduces uncertainties to the model output as a result (Hoyle et al. 2012). Observed declines in the catch rates of some domestic fisheries across the region suggest there may be some localised residency of Albacore and subsequent localised depletion of the stock (Langley 2006). Analysis of recent fishing patterns identified that there was a ‘notable risk’ of the adult biomass being reduced to below the Limit Reference Point under current fishing effort levels by 2030 (Pilling et al. 2014).

2.1.2. Biology

Albacore are distributed between approximately 50˚N and 40˚S across the Pacific Ocean (Sund et al. 1981; Collete and Nauen 1983), with distributions primarily concentrated in sub-tropical and temperate regions (Figure 2.2; Murray 1994). Based on larval distributions and gonad examination, spawning is generally accepted to occur in two separate areas in the Pacific Ocean on either side of the equator (Figure 2.2), consistent with the distributions of two genetically distinct stocks (Takagi et al. 2001). Spawning areas are distributed predominantly between 10 – 25˚ with spawning occurring during the austral and boreal spring and summer months in areas where surface water temperatures are greater than 24˚C (Otsu and Uchida 1959; Nishikawa et al. 1985; Ramon and Bailey 1996; Farley et al. 2013). In the South Pacific Ocean, spawning activity appears to be synchronised, peaking in October – December with smaller, younger females having a shorter spawning season on average than larger, older females (Farley et al. 2013). Spawning success appears to be related to regional oceanographic conditions with stronger recruitment during La Niña conditions (Langley 2006). Females attain sexual maturity across a relatively narrow size range, with Albacore across the WCPO sexually mature at lengths of 74 – 94cm fork length (FL).

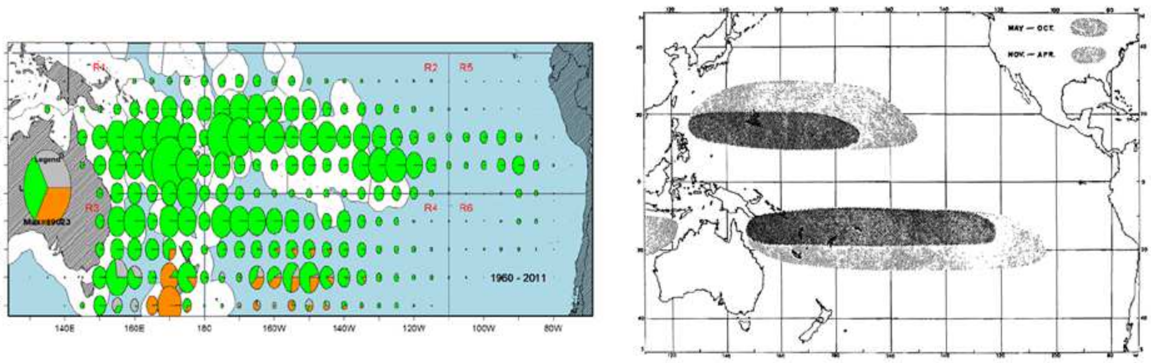


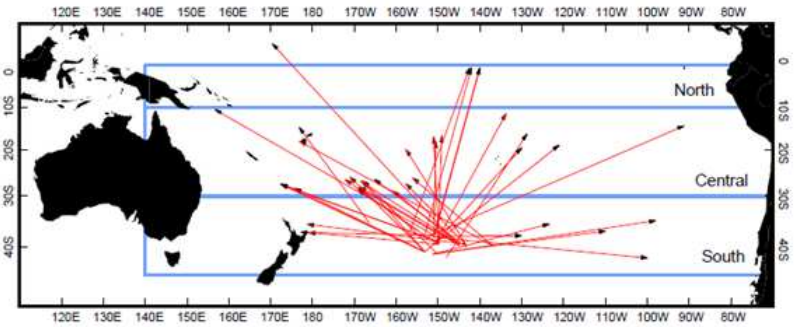
Figure 2.2. The distribution of total catches of Albacore in the south Pacific Ocean by 5˚ squares 1960 – 2011 in relation to the spatial domains of the 2012 stock assessment in the western and central Pacific Ocean (left) and estimated spawning regions in the north and south Pacific Ocean based on observations of larval distributions (right). Reproduced from Hoyle et al. (2012) and Ueyanagi (1969).

Some regional variation in gonad development in mature Albacore has been observed, with fish in easterly longitudes of the WCPO observed to have heavier gonads in relation to length than those in the west (Farley et al. 2013). There is additionally some indication that Albacore in the east have higher rates of maturity at length than those in the west (Farley et al. 2014). Individuals live to over 10 years with a maximum age of 14 years recorded (Farley et al. 2013). Longitudinal variability in growth has also been observed, with faster growth rates and higher asymptotic lengths occurring in fish in the eastern parts of the WCPO than those in the west, suggesting some spatial structure to the population of Albacore at broad scales across the WCPO (Williams et al. 2012). Variability in growth results in variability in estimations of age at sexual maturity with 50 % of females at 150˚E estimated to be mature at 4.5 years and 100 % at 7 years (Farley et al. 2014). As far as we are aware, no genetic studies investigating the potential for structuring of the Southern Hemisphere population of Albacore in the Pacific Ocean have been conducted to date.

2.1.3. Spatial dynamics

Albacore are one of four species of tuna considered to be truly 'migratory' (along with Southern Bluefin Tuna *Thunnus maccoyii*, Pacific Bluefin Tuna *T. orientalis* and Atlantic Bluefin Tuna *T. thynnus*), undertaking seasonal movements between spatio-temporally separated spawning and foraging areas (Schaefer 2001). In the Southern Hemisphere, juveniles are thought to move south away from the spawning grounds into the surface waters around New Zealand and the subtropical convergence zone at around 40˚S, where they are caught by longline, troll and driftnet fisheries at around 1 year. As they grow, individuals disperse into lower latitudes, and are distributed throughout waters north of 30˚S as adults where they are caught by longline fisheries. Recent investigations in the trophic ecology of Albacore also support latitudinal separation of age groups (Parrish et al. 2015) and parasite species collected from individuals also support these movements (Jones 1991). Seasonal trends in catch data suggest that as adults, Albacore migrate into sub-tropical waters during summer, returning to tropical waters during winter (Langley 2004; Langley and Hampton 2005; Hoyle et al. 2012) coincident with the seasonal oscillation in the location of the 20−28°C sea surface temperature isotherms (Langley 2006).

The details of these migrations, the pathways undertaken by individuals and any spatial variability in movements however, are largely unknown. Minimal tagging data are available for the species and what data are available, are limited both spatially and temporally (Labelle and Hampton 2003; Domokos et al. 2007; Hoyle et al. 2012; Williams et al. 2015). Conventional tag returns from releases conducted under scientific programs support connectivity between high and low latitudes and suggest a degree of mixing across foraging regions and dispersion across the both the western and eastern Pacific Ocean (Figure 2.3; Labelle and Hampton 2003). Areas in which tags were released however, have been limited to a restricted region between 35 – 40°S and 140 – 160°W. Conventional tag releases off the east coast of Australia via recreational fishers also support connectivity between high and low latitudes (Figure 2.3). Although recaptures demonstrate some dispersion from release sites primarily off New South Wales and Tasmania as far as the Solomon Sea and west of Fiji 73% of tags released were recaptured within 200nm of their release site. Given the limited spatial distribution of tag releases both within the ETBF and across the WCPO, it is unclear how temporally and spatially representative movements described by conventional tag recaptures are. More recently, additional deployments of a small number of conventional tags on Albacore have occurred further west in waters off the west coast of New Zealand. To date, recaptures reported have been extremely low, providing almost no further information on movements (A. Williams, Secretariat of the Pacific Community, pers. comm.). Small numbers of electronic tags have been released on Albacore in the waters off American Samoa (Domokos et al. 2007), Tonga, New Caledonia and New Zealand (Figure 2.4; Williams et al. 2015). All tags released have prematurely detached from tagged individuals, resulting in deployment periods of less than 50 days and in association, limited movements being recorded (Domokos et al. 2007; Williams et al. 2015).



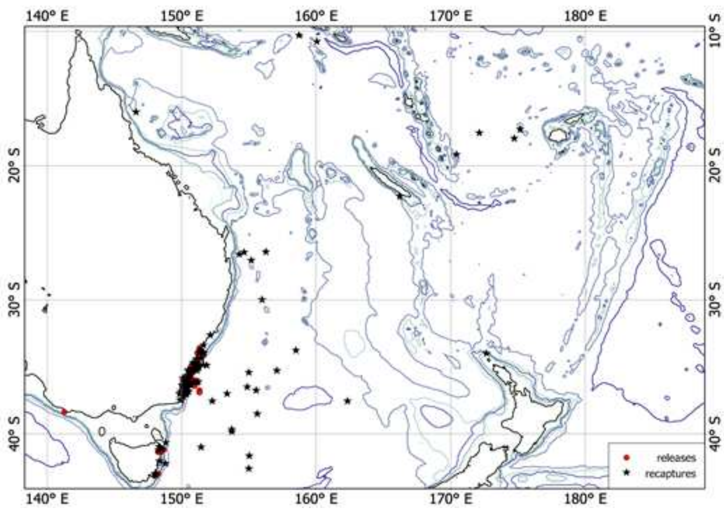


Figure 2.3. Displacement of Albacore tagged with conventional tags by scientific programs in the central South Pacific Ocean in relation to the spatial domains of the 2003 stock assessment in the western and central Pacific Ocean (top) and off the east coast of Australia by recreational fishers (bottom). Top figure reproduced from Labelle and Hampton (2003).

Recent investigations into the microchemistry of otoliths collected from mostly adult Albacore observed similar otolith core chemistry in individuals from New Caledonia and New Zealand, suggesting the possibility of mixing between larval pools or origins from areas of similar water chemistry (McDonald et al. 2013). Otoliths derived from Albacore caught in waters around French Polynesia were observed to contain quite different core chemistry suggesting that fish originated from geographically distant regions to those captured in waters off New Caledonia and New Zealand (McDonald et al. 2013). The locations of spawning sites or larval origins were not identified, but the preliminary results observed suggest the potential for spatial structuring of the population.

2.1.4 Summary

- Fishery catches from Pacific Island domestic fleets suggest some localised residency of Albacore. Catches of Albacore in the ETBF have demonstrated a declining trend since 2007. This trend has been attributed to changing targeting practices, management measures and a reduction in the fleet.
- There are two genetically distinct stocks of Albacore in the Pacific Ocean distributed on either side of the equator. To date, finer scale investigations of genetic structure have not been undertaken.
- Throughout the WCPO Albacore demonstrate broad longitudinal variation in growth rates and gonad development. Preliminary investigation of otolith microchemistry also suggests some spatial structuring of spawning sites.
- As juveniles, Albacore move from low latitudes into higher latitudes around New Zealand and the subtropical convergence zone. As they grow, they move into waters north of 30˚S.
- As adults, Albacore undertake seasonal migrations between low latitude spawning grounds and higher latitude foraging grounds. The details of these migrations and the pathways undertaken are largely unknown.

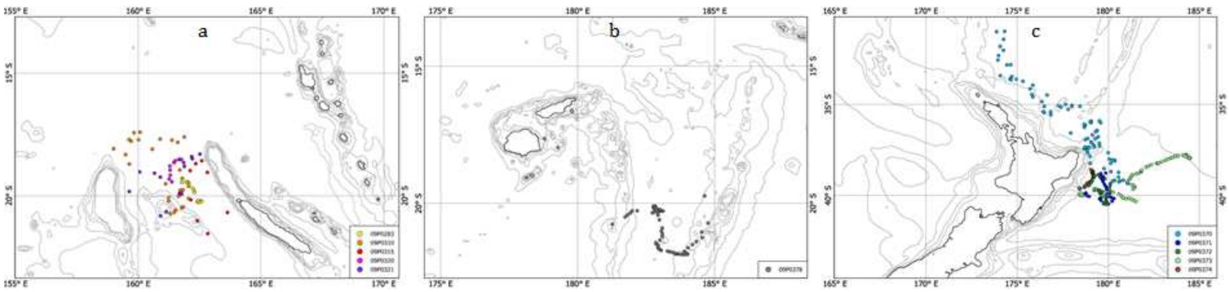


Figure 2.4. Movements of Albacore tagged with pop-up satellite archival tags in the waters around (a) New Caledonia, (b) Tonga and (c) New Zealand. Reproduced from Williams et al. (2015).

2.2 Bigeye tuna (BET)

2.2.1 The fishery

Large Bigeye Tuna have been specifically targeted by longline vessels in the WCPO for the sashimi market from the inception of longline fisheries in the 1950s (Miyabe 1994; Hampton et al. 2005). Throughout the 1950s, catches in the WCPO increased steadily to around 70,000 mt remaining at about that rate until the early 1960s, after which catches declined to approximately 50,000 mt (Figure 2.5). During the 1980s, longline catches ranged 44,000 – 62,000 mt, increasing through the 1990s to peak at 99,000 mt in 2004 (Davies et al. 2011). Subsequently, catches have ranged 67,000 – 77,000 mt (Davies et al. 2011).

With the development of the industrial purse seine fleet in the 1970s, catches of smaller juveniles increased as individuals were caught as byproduct by vessels targeting Yellowfin Tuna (Miyabe 1993). In the mid-1990s, developments in the purse seine fishery resulted rapid increases in the catches of juvenile Bigeye Tuna, mostly in association with purse seine vessels setting specifically on floating objects. At the same time, the domestic fisheries of the Philippines and Indonesia were increasingly catching Bigeye Tuna using a range of techniques (pole-and-line, ringnet, gillnet, handline, seine net), adding to overall catches in the WCPO (Hampton et al. 2005; Davies et al. 2011). The accuracy of catches of Bigeye Tuna from the purse seine fishery still remain uncertain, with catches reported on logsheets significantly under-estimated (Lawson 2008; 2009; 2010). Catches from purse seine vessels were thought to have first exceeded 20,000 mt in 1982, increasing to 40,000 – 50,000 mt, in the mid-1990s and peaking at 105,000 mt in 1997 Catches then remained at over 60,000 mt until 2001 after which they have ranged 36,000 – 65,000 (Davies et al. 2011; Harley et al. 2014). Coastal purse seine and pole and line fisheries around Japan are estimated to catch around 1,000 mt each. Of the total catches in the WCPO, catches by the longline fishery contribute 55 – 65 % (Hampton et al. 2005).

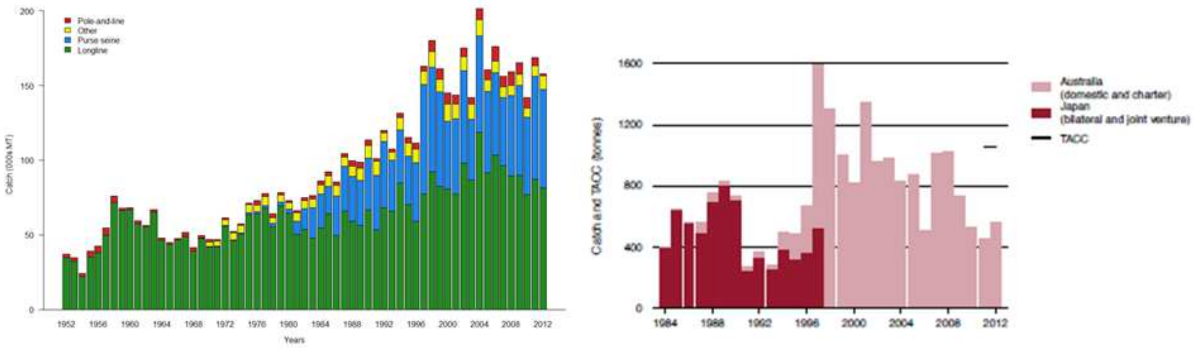


Figure 2.5. Annual catches of Bigeye Tuna in the south Pacific Ocean 1952 – 2010 (left) and the East Australian Billfish Fishery 1984 – 2012 (right). Reproduced from Harley et al. (2014) and Larcombe and New (2013). Purse seine catches in the south Pacific Ocean have been corrected for grab sample bias. LL: longline; PS: purse seine; PHID: Philippines and Indonesian domestic ; OTH: other; TACC: total allowable commercial catch.

Japanese longline vessels specifically targeting Yellowfin and Bigeye Tunas started fishing off the east coast of Australia in the 1950s. These vessels were joined by domestic longline vessels which were targeting Yellowfin Tuna for canning in the 1960s, but also catching Bigeye Tuna as a byproduct (Ward 2007). During the 1980s, longline operations increased with the establishment of air freighting of fresh tuna to Japanese sashimi markets with catches ranging 600 – 800 mt, peaking in 1989 at just over 800 mt (Figure 2.5). Catches dropped substantially in the 1990s as a result of a sharp drop in the number of vessels operating in the ETBF (as a result in highly variable catches of Yellowfin Tuna). Rapid expansion of the fishery in both northern (where Bigeye and Yellowfin Tunas were targeted) and southern Queensland waters (where Swordfish were targeted) in the late 1990s resulted in a sharp increase in catches, with catches peaking at nearly 1,600 mt in 1997 and 1,300 mt in 2001 (Ward 2007). During the 2000s catches declined to around 900 mt. The factors associated with this decline are not clear, but it has been postulated that changes in abundance associated with localised depletion, availability or catchability have all been postulated (Gunn et al. 2005; Ward 2007; Evans et al. 2008). Catches have subsequently reduced further to approximately 500 mt as a result of a reduction in the fleet under the 2006 'Securing our Fishing Future' structural adjustment package implemented by the Australian Fishing Management Authority (Larcombe et al. 2011).

Concerns over the representativeness of models used to assess Bigeye Tuna in the WCPO were raised during a review of the 2011 assessment (Ianelli et al. 2012; Harley et al. 2014). Of particular note was the highly sensitive nature of the model to the addition of available tagging data, particularly in relation to reporting rates included in the model. When fitted to tagging data from the Coral Sea region, where a large number of tags were recaptured close to the area in which tags were deployed (see section 2.2.3) and therefore includes a lot more tag returns than the model predicts, reporting rates within the model reach the upper boundary allowed in the model. In this situation reporting rates act similarly to a strong prior. The concern was that if the high reporting rate is an artefact of inadequate mixing of tags throughout the assessment area (as would be the case if the population demonstrates some semi-residence), biomass calculated by the model could be under-estimated (Hoyle et al. 2013). Preliminary investigations of conventional tagging data included in the stock assessment suggested that some form of semi-residence may be occurring in larger Bigeye Tuna and that mixing is occurring at variable rates across the WCPO (Hoyle et al. 2013; Kolody and Hoyle 2013).

A number of recommendations were put forward by the review and in response a number of changes have been implemented into the assessment, including those related to data included in the assessment, data analyses undertaken, regional structure and associated fisheries definitions, implementation and testing of the stock assessment model and assessment of model output (Harley et al. 2014 and associated references therein; SPC-OFP 2014). Of particular relevance is that the number of spatial regions within the assessment model has increased and a new region encompassing the Coral Sea included (Figure 2.6). The modifications implemented in the 2014 stock assessment are considered to have improved the assessment and in particular, reduced the previously observed increasing trend in recruitment and improved the fit to tagging data from the Coral Sea region (Harley et al. 2014). Conclusions from the 2014 assessment support those put forward in the previous assessment suggesting that the stock is currently being overfished and that the stock is most likely at an overfished state (Davies et al. 2011; Harley et al. 2014).

2.2.1 Biology

Bigeye Tuna are distributed across the Pacific Ocean from approximately 40°N - 40°S in the west and 40°N - 30°S in the east (Figure 2.5; Calkins 1980; Sund et al. 1981). Based on observed distributions of larvae, spawning is thought to occur in tropical and sub-tropical waters from the equator to 30°N and 20°S with higher concentrations of spawning in the western and eastern Pacific Ocean than in the central Pacific Ocean (Calkins 1980; Nishikawa et al. 1985; WPRFMC 2005). Spawning is thought to occur year round in tropical waters with a peak in February – September (Sun et al. 2006) and seasonally in sub-tropical waters of greater than 24°C (Miyabe 1994). In the north-west Coral Sea region, Bigeye Tuna have been observed to spawn during the months October – November (McPherson 1988). The size and age at maturity reported varies across the Pacific Ocean, with 50 % of females mature at 102.7 cm FL and 2.2 – 2.4 years in the north western Coral Sea, 102.85 cm FL in the western Pacific Ocean (Sun et al. 2013) and 135 cm in the central and eastern Pacific Ocean (Schaefer et al. 2005). Whether or not this is reflective of differing growth and maturity rates across the Pacific Ocean is unclear. Differences in fishing methods, fishing depths and classification methods confound the ability to undertake direct comparisons (WPRFMC 2005; Farley et al. 2006).

Individuals live to ages greater than 10 years, with the maximum recorded as 16 year (Farley et al. 2006). Growth appears to be variable between locations across the Pacific Ocean, however restricted size ranges of samples and varying techniques in both aging and estimating growth curves limit the ability to determine if spatial variability in growth does exist (Lehodey et al. 1999; Farley et al. 2006). Catch data also demonstrate an increase in average size of Bigeye Tuna caught from the western Pacific Ocean to the eastern Pacific Ocean. It is not clear if this is reflective of variability in growth rates or the age composition of catches (Hampton et al. 2005).

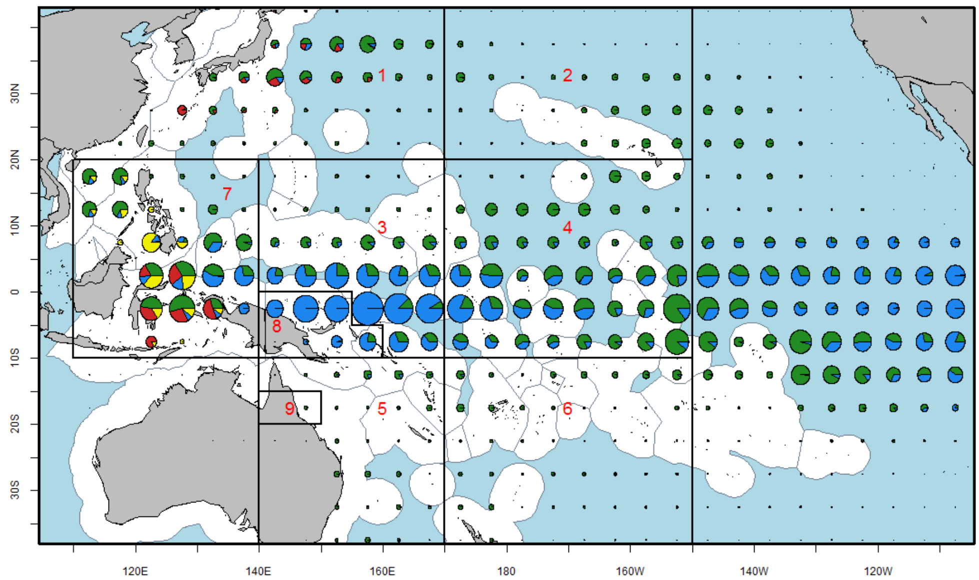


Figure 2.6. Distribution of total catches of Bigeye Tuna by fishery in the south Pacific Ocean by 5˚ x 5˚ squares 1990 – 2012 in relation to the spatial domains of the 2014 stock assessment in the western and central Pacific Ocean. Different gear types are represented by blue: longline; green: purse seine; red: pole and line; yellow: other. Taken from Harley et al. (2014).

More recent preliminary examination of the reproductive biology of Bigeye Tuna has reported significant differences in the maturity ogives for individuals sampled in WCPO to those in the eastern Pacific Ocean. Additionally, evidence of both latitudinal and longitudinal variation in growth has been observed (Nicol et al. 2011). Further work is recommended to better resolve variability in the reproductive dynamics and growth of Bigeye Tuna across the Pacific Ocean and the implications this might have on current stock assessment (Nicol et al. 2011; WCPFC 2014).

Molecular analyses carried out to date have found no evidence to refute a single panmictic Pacific-wide population of Bigeye Tuna based on mitochondrial DNA and microsatellite loci, although some evidence for restricted gene flow between the south-eastern and north-western Pacific Ocean has been reported (Grewe and Hampton 1998). Further analyses of much larger sample sizes are required to determine if such population structure does occur within the Pacific Ocean.

2.2.2 Spatial dynamics

Investigations into the regional connectivity of Bigeye Tuna in the western and central Pacific via scientific tagging programs have largely focused on life stages that are predominantly caught by commercial fisheries. Juvenile and subadult Bigeye Tuna have reported a mixture of long distance dispersal and semi residence in areas close to tag release sites over periods of up to three years (Figure 2.7; Hampton and Gunn 1998; Evans et al. 2008; Hoyle et al. 2013; Kolody and Hoyle 2013). Displacements of conventional tags have been observed to vary substantially between areas of deployments and also between size classes of Bigeye Tuna tagged. Conventional tags released in the north-west Coral Sea have been recaptured at, on average, smaller distances than those released elsewhere in the western and central Pacific Ocean (Figure 2.8) and smaller displacements have been reported to be more prevalent amongst larger fish in comparison to smaller fish within fish of 40 – 80 cm in length (Hoyle et al. 2013; Kolody and Hoyle 2013). Median displacements of Bigeye Tuna released in the Bismarck and Solomon Seas were close to 500km, whilst tags released further east in the WCPO stock assessment area 4 (see Figure 2.5) varied from less than 1000 km to 2000 km (Hoyle et al. 2013). Conventional tag releases from recreational fishers off the east coast of Australia have yielded very few recaptures. Similarly to conventional tag releases in the Coral Sea, tagged fish have demonstrated both localised and dispersive movements (Figure 2.7). It is difficult to infer movement rates from conventional tags recaptured from Bigeye Tuna both from scientific and recreational fishing programmes because they are released from relatively few locations are dependent on tag recoveries (and reporting) from commercial fisheries, which have a non-random distribution and in the case of those released by recreational fishers have very low recapture rates.

Subadult Bigeye Tuna tagged with archival tags in the northwest Coral Sea (Figure 2.9) have been observed to undertake a range of movements including cyclical movements between the Coral Sea and the greater western Pacific as well as residency within the northwest Coral Sea region (Clear et al. 2005; Gunn et al. 2005; Evans et al. 2008). Individuals were also observed to move eastward into the western Pacific Ocean, but whether or not this movement was part of a directed migration further east or a cyclical movement east with return to the north west Coral Sea was unable to be determined due to tag failure (Clear et al. 2005; Gunn et al. 2005). Movements of a latitudinal nature was almost non-existent, although numbers of individuals tagged outside of the north-west Coral Sea were very low and as a result linkages between equatorial regions and higher latitudes are unclear. Residential behaviour has been described from similarly sized Bigeye Tuna elsewhere in the Pacific, although this has been attributed to associative behaviour with topographical features or fish aggregating devices (Schaefer and Fuller 2002; Musyl et al 2003). Conventional tag data however also describes little latitudinal movement.

To date, the only detailed investigation of Bigeye Tuna movements throughout the WCPO as provided by archival tags has been that from the north-west Coral Sea, so it is unclear whether or not movements observed via conventional tags are representative of Bigeye Tuna populations throughout the WCPO. Deployments of archival tags throughout the WCPO under the Pacific Tuna Tagging Programme (Caillot et al. 2012) may provide further insights into the extent of movements of Bigeye Tuna throughout the region and the degree to which conventional tagging collected to date is representative of those movements. Initial analyses of these data have begun and it is expected that these data will be published in the coming months (S. Nicol, Secretariat of the Pacific Community pers. comm.).

Preliminary investigation into the stable isotope signatures of otoliths collected from age-0 Bigeye Tuna suggest spatial structuring of spawning populations with mixing decreasing as the distance between location increases (WPRFMC 2014). Individuals collected from Hawaiian waters shared signatures with those collected from waters around the Line Islands, but had no similarity with those further west. Otolith signatures collected from waters around the Marshall and Solomon Islands suggested local production dominated population with only small amounts of mixing with populations further east, while signatures from otoliths collected around Indonesia and the Philippines suggested no mixing with populations further east (WPRFMC 2014).

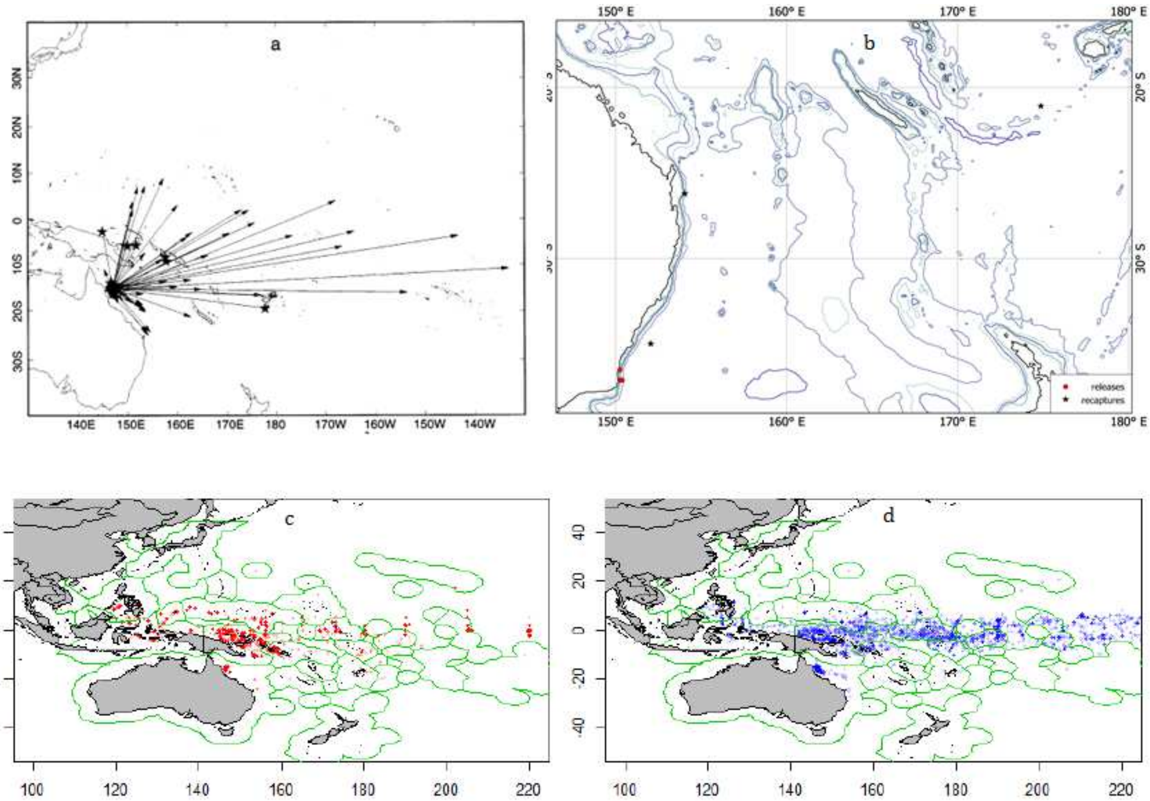


Figure 2.7. Displacements of conventional tag releases on Bigeye Tuna tagged in (a) the northwest Coral Sea 1991 – 1992 as part of the Regional Tuna Tagging Programme. Arrowheads: longline vessel recaptures; stars: purse seine and pole and line recaptures. (b) Release and recapture positions of conventional tags deployed on Bigeye Tuna off the east coast by recreational fishers. (c) release positions of Bigeye Tuna tagged with conventional tags from all tagging programs conducted in the western and central Pacific Ocean 1989 – 2012. (d) recapture positions of conventional tags deployed on Bigeye Tuna tagged from all tagging programs conducted in the western and central Pacific Ocean 1989 – 2012. Reproduced from (a) Hampton and Gunn (1998); (c-d) Kolody and Hoyle (2013).

Little is known of the dispersion of larval life stages or of the movements of adult Bigeye Tuna. The occurrence of fisheries and the individuals that support those fisheries suggest that there is movement away from lower latitudes into higher latitudes, although at what life stage this occurs is largely unknown (Sund et al. 1981). Catch data from the ETBF suggest some seasonal movement of adults with movements into higher latitudes with seasonal warming of these waters (Evans et al. 2008).

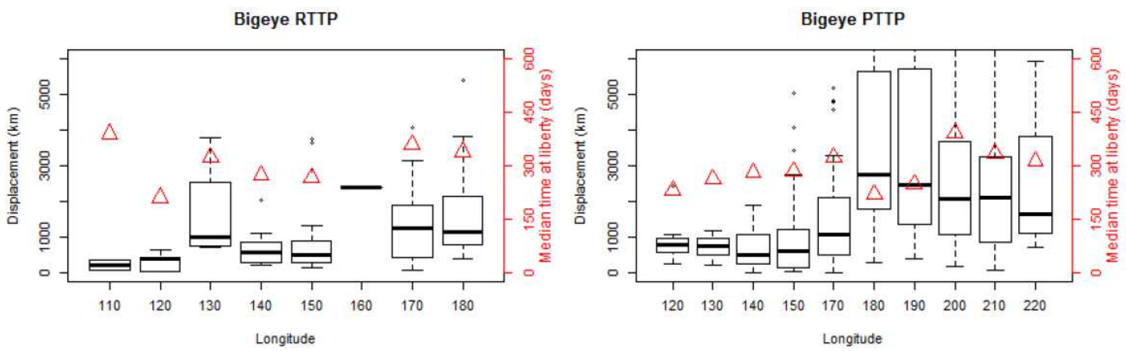


Figure 2.8. Box plots of observed displacements and median displacement (red triangles) greater than 182 days by release longitude by Bigeye Tuna during the Regional Tuna Tagging Programme (RTTP, left panel) and the Pacific Tuna Tagging Program (PTTP, right panel). Taken from Hoyle et al. (2013).

2.2.3 Summary

- Genetic analyses carried out to date have observed no significant genetic differentiation within Bigeye Tuna throughout the Pacific Ocean.
- There is some evidence for broad longitudinal variation in the growth rates and maturity ogives of Bigeye Tuna.
- Data from conventional tagging and archival tagging programs suggest semi-residency of juvenile and subadult Bigeye Tuna in the northwestern Coral Sea. At the same time, large scale movements have been recorded.
- Preliminary investigations into otolith stable isotopes suggest spatial structuring of spawning populations with mixing decreasing as the distance between location increases.
- Almost nothing is known of dispersion of larvae or the movements of adults.

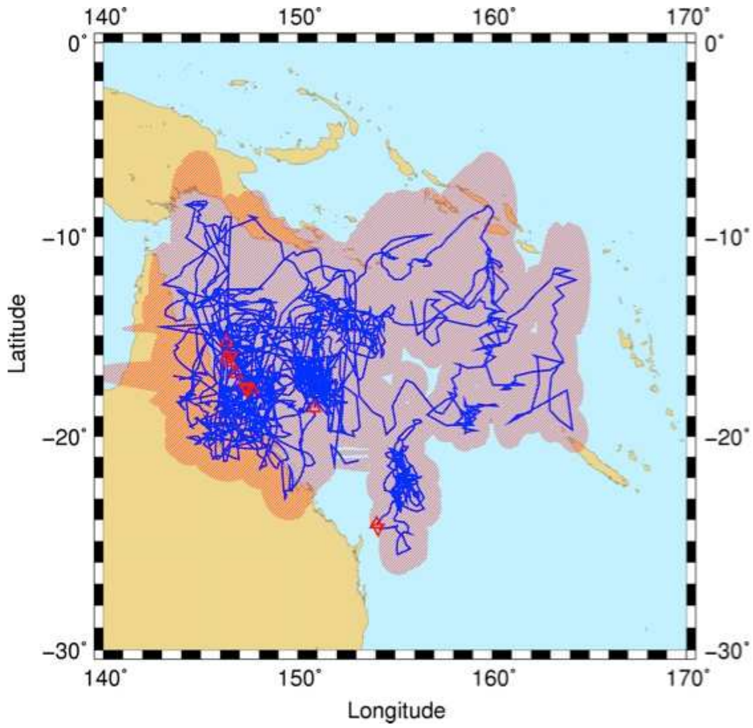


Figure 2.9. Estimated tracks from juvenile and sub-adult Bigeye Tuna tagged with archival tags in the northern Coral Sea 1999-2001. Inverted red triangles depict release locations, upright red triangle depict recapture locations. The 95% Confidence interval associated with each position estimate is represented by the pink hatching.

2.3 Swordfish (SWO)

2.3.1 The fishery

Swordfish are predominantly caught as bycatch by longline vessels targeting tuna species throughout the WCPO, with the majority of historical catches taken by Japanese fleets (Davies et al. 2013). Across the WCPO, annual catches of Swordfish historically increased slowly from the 1950s to around 2000 mt in the 1970s with catches remaining at about this level through to the mid 1990's (Figure 2.10; Kolody et al. 2008). During the second half of the 1990s, catches increased rapidly as targeted fisheries developed in Australian and New Zealand waters and then declined shortly after (see below). Catches by Japanese, Spanish and Chinese fleets increased in the south central Pacific Ocean in the early 2000s, with the Spanish fleet recording the largest catches of all nations across the WCPO in 2006 (Kolody et al. 2008; Davies et al. 2013).

Swordfish have been caught in Australian waters as bycatch by Japanese longline vessels targeting tuna since the 1950s and by domestic longline vessels since the 1960s (Ward et al. 2000). During the 1980s, catches were relatively stable at around 500 mt before a rapid increase in the mid-1990s with rapid expansion of the domestic fleet to specifically target Swordfish as access markets in the United States for Swordfish improved (Ward et al. 2000; Ward 2007). Catches peaked in 1999 at over 2500 mt before declining progressively to just over 1500 mt in 2004 (Figure2.10). Increases in bait and fuel prices and associated shift in targeting to Albacore resulted in further declines to just over 1000mt in 2006 (Ward 2007). A switch back from targeting Albacore to other species, including Swordfish resulted in an increase in catches in 2007 and 2008, although catches were still limited, largely as a result of management measures which capped catches and a reduction in the fleet under the 2006 'Securing our Fishing Future' structural adjustment package implemented by the Australian Fishing Management Authority (Sands et al. 2009). Catches have remained at 1000 – 1500 mt since. There is some evidence of sequential depletion of localised populations in the ETBF with longline catch rates declining over time in areas fished. As catch rates declined in inshore areas around topographic features such as seamounts, effort expanded further offshore in response (Ward et al. 2000; Campbell and Hobday 2003). It remains unclear however, the occurrence and extent of localised depletion or if instead there is a general gradient in population density with higher densities of Swordfish generally further offshore.

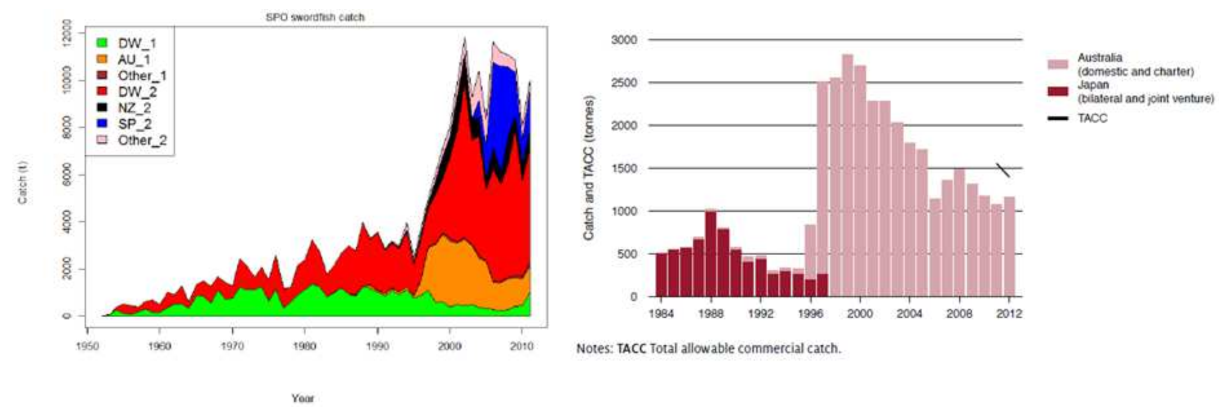


Figure 2.10. Annual catches of Swordfish in the south-west Pacific Ocean 1952 – 2011 (left) and the East Australian Billfish Fishery 1984 – 2012 (right). Taken from Davies et al. (2013) and Larcombe and New (2013). TACC: total allowable catch.

The most recent stock assessment for Swordfish in the WCPO reported a decline in biomass across the period 1997 to 2011 concurrent with increases in catches, declines in CPUE and declines in mean sizes of fish caught (Davies et al. 2013). Uncertainties in the assessment are largely associated with estimates of growth, maturity and mortality at age. Although a number of studies have been conducted on the age, growth and reproductive biology of Swordfish, results and estimates calculated have varied with little agreement on estimates of growth, maturity and mortality at age (see Section 2.3.2.). As a result, assessments use two estimates of growth, maturity schedules and mortality at age (Kolody et al. 2008; Davies et al. 2013). Based on the two estimates, overfishing of Swordfish may or may not be occurring, but that current stock status is predicted to be above the level supporting maximum sustainable yield and the stock is not in an overfished state (Davies et al. 2013). Reducing uncertainty in estimates of growth, maturity and mortality at age has been identified as a high priority in the recommendations resulting from the stock assessment (Davies et al. 2013) and research recently funded jointly through the Western and Central Pacific Fisheries Commission and the Australian Fisheries Management Authority aims to re-examine growth and maturity in Swordfish across the WCPO.

2.3.2 Biology

Swordfish have a widespread geographical distribution throughout temperate, subtropical and tropical regions in the Pacific Ocean (Figure 2.11). The distribution of individuals has been observed to vary seasonal scales and has been associated with the seasonal extension and retraction of warmer waters into higher latitudes and variability in prey distributions (Palko et al. 1981). Latitudinal distribution appears to be reflective of the sexual dimorphism demonstrated by this species and the size of individuals with fewer, smaller males occurring in colder, higher latitudes than larger females (Palko et al. 1981). In waters close to the equator, spawning occurs throughout the year, becoming more seasonally defined at higher latitudes (Figure 2.11; Palko et al. 1981; Young et al. 2003). In the east Australian region, Swordfish at latitudes lower than 25°S demonstrate a protracted spawning season with spawning occurring in waters with surface temperatures of greater than 24°C between September and March with a peak in December to March (Young et al. 2003).

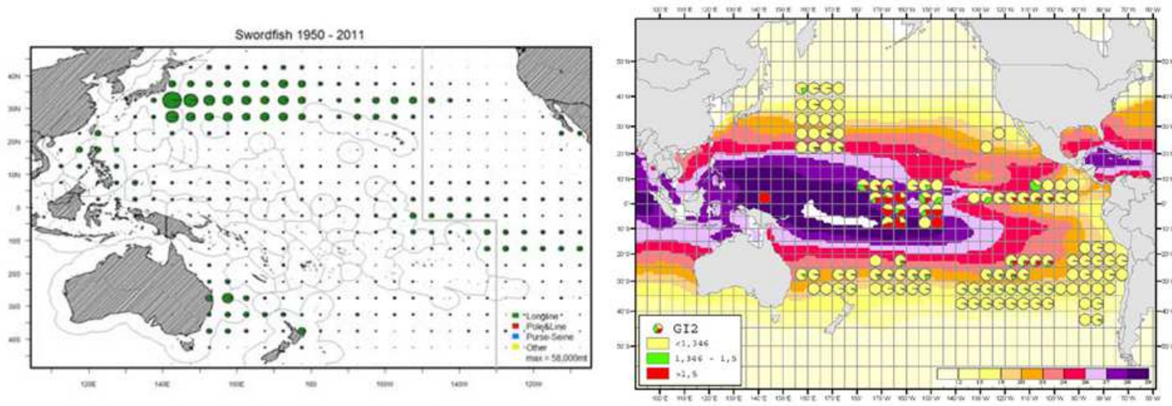


Figure 2.11. Distribution of total catches of Swordfish in the Pacific Ocean by gear type 1950 – 2011 by 5˚x5˚ squares (left panel).Distribution of gonad indices of female Swordfish ≥145 cm lower jaw to fork length by 5˚x5˚ squares (right panel). Reproduced from Mejuto et al. 2008 and Harley et al. (2012).

Males reach sexual maturity at smaller sizes than females, with the L_{50} of males reported to occur at approximately 85cm orbit to fork length (OFL) in the western Pacific Ocean (Young et al. 2003) and approximately 105cm OFL in the eastern Pacific Ocean (De Martini et al. 2000). The L_{50} of females is reported to occur at approximately 195cm OFL in the western Pacific Ocean (Young et al. 2003) and approximately 145cm OFL in the eastern Pacific Ocean (De Martini et al. 2000). Subsequent review of the results of the two studies found that differences in methodologies were largely responsible for differences between the two studies and that direct validation of age should be a priority for the species to reduce subjectivity in age determination (Young et al. 2008). Estimates of growth rates suggest that males reach their maximum size at nine years, while females reach their maximum size at 15 years. Individuals are thought to rarely attain ages of 25 years (Ward et al. 2000). Maximum ages of 18 years in females and 15 years in males have been observed in Swordfish in the western Pacific Ocean (Young and Drake 2004).

Investigations of catches and molecular data have suggested some ocean basin scale population structure to Swordfish stocks across the Pacific, Indian and Atlantic Oceans (Alvarado-Bremer et al. 2005; Reeb et al. 2000), but finer-scale structure within basins is less certain. Genetic studies on Swordfish in the Pacific Ocean have found both little evidence of genetic differentiation in samples collected across the basin (Rosel and Block 1996; Ward et al. 2001; Kasapidis et al. 2008) and some evidence of population subdivision (Reeb et al. 2000). Subdivision that has been observed suggest low levels of mitochondrial gene flow which appears to have a ⊃-shaped pattern, with connectivity of animals east-west in the Northern and Southern Hemispheres and connections across the equatorial zone along the west coast of the Americas (Reeb et al. 2000). This is consistent with larval distributions (Grall et al. 1983; Nishikawa et al. 1985) and the hypothesis of separate stocks in the north and southwest Pacific Ocean (Sakagawa and Bell 1980).

2.3.3 Spatial dynamics

Analyses of declines in catch rates and anecdotal evidence from fishermen in the ETBF suggest that Swordfish are in higher abundance near seamounts than in other areas of the ETBF. It is thought that at least a portion of the population follows an annual migratory pattern, moving from spawning grounds in the Coral Sea, south through the fishing grounds off south east Queensland, and then south and east toward New Zealand, eventually returning to the spawning grounds off Australia's northern east coast. In the context of this scenario, higher densities of Swordfish near eastern Australian seamounts may be the result of directed movement or attraction of individuals to the seamounts or a retention of individuals at seamounts once encountered.

Conventional tagging of Swordfish has been limited to date with programs involving commercial (Stanley et al 2000) and recreational fishers reporting very few recaptures (Figure 2.12).

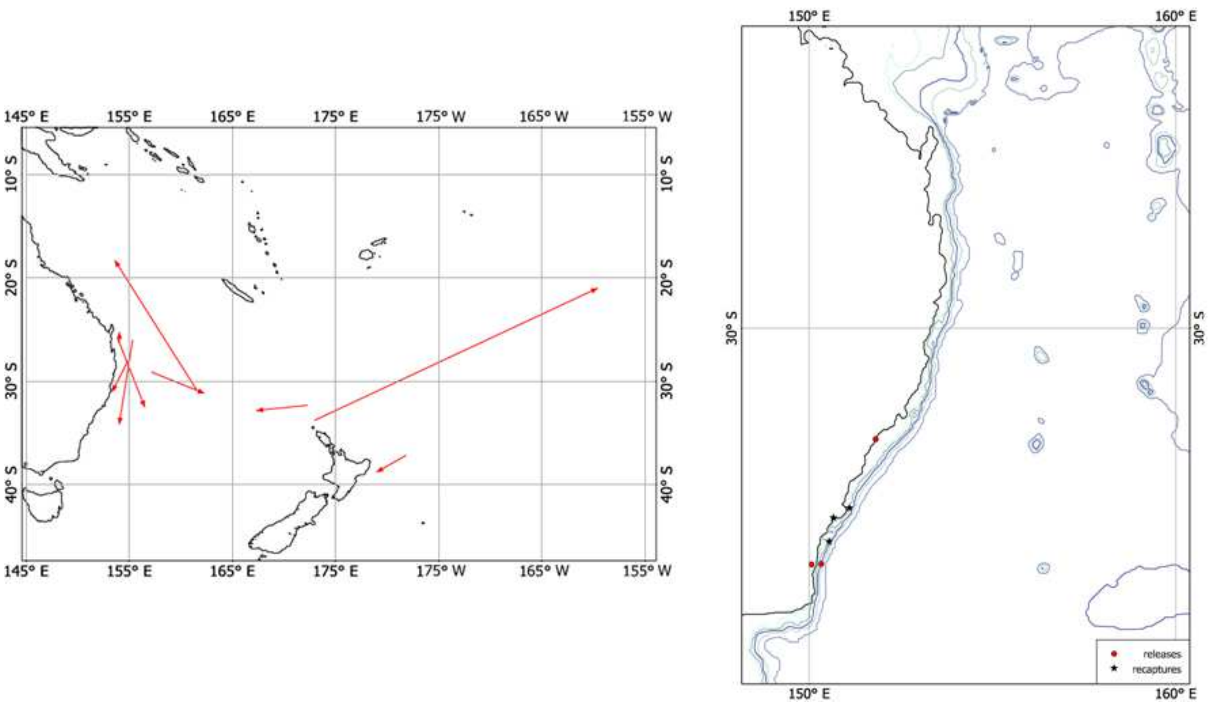


Figure 2.12. Conventional tag releases and recaptures from commercial fishing (left) and recreational fishing (right) tagging programmes.

Electronic tagging data (Figure 2.13) from the WCPO suggest some differences in the extent of movement undertaken by Swordfish in different regions and in association some spatial structuring of Swordfish across the WCPO region (Evans et al. 2012; Evans et al 2014). Movements observed across the WCPO suggest that fish tagged east of 165˚ E are likely to move larger distances with respect to both latitude and longitude than those tagged to the west of 165˚ E. At least some Swordfish in tropical waters extending from around Vanuatu to French Polynesia appear to undertake movements to waters around New Zealand. These movements are suggestive of directed seasonal migrations between tropical spawning grounds and temperate foraging areas. How temporally stable these movements are is unknown; current data derived from tag deployments are limited by short attachment durations and small sample sizes (Evans et al. 2014).

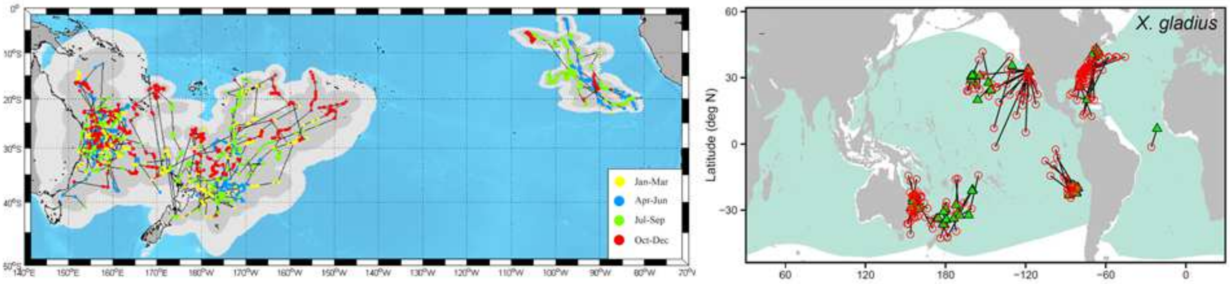


Figure 2.13. Estimated tracks from electronic tag deployments on Swordfish in the south Pacific Ocean (left) and release and transmission positions of electronic tags deployed globally on Swordfish. Reproduced from Evans et al. (2014) and Braun et al. (2015).

Movements observed also suggest a lack of connectivity between the southern and northern regions of the WCPO and limited connectivity between the eastern and western parts of the Tasman and Coral Seas in the south-western Pacific Ocean (Evans et al. 2014). Swordfish in the eastern Australian region may represent a somewhat distinct population, although further tag deployments are required from the eastern side of the Tasman Sea to determine the extent of any connectivity of Swordfish across the Tasman and Coral Seas. Observations to date have not indicated movement between the WCPO and the eastern Pacific Ocean, although data from boundary areas are lacking. Little is known of the dispersion of larval life stages or of the movements of juvenile Swordfish in the WCPO. It is generally thought that as juveniles grow, they move from tropical and subtropical regions into higher latitude waters (Yabe et al. 1959; Palko et al. 1981).

2.3.4 Summary

- Adult Swordfish exhibit seasonal latitudinal shifts in distributions associated with the seasonal extension and retraction of warmer waters into higher latitudes.
- Molecular analyses conducted to date are inconclusive in regards to within basin stock structure, reporting both little evidence of genetic differentiation in samples collected across the basin and some evidence of population subdivision.

- Data derived from tag deployments suggest at least some Swordfish in tropical waters extending from around Vanuatu to French Polynesia appear to undertake movements to waters around New Zealand potentially associated with directed migration between lower latitude spawning grounds and higher latitude foraging grounds.
- Tagging data also suggest a lack of connectivity between the southern and northern regions of the WCPO and limited connectivity between the eastern and western parts of the Tasman and Coral Seas in the south-western Pacific Ocean.
- Anecdotal evidence from fishermen in the ETBF suggest that Swordfish are in higher abundance near seamounts than in other areas of the ETBF and catch data suggest semi residency of Swordfish in these regions.

2.4 Striped Marlin

2.4.1 The fishery

Striped Marlin are predominantly caught by longline fisheries throughout the WCPO and are also targeted by recreational game fishers, largely in the southwest Pacific Ocean (Davies et al. 2012). In addition, individuals are caught incidentally in a number of fisheries including purse seine and drifting gillnet fisheries (Bromhead et al. 2004). Expansion of Japanese longline fisheries in the 1950s and 1960s resulted in massive increases in catches of Striped Marlin, with catches peaking in the mid-1950s at more than 6,000 mt (Figure 2.14; Ueyanagi et al. 1989; Bromhead et al. 2004; Davies et al. 2012). During the 1960s, catches varied between 2,000 and 4,000 mt before decreasing to around 1,500 mt and then increasing again to close to 4,000 mt. Changes in gear methods, targeting practices and fishing areas to concentrate on tropical tunas resulted in a decline in catches in the late 1960s before catches increased again in 1970 as Taiwanese and Korean fleets began to report catches (Bromhead et al. 2004; Davies et al. 2012). During the mid-1970s through to the late 1990s catches of Striped Marlin varied between 1,000 and 2,500 mt. In the late 1990's, catches increased to around 3,000 mt, largely associated with increased targeting of Striped Marlin by Australian and New Zealand longline fleets. Catches have demonstrated a declining trend since (Davies et al. 2012).

Striped Marlin have been caught off the east coast of Australia as byproduct by Japanese and domestic longline vessels targeting Yellowfinand Bigeye Tunas since the Japanese started fishing these waters in the 1950s (Ward 2007). During the 1980s and 1990s catches of Striped Marlin by the Japanese fleet largely fluctuated between 200 - 400 mt, with a peak of close to 600 mt in 1990. Catches by the domestic fleet increased in the late 1990s as fishers started to target Striped Marlin with catches peaking in 2001 at over 800 mt (Figure 2.14). Since 2001, catches have demonstrated a consistent declining trend. Reasons for this trend and inter-annual variation in catches is largely unknown, but may be related to recruitment, migration, changes in targeting practices and substantive reduction in the domestic fleet under the 2006 'Securing our Fishing Future' structural adjustment package implemented by the Australian Fishing Management Authority (Larcombe et al. 2011). On the basis of catch time series spanning 1952 – 2012, the ETBF and adjacent seas of the Coral Sea represent areas in which catches have been consistently higher than all other regions in the WCPO (Harley and Williams 2013).

The most recent stock assessment of Striped Marlin in the WCPO suggests that the stock is currently being fished at levels below maximum sustainable yield and that overfishing is not occurring. Recent trends in recruitment and spawning biomass however, suggest that the stock is approaching an overfished state (Davies et al. 2012). Estimates of biomass produced by the model used are primarily sensitive to assumptions associated with natural mortality, conflicts between the standardised CPUE time series used, and to a lesser extent by the steepness of the stock-recruitment relationship (Davies et al. 2012). Reducing the uncertainty in natural mortality rates and examining CPUE indices of relative abundance for unrepresentative trends have been identified as top priorities in the recommendations resulting from the stock assessment. Additionally, uncertainty in discard mortalities resulting from fish tagged and released by recreational fisheries for Striped Marlin (estimated at 1178 mt and 1459 mt annually in Australia and New Zealand respectively) needs to be considered and inclusion of these mortalities in future stock assessments recommended (Davies et al. 2012).

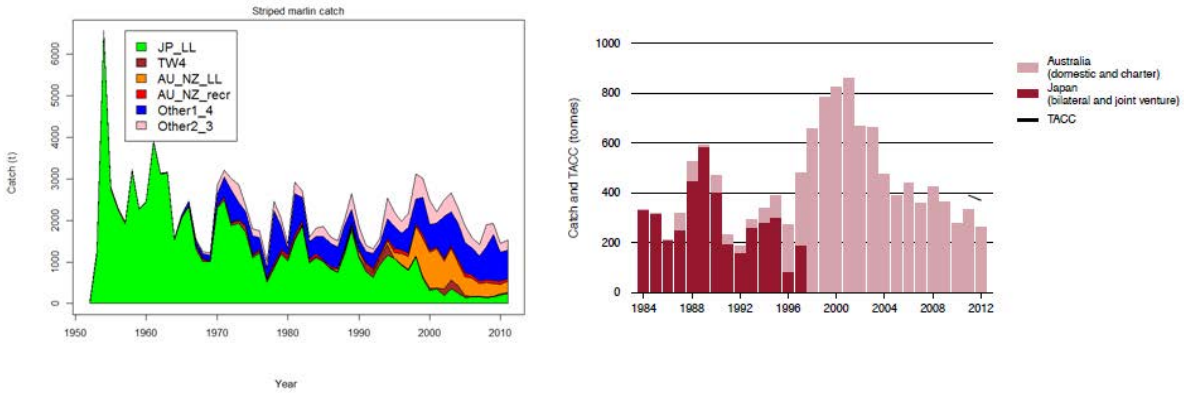


Figure 2.14. Annual catches of Striped Marlin in the south-west Pacific Ocean 1952 – 2011 (left) and the East Australian Billfish Fishery 1984 – 2012 (right). Reproduced from Davies et al. (2012) and Larcombe and New (2013). TACC: total allowable catch.

2.4.2 Biology

Striped Marlin are distributed throughout equatorial to temperate waters in the Pacific Ocean from 45˚N - 40˚S, with highest catches of the species occurring in subtropical regions (Figure 2.15; Bromhead et al. 2004). Based on observations of larvae and the occurrence of mature females, spawning is thought to occur predominantly in the spring and summer months in each Hemisphere. Within the Pacific Ocean, spawning has been identified to occur in the north west in a region southeast of Japan and in the South China Sea, in the north east in the Gulf of California, in the south east and in the southwest in the south Coral Sea (Figure 2.12; Hanamoto 1977; Nakamura 1983; Nishikawa et al. 1985; Bromhead et al. 2004). More recently, larvae have been observed in the waters around Hawaii (Hyde et al. 2006).

Age estimates for Striped Marlin have not been validated directly. Indirect validation of age suggest that Striped Marlin mature at 2-3 years, whilst length at maturity varies between 140 – 180 cm (eye to fork length; Skillman and Yong 1976; Nakamura 1985). Growth rates have been observed to be higher in females than males, with females growing to a larger asymptotic size (Kopf et al. 2011).

Growth also varies spatially with higher growth rates in Striped Marlin from WCPO than those from waters around Hawaii and Mexico (Skillman and Yong 1976; Melo-Barrera et al. 2003; Kopf et al. 2005; Kopf et al. 2011). The extent to which these differences are due to varying techniques and selectivity of fisheries from which samples were derived rather than natural variation however, are unknown. Individuals have been estimated to live to a maximum of 6 – 12 years (Skillman and Yong 1976; Davie and Hall 1990; Melo-Barrera et al. 2003; Kopf et al. 2011). Little has been published on the reproductive biology of Striped Marlin.

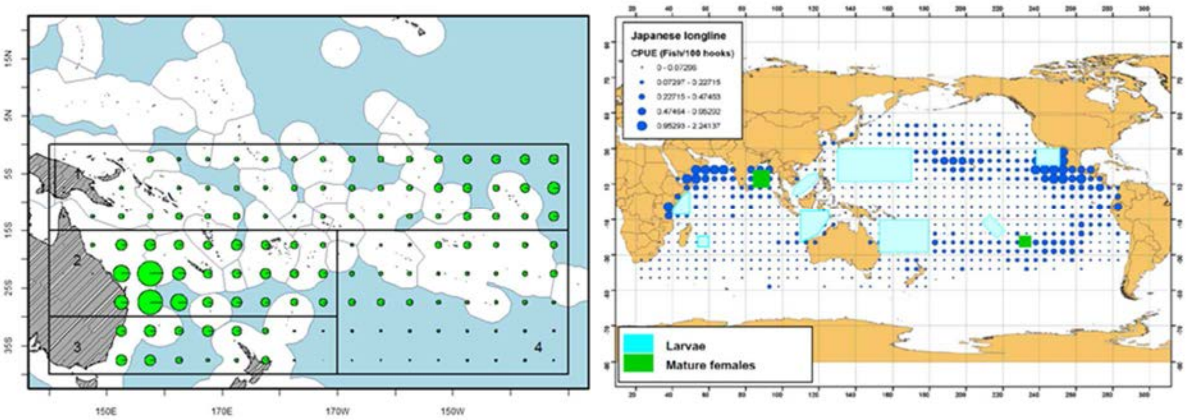


Figure 2.15. Distribution of total catches of Striped Marlin in the south Pacific Ocean by 5˚ squares as indicated by longline catches in the Western and Central Pacific Commission area 1952 – 2011 in relation to the spatial domains of the 2013 stock assessment (left panel). Distribution of Japanese longline catches 1970 – 2000 throughout the Pacific Ocean in relation to spawning grounds identified by observations of larvae and mature females (right panel). Reproduced from Bromhead et al. (2004) and Davies et al. (2013).

Molecular analyses conducted on Striped Marlin in the Pacific Ocean based on allozyme and mitochondrial DNA variation have recorded significant variation between samples from the south-western (Australia), north-central (Hawaii), north-eastern (Mexico) and south-eastern (Ecuador) Pacific Ocean (Graves and McDowell 1994). Further analyses of larger sample sizes which included samples from the additional sites of Japan, Taiwan and California using a combination of mitochondrial DNA and microsatellite loci confirmed temporal stability of the degree of genetic variability and recorded similar spatial genetic heterogeneity to that observed in earlier studies (McDowell and Graves 2008). These results suggest the presence of at least four genetically discrete groups that correspond with discrete spawning areas observed on the basis of larval distributions and the presence of mature females (McDowell and Graves 2008). In particular, samples collected off eastern Australia demonstrated long-term temporal stability and were clearly separated from all other sample locations, supporting the hypothesis that Striped Marlin off the east coast of Australia comprise a distinct genetic stock from those in the Northern Hemisphere, and from waters off

Mexico and Ecuador (McDowell and Graves 2008). Molecular analyses to investigate the genetic diversity of Striped Marlin on smaller scales within the WCPO have not been conducted to date.

2.4.3 Spatial dynamics

In general, Striped Marlin have been associated with waters of 22 – 26˚C, with individuals moving latitudinally as preferred isotherms shift seasonally (Hanamoto 1977; Ortega-Garcia et al. 2003; Bromhead et al. 2004; Sippel et al. 2007). Adults are thought to move into lower latitude waters to spawn in the spring and summer months, and then into higher latitude waters in the late summer and autumn months to forage (Squire and Suzuki 1990). Little is known of the dispersion of larvae or the movements of juveniles.

Movements of Striped Marlin as recorded by conventional tag returns from gamefish tag and release programs describe a mixture of short and long distance dispersal across the WCPO (Figure 2.16). Of those tags deployed off the east coast of the Australia 67% of all tags recorded displacements of < 200 nm. Most tag deployments to date have been of short duration with 90 % of all conventional tags returned within one year (Oritz et al. 2003; Bromhead et al. 2004)

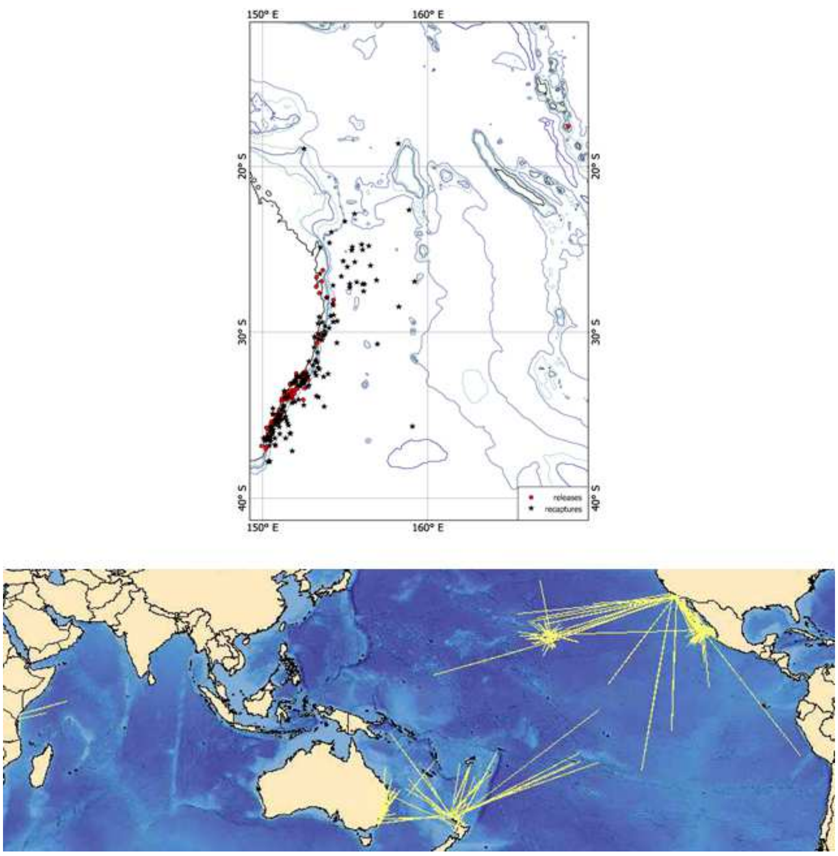
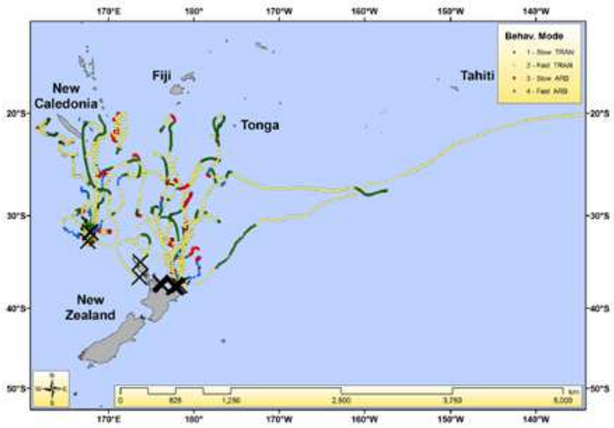


Figure 2.16. Displacements of conventional tags released on Striped Marlin by gamefishing tagging programs off the east coast of Australia (top) and across the Pacific and Indian Oceans (bottom). Reproduced by Bromhead et al. (2004).

Striped Marlin tagged with electronic tags under differing research programs have demonstrated displacements similar ns to those from conventional tags, with movements of fish tagged around the waters of New Zealand describing connectivity with waters around New Caledonia, Fiji and Tonga (Figure 2.17). Small numbers of tags have also described linkages waters around the Cook Islands and French Polynesia (Domeier 2006; Sippel et al. 2011). The similar movements recorded by the two tag types, suggests that there is some temporal stability in the connectivity between these regions in the WCPO (Oritz et al. 2003; Bromhead et al. 2004).



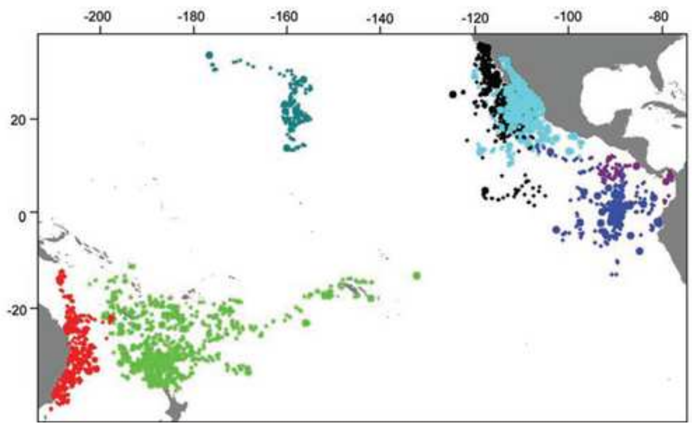


Figure 2.17. Estimated movements of 25 Striped Marlin tagged with electronic tags in waters to the north and north-west of New Zealand (top) and estimated movements of 125 Striped Marlin tagged with electronic tags in waters in the Pacific Ocean off Australia (red), New Zealand (green), Ecuador (dark blue), Costa Rica and Panama (purple), Mexico (light blue), California (black) and Hawaii (dark green; bottom). Black crosses on the top panel represent release locations. Reproduced from Domeier (2006) and Sippel et al. (2011).

Both conventional tag returns and electronic tags suggest little eastward movement of Striped Marlin tagged in waters off Australia, with the majority of movements recorded being latitudinal rather than longitudinal, suggesting a degree of residency of Striped Marlin in this region (Oritz et al. 2003; Bromhead et al. 2004; Domeier 2006). Small numbers of conventional tags deployed in New

Zealand waters have recorded westward movement of individuals into the western Tasman and Coral Seas suggesting potential connectivity of individuals across the Tasman and Coral Seas (Oritz et al. 2003; Bromhead et al. 2004). Care must be taken when describing the extent of potential connectivity of Striped Marlin in the south west Pacific Ocean as tag deployments are limited by short tag attachment durations and deployments across limited spatial areas. Average time at liberty for electronic tags less than 100 days, with the longest deployment 259 days (Domeier 2006; Sippel et al. 2007; Sippel et al. 2011). To date, there have been no recorded movements of Striped Marlin between the WCPO and the eastern Pacific Ocean.

2.4.4 Summary

- Catch data suggest annual latitudinal movements of adults in the spring and summer to low latitude spawning areas and movements in the late summer and autumn to higher latitude foraging areas.
- Striped Marlin associate predominantly with waters of 21 – 24˚C with individuals moving latitudinally as preferred isotherms shift seasonally.
- Molecular analyses carried out to date suggest the presence of at least four genetically discrete groups that correspond with discrete spawning areas observed on the basis of larval distributions and the presence of mature females. Analyses of samples collected off eastern Australia demonstrated long-term temporal stability and were clearly separated from all other sample locations.
- Tagging data suggest semi-residence of Striped Marlin in waters off eastern Australia with individuals tagged in these waters, in general, demonstrating lower displacement rates than Striped Marlin tagged elsewhere and little longitudinal movement. Striped Marlin tagged off New Zealand demonstrate higher displacement rates than those tagged off eastern Australia and linkages with waters around New Caledonia, Fiji and Tonga and to a lesser extent the Cook Islands and French Polynesia. The extent of connectivity with waters around the Cook Islands and French Polynesia is unknown and is limited by low samples sizes and short duration tag attachments.

2.5 Yellowfin Tuna

2.5.1 The fishery

Yellowfin Tuna are caught throughout the WCPO using a wide range of fishing gears including longline which principally target adult Yellowfin Tuna, purse seine which primarily target juveniles, pole and line, handline, gillnet, ringnet and others which target a range of sizes of fish. Fisheries range in size from small scale artisanal fisheries to large distant water longline and purse seine fisheries (Langley et al. 2011).

Yellowfin Tuna were first caught by Japanese longline vessels during the 1950s and 1960s for the canning industry. After an initial increase in catches, catches stabilised during this period at just below 100,000 mt (Figure 2.18; Miyake et al. 2004; Langley et al. 2011). During the 1970s, targeting of Yellowfin Tuna shifted to the sashimi market, purse seining was introduced and an increase in effort with the development of distant water fleets from Taiwan and the Republic of Korea and domestic fleets in the Philippines and Indonesia occurred. The industrial purse seine fishery quickly began to dominate catches and has accounted for the largest proportion of catches in the WCPO since the 1980s (Langley et al. 2011). Purse seiners target both free-swimming schools of Yellowfin Tuna (unassociated schools) and schools associated with floating objects (associated schools). This tendency of Yellowfin Tuna to associate with floating objects has been utilised by the fishery with deployments of both fixed and floating artificial fish aggregating devices allowing for greater reliability and efficiencies in fishing (Leroy et al. 2012). There is considerable uncertainty associated with reported catches from the purse seine fleet and catches are thought to under-estimate actual catch levels of Yellowfin Tuna (Lawson and Sharples 2011). Overall catches have increased from around 100,000 to a peak of 650,000 mt in 2008 before declining to around 550,000 mt in 2009 and 2010 (Langley et al. 2011). Of these, catches by longline vessels peaked at 110,000 mt in the early 1980s before stabilising at around 70,000 – 80,000 mt where they have remained since (Langley et al. 2011; Davies et al. 2014).

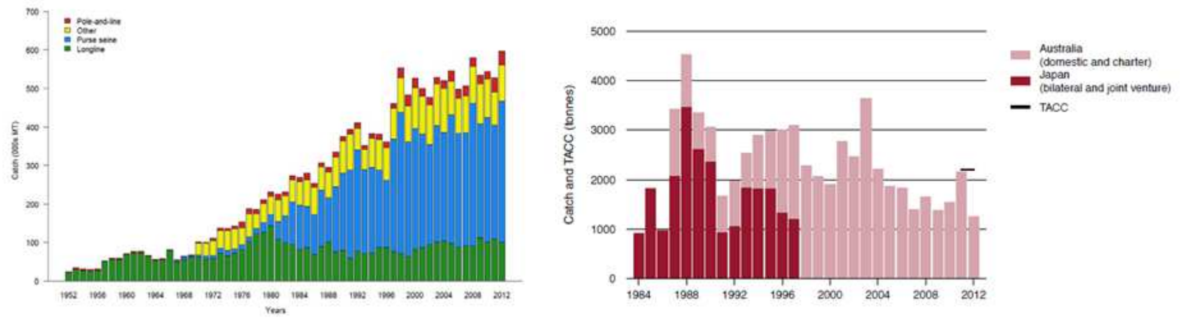


Figure 2.18. Annual catches of Yellowfin Tuna in the western and central Pacific Ocean 1952 – 2012 (left) and the East Australian Billfish Fishery 1984 – 2012 (right). Reproduced from Davies et al. (2014) and Larcombe and New (2013). TACC: total allowable catch.

Yellowfin Tuna have been caught in the waters off eastern Australia since the introduction of live bait and pole fishing in the 1950s. Domestic longline vessels began targeting Yellowfin Tuna for cannery operations in the 1960s and the introduction of purse seine vessels in the 1970s increased catches further (Ward 2007). Catch rates throughout the 1980s were highly variable (Figure 2.18) and resulted in many vessels either leaving the fishery or refocusing their targeting to other species. Factors driving this variability are unknown, but have been associated with variable natural abundance throughout the southern ETBF, local depletion and periodic immigration of juveniles from other parts of the WCPO as abundance throughout the WCPO varies (Campbell 1999; Ward 2007). During the 1990s catch rates increased again with rapid expansion of longline vessels in the northwest Coral Sea (Ward 2007). Shifts in targeting are most likely associated with variable catches in the late 1990s and through the first half of the 2000s, with catches peaking at 3,096 mt in 2003 (Hender and Ward 2006). A decrease in fishing effort in the ETBF associated with market forces, management measures and a reduction in the fleet under the 2006 ‘Securing our Fishing Future’ structural adjustment package implemented by the Australian Fishing Management Authority resulted in a decrease in overall catches. Catches have varied between around 1,000 – 2,000 mt since with 1101 mt caught in 2012 (Figure 2.18; Patterson et al. 2013).

Similar concerns over the representativeness of models used to assess Yellowfin Tuna in the WCPO as those raised during a review of the 2011 Bigeye Tuna assessment were put forward during the review process (Ianelli et al. 2012; Davies et al. 2014). In response to the recommendations put forward by the review the same changes have been implemented into the assessment for Bigeye Tuna have also been implemented for Yellowfin Tuna. These relate to data included in the assessment, data analyses undertaken, regional structure and associated fisheries definitions, implementation and testing of the stock assessment model and assessment of model output (Harley et al. 2014 and associated references therein; SPC-OFP 2014). Of particular relevance is that the number of spatial regions within the model used to assess Yellowfin Tuna has increased and a new region encompassing the Coral Sea included (Figure 2.19). The modifications implemented in the 2014 stock assessment are considered to have improved overall outputs from the assessment by reducing data conflicts and inconsistencies and uncertainties in recruitment estimates (Davies et al. 2014). Conclusions from the 2014 assessment support those put forward in the previous assessment suggesting that depletion of Yellowfin Tuna in the WCPO has increased over time reaching 60% of the unexploited biomass in 2012. The extent of depletion varies spatially with the greatest depletion occurring in the western equatorial region (regions 4 and 8) and as a result this region is considered to be fully exploited while all other regions are considered under-exploited (Davies et al. 2014). Overall, it is considered that overfishing is not occurring and that the population is not in an overfished state, but that any increase in fishing mortality would most likely increase depletion in the western equatorial regions (Davies et al. 2014).

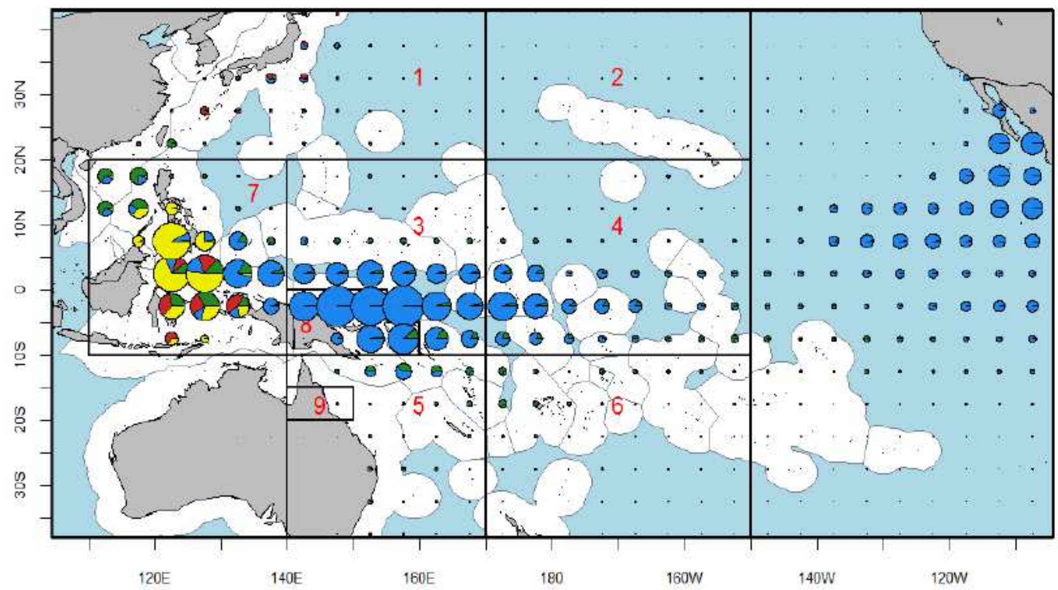


Figure 2.19. Distribution of cumulative catches of Yellowfin Tuna by 5˚x 5˚ squares 1990 – 2010 in relation to the spatial domains of the 2014 stock assessment in the western and central Pacific Ocean. Different gear types are represented by green: longline; blue: purse seine; red: pole and line; yellow: other. Reproduced from Davies et al. (2014).

2.2.1 Biology

Yellowfin Tuna have a pan-tropical distribution in the Pacific Ocean primarily between 30°N and 30°S and extending to around 40° in both Hemispheres seasonally (Figure 2.19; Sund et al. 1981). They are primarily distributed in waters where surface temperatures range 20 – 30°C, although have been observed to occur in waters down to 15°C in low numbers (Sund et al. 1981). Catches throughout the Pacific are highest in the western equatorial region (Figure 2.19) and variation in the distribution of catches has been associated with the El Niño Southern Oscillation (Lu et al. 2001). The distribution of Yellowfin Tuna in south-eastern Australian waters has been associated with warm core eddies formed from the East Australian Current. Such oceanographic features provide warm water habitat suitable for individuals and also aggregate prey species at their productive edges, providing concentrations of prey accessible to Yellowfin Tuna at the limits of their preferred temperature habitat (Young et al. 2001).

Spawning, in general, occurs in tropical regions with waters warmer than 26°C, although has been reported in waters as low as 22°C (Schaefer 1998) and larvae have been caught in waters of 24°C (Boehlert and Mundy 1994). Spawning occurs essentially continuously throughout the year at tropical latitudes, becoming progressively more seasonal at higher latitudes and restricted to the summer months when surface water temperatures are above 24°C (McPherson 1991; Schaefer 1998; Itano 2000; Sun et al. 2005). Length at 50% maturity (L_{50}) varies spatially ranging 56.6 – 73.8 cm length to caudal fork (LCF) in males and 79.1 – 98.1 cm LCF in females in the EPO (Schaefer 1998) and 98.13 – 112.54 cm LCF in females across the central and western equatorial Pacific (Itano 2000). Individuals from Indonesia and the Philippines appear to have slower growth rates than those in the wider WCPO and in association have been observed to have a L_{50} smaller (93.86 cm) than that observed elsewhere in the WCPO (Itano 2000; Hoyle et al. 2009). In the Coral Sea region, L_{50} in female Yellowfin Tuna has been reported as ranging 107.9 – 120.0 cm LCF, with fish caught by the pole and line fishery maturing at smaller lengths compared to the longline fishery (McPherson 1991). Males tend to dominate sex ratios in size classes greater than 130 cm (Schaefer 1998; Sun et al. 2005; Hoyle et al. 2009). Ageing studies on Yellowfin Tuna are limited generally. Within the Pacific Ocean age estimates derived from counts of daily increments have been restricted to fish of less than 3.4 years (Lehodey and Leroy 1999). The maximum time at liberty recorded by a game fish tagging program conducted off eastern Australia is 7.3 years (NSW DPI 2005). This is higher than maximum ages recorded by age and growth studies conducted in both the Atlantic (6.5 years) and Indian Oceans (6 years), but less than the current maximum bound used in the stock assessment for the Yellowfin Tuna in the WCPO which is 8+ years (Lessa and Duarte-Neto 2004; Filmalter et al. 2009; Langley et al. 2011).

2.2.1 Spatial dynamics

An investigation into the population structure of Yellowfin Tuna in the western Coral Sea utilising electrophoresis of four polymorphic loci has suggested some degree of structure both latitudinally and longitudinally (Smith et al. 1988). Genetic data have revealed only minor levels of heterogeneity in Pacific Ocean populations based on investigations of mitochondrial DNA and microsatellite loci (Scoles and Graves 1993; Appleyard et al. 2001; Gunn et al. 2002), suggesting that there is sufficient mixing and gene flow within the Pacific to prevent genetic differentiation. More recently, genetic investigations utilising a larger number of microsatellite loci (Diaz-Jaimes and Uribe-Alcocer 2006), investigations into the microchemistry of otoliths (Itano et al. 2008; Wells et al. 2012) and those utilising electronic tagging have documented evidence supporting population structure in Yellowfin Tuna across the Pacific (Itano and Holland 2000; Schaefer et al. 2007). Similarly to Bigeye Tuna, stable isotope signatures from otoliths suggest spatial structuring of spawning populations with mixing decreasing as the distance between location increases. Otoliths collected from individuals caught in the waters of the western Pacific Ocean showed no similarities with those collected from individuals caught in the waters of the central Pacific Ocean (Wells et al. 2012). Investigations into geographic variation in morphological features and life history characteristics have also suggested limited mixing and a degree of structure to populations (Schaefer 1992; Schaefer 1998).

An investigation into the origins of Yellowfin Tuna caught off the east coast of Australia using otolith microchemistry reported that the Coral Sea region was a major source of recruits to the fishery within the ETBF, but that there were also linkages between Yellowfin Tuna across the western Pacific Ocean with smaller associations with fish from Indonesia and the Solomon Islands (Gunn et al. 2002). It was concluded that in some years the majority of Yellowfin Tuna caught in the ETBF were derived from localised spawning in the Coral Sea and in other years fish are derived from influxes of fish from equatorial regions around Indonesia and the Solomon Islands (Gunn et al. 2002). This supported previous assumptions made on the origin of recruits to the ETBF (Hampton and Gunn 1998; Campbell 1999).

Conventional tagging data throughout the Pacific have demonstrated that Yellowfin Tuna are capable of extensive movements and so have the potential to mix across their range (Figure 2.20; Itano and Williams 1992; Hampton and Gunn 1998; Hoyle et al. 2009; Kolody and Hoyle 2013). At the same time, a large proportion of recaptures have been recorded close to release sites, suggesting some degree of regional fidelity (Itano and Williams 1992; Hampton and Gunn 1998). Median displacements of tags released on Yellowfin Tuna in the Bismarck and Solomon Seas and also the far western Indonesia-Philippines area have been observed to be smaller than those released elsewhere in the WCPO (Hoyle et al. 2013). In the Australian region, both conventional tags released in the Coral Sea under the Regional Tuna Tagging Programme (Gunn and Hampton 1998) and by recreational fishers demonstrate similar patterns with a large proportion of tag recaptures recorded close to release sites. Of all tags recaptured from Yellowfin Tuna tagged by recreational fishers 78% of recaptures were reported < 200 nm from their release location.

The vast majority of tags released on Yellowfin Tuna in the WCPO have been conventional tags, with juveniles comprising the majority of individuals tagged. More recently both acoustic and archival tags have been deployed on juvenile Yellowfin Tuna throughout the WCPO under the Pacific Tuna Tagging Programme (Caillot et al. 2012) and may provide further insights into the extent of movements of Yellowfin Tuna across a range of age groups (juvenile, sub-adult and adult) throughout the region and the degree to which conventional tagging collected to date is representative of those movements. Initial analyses of these data have begun (e.g. Scutt Phillips et al. 2013; Leroy et al. 2014) and it is expected that these data will be published in the coming months (S. Nicol, Secretariat of the Pacific Community pers. comm.). Preliminary results from the deployment of archival tags in juvenile Yellowfin Tuna in the Solomon and Bismark Seas demonstrate limited dispersal from the region, with only one individual of 12 recaptured moving out of the region and into the greater western Pacific Ocean (Leroy et al. 2014).

Juvenile Yellowfin Tuna tagged outside of Australian waters and recaptured in the ETBF have exclusively been derived from the Solomon Sea region (Langley et al. 2011). Returns of tags deployed on Yellowfin Tuna outside of Australian waters have been extremely low however, with only four tags recaptured from the Pacific Tuna Tagging Program (Bruno Leroy, SPC, pers. comm). Conversely, conventional tags deployed on juvenile Yellowfin Tuna in the north Coral Sea have been observed to disperse the north and east, demonstrating some degree of mixing and connectivity with these areas (Figure 2.20). Similar to conventional tag deployment elsewhere in the WCPO, many tags released on Yellowfin Tuna in the ETBF under research and game fish tagging programs describe limited dispersion with recaptures recorded within 500km from release sites suggesting semi residency of individuals on the continental shelf region of eastern Australia (NSW DPI 2005).

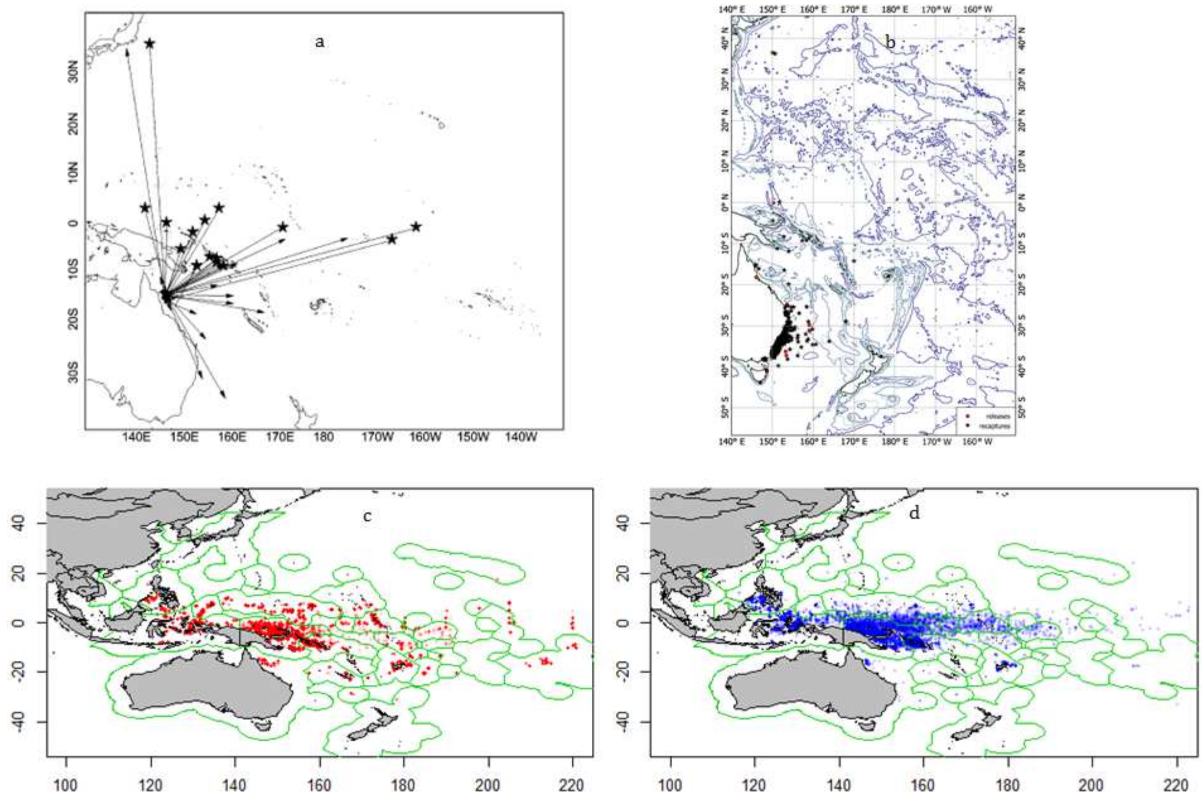


Figure 2.20. (a) Displacements of conventional tag releases on juvenile Yellowfin Tuna tagged in the northwest Coral Sea 1991 – 1992. Arrowheads: longline vessel recaptures; stars: purse seine and pole and line recaptures. (b) release and recapture positions of conventional tags released on Yellowfin Tuna by recreational fishers off the east coast of Australia. (c) release positions of Yellowfin Tuna tagged with conventional tags from all tagging programs conducted in the western and central Pacific Ocean 1989 – 2012. (d) positions of recaptured conventional tags Yellowfin Tuna tagged with conventional tags from all tagging programs conducted in the western and central Pacific Ocean 1989 – 2012. Reproduced from Hampton and Gunn (1998) and Kolody and Hoyle (2013).

Very little is known of the movements of adult Yellowfin Tuna. To date, the only detailed investigation of the movements of adults in the WCPO as provided by electronic tags has been that off eastern Australia (Evans et al. 2011). Pop-up satellite archival tags deployed on adult Yellowfin Tuna, similarly to tags deployed on juvenile Yellowfin Tuna also recorded a mixture of movements. Although a number of Yellowfin Tuna undertook substantive movements (distances between release and tag pop-up positions ranged 54.03 – 1,462.88km), all remained within the Coral and Tasman Seas (Figure 2.22; Evans et al. 2011). Of 20 tags from which data were recovered, only five individuals were observed to undertake movements of greater than 500km straight-line distance between deployment and pop-up transmission positions. Individuals were observed in the 25 - 35°S region throughout all months of the year and were only observed south of 35°S during late summer/autumn. Larger scale movements were variable in nature and occurred in north-south and east-west directions, demonstrating linkages of Yellowfin Tuna between the ETBF and the wider western Pacific Ocean and also between the northern and far southern parts of the ETBF. This movement behavior is compatible with that reported from conventional tagging studies of Yellowfin Tuna conducted previously in the region (Pepperell and Diplock 1989; Hampton and Gunn 1998). Although limited by short attachment durations of tags, a state-space behavioural switching model identified an area of high residency in the region of the Tasmantid Seamount chain and the Lord How Rise as well as the outer edge of the East Australian Current (Evans et al. 2011).

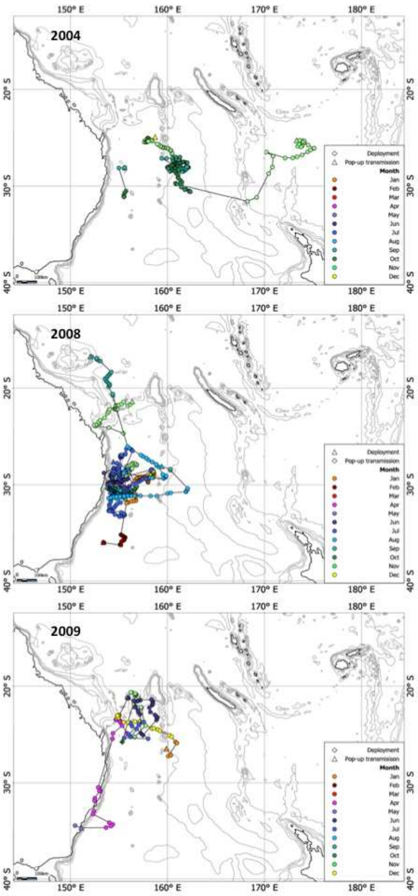


Figure 2.22. Estimated tracks of adult Yellowfin Tuna tagged with electronic tags off the east coast of Australia 2004, 2008-2009. Reproduced from Evans et al. (2011).

2.2.2 Summary

- Molecular analyses conducted to date are inconclusive in regards to within basin stock structure, reporting both little evidence of genetic differentiation in samples collected across the basin and some evidence of population subdivision.
- Investigations into the microchemistry of otoliths have documented some evidence for population structure, concluding that in some years the majority of Yellowfin Tuna caught in the ETBF were derived from localised spawning in the Coral Sea and in other years fish are derived from influxes of fish from equatorial regions around Indonesia and the Solomon Islands.
- Data derived from tag deployments suggest Yellowfin Tuna are capable of undertaking large scale movements but the majority of movements are limited, suggesting some regional fidelity.
- Tagging data suggest semi residency of Yellowfin Tuna in continental shelf areas of the ETBF in association with the East Australian Current, seamounts in the Tasmantid chain the Lord Howe Rise region.

3. Current key knowledge gaps relating to species connectivity and movement in the western Pacific Ocean

Many of the knowledge gaps on the spatial dynamics and connectivity of the five species targeted in the ETBF that were highlighted by the evaluation of the harvest strategy framework for the ETBF (Kolody et al. 2010) and more recently highlighted in the review of the harvest strategy policy (DAFF 2013) still remain.

In general, Bigeye and Yellowfin Tunas, Swordfish and Striped Marlin appear to demonstrate some degree of residency in the Coral and Tasman Sea region, with tagging studies predominantly establishing small scale movements in individuals, with a smaller degree of larger scale movements demonstrating connectivity with the wider western Pacific Ocean. The extent to which this behaviour has been recorded across life stages however varies, with the majority of studies conducted on Bigeye and Yellowfin Tunas restricted to juveniles and those conducted on Swordfish and Striped Marlin restricted to adults. Knowledge of the movements of Albacore throughout the ETBF and the degree of connectivity with the wider western Pacific Ocean is sparse with a lack of tagging data resulting in high uncertainty in any interpretation of movement data collected.

In association, the extent to which localised residency within the ETBF occurs is unknown. Detailed movements recorded by juvenile Bigeye Tuna tagged with electronic tags in the north and in the south Coral Sea (Clear et al. 2005; Gunn et al. 2005; Evans et al. 2008), adult Swordfish in the south Coral Sea (Evans 2010; Evans et al. 2012; Evans et al. 2013) and adult Yellowfin Tuna in the south Coral Sea/north Tasman Sea (Evans et al. 2011), suggest that localised residency on scales smaller than the ETBF may occur. Small sample sizes, limited deployment periods and the coarse resolution of position estimates derived via geolocation, particularly those associated with latitude however, limit the ability to determine spatial dynamics at these scales. As a result, residencies in particular region have been restricted to observations of a number of months and it is unknown if such residency behaviours occur over longer time scales.

It has been postulated that Swordfish spawn in the Coral Sea region (Young et al. 2003) and that aggregations of Bigeye and Yellowfin Tunas in the northern Coral Sea are associated with spawning (McPherson 1991). Examination of the gonads of female Yellowfin Tuna from the northern Cora Sea region of the ETBF documented advanced stages of oocyte maturation, suggesting individuals were spawning in the region during the months of October and November (McPherson 1991). Scombrid larvae have been observed in plankton tows in the northern waters of the Great Barrier Reef (Leis and Goldman 1984). The species identification of these larvae however, was not undertaken, so it unclear if larvae were Yellowfin or Bigeye Tunas or other scombrid species known to occur in the region (e.g. Longtail Tuna, *Thunnus tonggol*; Kawakawa or Mackerel Tuna, *Euthynnus affinis*; Spanish Mackerels, *Scomberomorus* spp.). Preliminary analysis of the microchemistry of Yellowfin Tuna otoliths support the hypotheses that the Coral Sea region is a major source of recruits to the fishery within the ETBF, but that there are also linkages with Indonesia and the Solomon Islands (Gunn et al. 2002). Further analyses to establish the degree to which Yellowfin Tuna recruits are sourced from within the Coral Sea region as opposed to recruits from outside the Coral Sea and their ongoing residency within the Coral Sea has not been undertaken. Small Swordfish (of approximately 100cm and thought to be first year recruits) are caught periodically in the ETBF in the southern Coral Sea (CSIRO unpublished data), supporting the hypothesis that spawning may occur in proximal waters. The origin of these recruits to the fishery however is unknown at present. For most species, identification of specific spawning areas, the degree of fidelity to spawning sites and the origin of recruits within the ETBF are still largely unknown.

Mixing rates used in stock assessments for Albacore, Bigeye and Yellowfin Tunas and Striped Marlin throughout the western and central Pacific Ocean assume relatively high and stable levels of movement (Davies et al. 2011; Langley et al. 2011; Davies et al. 2012; Hoyle et al. 2012). A recent investigation into the mixing rates of tags deployed on bigeye, skipjack and Yellowfin Tunas found strong evidence for incomplete mixing after one quarter for Bigeye Tuna and after five quarters for Yellowfin Tuna (Kolody and Hoyle 2013). Estimated periods of incomplete mixing were regarded as minimums largely because observations (tags at liberty for extended periods of time) restricted the ability to make inferences on mixing in relation to longer periods at liberty (Kolody and Hoyle 2013). This suggested that rates of mixing used in stock assessments for these species may not be appropriate and that mixing occurs on longer time scales than currently assumed. Recent investigation of tagging data from Swordfish estimated a diffusive mixing rate across boundary regions within the stock assessment of 0.11, although noted that the estimate was predicated on the assumption that there was purely diffusive mixing, while it was recognized that the model was inappropriate for describing more complicated population structure (Evans et al. 2012; Davies et al. 2013). A range of diffusive mixing rates were incorporated into the stock assessment in response (Kolody and Davies 2008; Davies 2013). Semi-residency in Bigeye and Yellowfin Tunas has posed problems for resolving issues with tag reporting rates within stock assessment models and has led to recent restructure of spatial domains within stock assessments for these species within the WCPO. Assessments however, still remain sensitive to assumptions associated with tagging data including assumed mixing periods. More definitive rates of mixing across regions in the western and central Pacific Ocean are required across all species.

4. Research priorities addressing key knowledge gaps on connectivity and movement of species in the western Pacific Ocean

4.1 Tagging programs

In nearly all species, information on movement and connectivity has been largely derived from conventional tagging programs. Conventional tagging programs have several advantages over electronic tagging programs in that they can provide valuable information for fisheries biology and stock assessment beyond just movement (including estimation of growth rates, mortality and abundance) and in relation to electronic tagging programs are considerably less expensive. Conventional tagging however, is a fishery-dependent mark-recapture technique that depends almost entirely on animal recaptures within fisheries. Because tag releases and fishing effort are not randomly distributed through time and space, and tag mixing appears to be incomplete for the WCPO tuna species examined, information from conventional tag returns is likely to be biased. Reporting rates for conventional tag returns are also often low and may be inconsistent across fleets, which can further bias the perception of movement (Hoenig et al. 1998; Pollock et al. 2001; Polacheck et al. 2006). Even with large numbers of deployments, it is often logistically impossible to release tags in a manner that is representative of the distribution of the population, particularly for widespread species such as tunas and billfishes. Observations from limited and uneven deployments have the potential to be misleading and may not be representative of the population as a whole. Electronic tagging programs alternatively, can provide substantially more information on the movement dynamics of individuals, are largely fisheries independent (archival tags still rely on fisheries for tag returns) and can provide additional useful information on the behaviour and physiology of individuals (e.g. Bestley et al. 2008, Bestley et al. 2010, Aranda et al. 2013). Their expense however, often results in limited numbers of deployments and deployments across restricted and uneven spatial distributions in relation to the distribution of the population being studied. As a result, like many conventional tagging programs, there is the potential for such programs to be biased in their description of movements and connectivity.

Further, many electronic tagging programs to date have been designed with biological or ecological questions in mind and are subsequently not optimised for provision of data into stock assessments (Sippel et al. 2015), resulting in a lack of uptake and integration. Closer collaborations between researchers involved in stock assessments and tagging program in the design of electronic tagging studies would serve to help to inform experimental designs for tagging programs and thereby provide data more appropriate for integration into stock assessments. Deployment of an adequate number of electronic tags within carefully selected regions across a species' distribution can allow for robust observations of dispersal and movement throughout regions. In particular, tag deployments across a range of size groups within each of the main species within the ETBF and from either side of boundary regions in the Tasman and Coral Seas across the latitudinal range of the ETBF would be useful in determining the degree of movement across this boundary.

4.2 Biochemical analyses

Most analyses of the stable isotopes of otolith cores conducted to date aimed at discriminating the origins, broad scale movements and fidelity to particular spawning regions by individuals caught in the ETBF have been preliminary in nature and restricted to Yellowfin Tuna and Albacore. Across the WCPO, these techniques have shown some promise in discriminating a degree of spatial structure in both Bigeye and Yellowfin Tunas (Wells et al. 2012; WPRFMC 2014).

Collection and analysis of otoliths from both juveniles and adults of each of the five species within the ETBF and those from young of the year derived from carefully selected nursery areas across the western and central Pacific Ocean would allow for investigation of origins of individuals and potentially any regular migrations undertaken by individuals.

Signature fatty acids have recently been used to identify broad scale latitudinal differences in Albacore and skipjack tuna diets (Parrish et al. 2015). Results from these analyses suggest that such studies could potentially be used to examine region specific differences in habitat and the extent of broad scale residency within regions on scales of weeks to months. More comprehensive biochemical analyses could potentially be used to investigate broad scale latitudinal and longitudinal residency in individuals from the five target species in the ETBF.

4.3 Molecular analyses

Molecular analyses to date have been unable to resolve fine-scale structure within populations in the majority of species within the Pacific Ocean. This could be the result of a number of factors. Firstly, only a small amount of gene flow (a few migrants per generation) may be sufficient to obscure genetic differentiation between conspecific stocks (Hauser and Ward 1998). Secondly, connectivity might be largely facilitated by larval dispersal, with larvae transported regularly between regional and distant populations (Cowen et al. 2007; Cowen and Sponaugle 2009). Identification of larval origins and dispersal pathways of all five species are largely unknown. Spawning occurs over extended temporal and spatial scales and the patchy nature of surveys conducted further precludes determination of these pathways (Grall et al. 1983). Thirdly, the molecular markers investigated to date may not be sufficient to identify stocks with only a small degree of isolation and finally, sample sizes required to resolve any structure within the population may not have been adequate and larger sample sizes may be required (Kasapidis et al. 2008). New genetic techniques (e.g. single nucleotide polymorphisms; Nielsen et al. 2009) show promise in resolving structure in populations that may not have been possible using older, less sensitive techniques (e.g. Wirgin et al. 2007; Narum et al. 2008). Collection and analysis of samples from both juveniles and adults of each of the five species within the ETBF and those from carefully selected areas across the western and central Pacific Ocean would allow for investigation of spatial structure within populations across the WCPO and potentially resolve some of the issues associated with spatial division of fisheries data and mixing within regional stock assessments.

5. References

Alvarado-Bremer JR, Mejuto J, Gómez-Márquez J, Boán F, Carpintero P, Rodríguez JM, Viñas J, Greig TW, Ely B. 2005. Hierarchical analyses of genetic variation of samples from breeding and feeding grounds confirm the genetic partitioning of northwest Atlantic and South Atlantic populations of Swordfish (*Xiphias gladius* L.). Journal of Experimental Marine Biology and Ecology 327: 167 – 182. doi:10.1016/j.jembe.2005.06.022.

Alvarado Bremer JR, Stequert B, Robertson NW, Ely B. 1998. Genetic evidence for inter-oceanic subdivision of Bigeye Tuna (*Thunnus obesus*) populations. Marine Biology 132: 547 – 557.

Appleyard SA, Grewe PM, Innes BH, Ward RD. 2001. Population structure of Yellowfin Tuna (*Thunnus albacares*) in the western Pacific Ocean, inferred from microsatellite loci. Marine Biology 139: 383 – 393.

Aranda G, Abascal FJ, Varela JL, Medina A. 2013. Spawning behaviour and post spawning migration patterns of Atlantic bluefin tuna (*Thunnus thynnus*) ascertained from satellite archival tags. Plos One 8: e76445. doi:10.1371/journal.pone.0076445.

Bestley S, Patterson TA, Hindell MA, Gunn JS. 2008. Feeding ecology of wild migratory tunas revealed by archival tag records of visceral warming. Journal of Animal Ecology 77: 1223 – 1233. doi:10.1111/j.1365-2656.2008.01437.

Bestley S, Patterson TA, Hindell MA, Gunn JS. 2010. Predicting foraging success in a migratory predator: integrating telemetry, environment, and modelling techniques. Ecology 91: 2373 – 2384.

Boehlert GW, Mundy BC. 1994. Vertical and onshore-offshore distributional patterns of tuna larvae in relation to physical habitat features. Marine Ecology Progress Series 107: 1 – 13.

Bromhead D, Pepperell J, Wise B, Findlay J. 2004. Striped Marlin: biology and fisheries. Final report to the Australian Fisheries Management Authority. Bureau of Rural Sciences, Canberra.

Caillot S, Leroy B, Sanchez C, Kolody D, Nicol J, Hampton J, Lewis A, Usu T, Kumasi B, Kumoru L. 2012. Pacific tuna tagging and PNG tagging project progress report and workplan for 2012-2013. Paper WCPFC-SC8-2012/RP-PTTP-02 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7 – 15 August 2012, Busan, Republic of Korea.

Calkins TP. 1980. Synopsis of biological data on the Bigeye Tuna (*Thunnus obesus*) (Love 1839), in the Pacific Ocean. IATTC Special Report 2: 213 – 260.

Campana SE. 1999. Chemistry and composition of fish otoliths: pathways, mechanisms and application. Marine Ecology Progress Series 188: 263 – 297.

Campbell RA. 1999. Long term trends in Yellowfin Tuna abundance in the south-west Pacific – with an emphasis on the eastern Australian fishing zone. Final report to the Australian Fisheries Management Authority. CSIRO Marine Research, Hobart.

Campbell R, Hobday A. 2003. Swordfish – seamount – environment – fishery interactions off eastern Australia. Working paper BBRG-3 presented to the sixteenth meeting of the Standing Committee on Tuna and Billfish, 9 – 15 July 2003, Mooloolabah, Australia.

Chiang H-C, Hsu C-C, Lin H-D, Ma GC, Chiang T-Y, Yang HY. 2006. Population structure of Bigeye Tuna (*Thunnus obesus*) in the South China Sea, Philippine Sea and western Pacific Ocean inferred from mitochondrial DNA. Fisheries Research 79: 219 – 225. doi:10.1016/j.fishres.2005.11.026.

Clear NP, Evans K, Gunn J, Hampton J, Bestley S, Hartmann K, Patterson T, Sibert J. 2005. Movement of Bigeye Tuna (Thunnus obesus) determined from archival tag light-levels and sea surface temperatures. Working paper WCPFC-SC1 BI WP-6 presented to the Western and Central Pacific Fisheries Commission Scientific Committee first regular session, 8 – 19 August, Noumea, New Caledonia.

Collete B, Nauen C. 1983. Scombrids of the world. An annotated and illustrated catalogue of tunas, mackerels, bonitos and related species known to date. FAO Fisheries Synopsis 125, Volume 2. FAO, Rome.

Cowen RK, Gawarkiewicz G, Pineda J, Thorrold SR, Werner FE. 2007. Population connectivity in marine systems. An overview. Oceanography 20: 14 – 21.

Cowen RK, Sponaugle S. 2009. Larval dispersal and marine population connectivity. Annual Reviews in Marine Science 1: 443 – 466. doi:10.1146/annurev.marine.010908.163757.

DAFF. 2007. Commonwealth fisheries harvest policy and guidelines. Department of Agriculture, Fisheries and Forestry, Canberra.

DAFF. 2012. Review of the Commonwealth fisheries harvest strategy policy and guidelines. Department of Agriculture, Fisheries and Forestry, Canberra.

DAFF. 2013. Final report on the review of the Commonwealth fisheries harvest strategy policy and guidelines. Department of Agriculture, Fisheries and Forestry, Canberra.

Davie PS, Hall I. 1990. Potential of dorsal and anal spines and otoliths for assessing age structure of the recreational catch of Striped Marlin. In Stroud RH (ed.). Planning the future of billfishes: research and management in the 90s and beyond. Proceedings of the second international billfish symposium, Kailua-Kona, Hawaii, August 1-5, 1988. Part 2: Contributed papers. Marine Recreational Fisheries 13: 287 – 294.

Davies N, Harley S, Hampton J, McKechnie S. 2014. Stock assessment of Yellowfin Tuna in the western and central Pacific Ocean. Working paper WCPFC-SC10-2014/SA-WP-04 presented to the Western and Central Pacific Fisheries Commission Scientific Committee tenth regular session, 6 – 14 August 2014, Majuro, Republic of the Marshall Islands.

Davies N, Hoyle S, Hampton J. 2012. Stock assessment of Striped Marlin (*Kajikia audax*) in the southwest Pacific Ocean. Working paper WCPFC-SC8-2012/SA-WP-05 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7 – 15 August 2012, Busan, Republic of Korea.

Davies N, Hoyle S, Harley S, Langley A, Kleiber P, Hampton J. 2011. Stock assessment of Bigeye Tuna in the western and central Pacific Ocean. Working paper WCPFC-SC7-2011/SA-WP-02 presented to the Western and Central Pacific Fisheries Commission Scientific Committee seventh regular session, 9 – 17 August 2011, Pohnpei, Federated States of Micronesia.

Davies N, Pilling G, Harley S, Hampton J. 2013. Stock assessment of Swordfish (*Xiphias gladius*) in the southwest Pacific Ocean. Working paper WCPFC-SC9-2013/SA-WP-05 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

DeMartini EE, Uchiyama JH, Williams HA. 2000. Sexual maturity, sex ratio, and size composition of Swordfish, *Xiphias gladius*, caught by the Hawaii-based longline fishery. Fishery Bulletin 105: 356 – 367.

Díaz-Jaimes P, Uribe-Alcocer M. 2006. Spatial differentiation in the eastern Pacific Yellowfin Tuna revealed by microsatellite variation. Fisheries Science 72: 590 – 596.

Domeier ML. 2006. An analysis of Pacific Striped Marlin (*Tetrapturus audax*) horizontal movement patterns using pop-up satellite archival tags. Bulletin of Marine Science 79: 811 – 825.

Domokos R, Seki MP, Polovina JJ, Hawn DR. 2007. Oceanographic investigation of the American Samoa Albacore (*Thunnus alalunga*) habitat and longline fishing grounds. Fisheries Oceanography 16: 555 – 572. doi:10.1111/j.1365-2419.2007.00451.x.

Evans K, Abascal F, Kolody D, Sippel T, Holdsworth J, Maru P. 2013. The horizontal and vertical dynamics of Swordfish in the South Pacific Ocean. Journal of Experimental Marine Biology and Ecology 450: 55 – 67. doi:10.1016/j.jembe.2013.10.025.

Evans K, Kolody D, Abascal F, Holdsworth J, Maru P, Sippel T. 2012. Spatial dynamics of Swordfish in the south Pacific Ocean inferred from tagging data. Working paper WCPFC-SC8-2012/SA-IP-05 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7–15 August 2012, Busan, Republic of Korea.

Evans K, Langley A, Clear NP, Williams P, Patterson T, Sibert J, Hampton J, Gunn JS. 2008. Behaviour and habitat preferences of Bigeye Tuna (*Thunnus obesus*) and their influence on longline fishery catches in the western Coral Sea. Canadian Journal of Fisheries and Aquatic Science 65: 2427 – 2443.

Evans K, Patterson T, Pedersen M. 2011. Movement patterns of Yellowfin Tuna in the Coral Sea region: defining connectivity with stocks in the western Pacific Ocean region. Final report to the Australian Fisheries Management Authority. CSIRO Marine and Atmospheric Research, Hobart.

Farley JH, Clear NP, Leroy B, Davis TLO, McPherson G. 2006. Age, growth and preliminary estimates of maturity of Bigeye Tuna, *Thunnus obesus*, in the Australian region. Marine and Freshwater Research 57: 713 – 724. doi:10.1071/MF05255.

Farley JH, Hoyle SD, Eveson JP, Williams AJ, Davies CR, Nicol SJ. 2014. Maturity ogives for south Pacific Albacore (*Thunnus alalunga*) that account for spatial and seasonal variation in the distributions of mature and immature fish. Plos One 9: e83017. doi:10.1371/journal.pone.0083017.

Farley JH, Williams AJ, Hoyle SD, Davies CR, Nicol SJ. 2013. Reproductive dynamics and potential annual fecundity of south Pacific Albacore (*Thunnus alalunga*). Plos One 8: e60577. doi:10.1371/journal.pone.0060577.

Grall C, de Silva DP, Houde ED. 1983. Distribution, relative abundance and seasonality of Swordfish larvae. Transactions of the American Fisheries Society 112: 235 – 246.

Graves JE, McDowell JR. 1994. Genetic analysis of Striped Marlin (*Tetrapturus audax*) population structure in the Pacific Ocean. Canadian Journal of Fisheries and Aquatic Science 51: 1762 – 1768.

Graves JE, McDowell JR. 2003. Stock structure of the world's istiophorid billfishes: a genetic perspective. Marine and Freshwater Research 54: 287 – 298. doi:10.1071/MF01290.

Grewe PM, Hampton J. 1998. An assessment of Bigeye(*Thunnus obesus*) population structure in the Pacific Ocean, based on mitochondrial DNA and DNA microsatellite analysis. School of Ocean and Earth Science and Technology Publication 98-05. Joint Institute for Marine and Atmospheric Research Contribution 98-320. University of Hawaii, Honolulu.

Gunn JS, Clear NP, Ward RD, Appleyard SA, Grewe PM, Innes BH. 2002. The origin of recruits to the east coast Yellowfin Tuna fishery and the delineation of the structure of Yellowfin Tuna stocks in the western Pacific. Final report to the Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Gunn J, Hampton J, Evans K, Clear N, Patterson T, Langley A, Bigelow K, Leroy B, Williams P, Miyabe N, Bestley S, Hartmann K and Sibert J. 2005. Migration and habitat preferences of Bigeye Tuna, *Thunnus obesus*, on the east coast of Australia – a project using archival and conventional tags to determine key uncertainties in the species stock structure, movement dynamics and CPUE trends. Final report to the Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Hampton J, Gunn J. 1998. Exploitation and movements of Yellowfin Tuna (*Thunnus albacares*) and Bigeye Tuna (*T. obesus*) tagged in the north-western Coral Sea. Marine and Freshwater Research 49: 475 – 489.

Hampton J, Langley A, Williams P. 2005. Recent developments in fisheries, data collection and stock assessment for Bigeye Tuna (*Thunnus obesus*) in the western and central Pacific Ocean. Collected Volumes of Scientific Papers ICCAT 57: 242 – 270.

Hanamoto E. 1977. Fishery oceanography of Striped Marlin. I. Fishing season, fishing ground and movement pattern of the fish in the southern Coral Sea. Bulletin of the Japanese Society for Scientific Fisheries 43: 649 – 657.

Harley S, Davies N, Hampton J, McKechnie S. 2014. Stock assessment of Bigeye Tuna in the western and central Pacific Ocean. Working paper WCPFC-SC10-2014/SA-WP-01 presented to the

Western and Central Pacific Fisheries Commission Scientific Committee tenth regular session, 6 – 14 August 2014, Majuro, Republic of the Marshall Islands.

Harley S, Williams P. 2013. Distribution of longline catches for southwest Pacific Striped Marlin. Working paper WCPFC-SC9-2013/SA-WP-07 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

Harley S, Williams P, Hampton J. 2012. A compendium of fisheries indicators for bigeye, skipjack, Yellowfinand south Pacific Albacores and south Pacific Swordfish. Working paper WCPFC-SC8-2012/SA-WP-02 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7 – 15 August 2012, Busan, Republic of Korea.

Hauser L, Ward RD. 1998. Population identification in pelagic fish: the limits of molecular markers. Pages 191 – 224 in Carvalho GR (ed.). Advances in molecular ecology. IOS Press, Amsterdam.

Hender J, Ward P. 2006. National tuna fishery report. Australia. Working paper FR WP-1 presented the Western and Central Pacific Fisheries Commission Scientific Committee second regular session, 7 – 18 August 2006, Manila, Philippines.

Hoenig JM, Barrowman NJ, Hearn WS Pollock KH. 1998. Multiyear tagging studies incorporating fishing effort data. Canadian Journal of Fisheries and Aquatic Science 55: 1466 – 1476.

Hoyle S, Hampton J, Davies N. 2012. Stock assessment of Albacore in the south Pacific Ocean. Working paper WCPFC-SC8-2012/SA-WP-04-REV1 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7 – 15 August 2012, Busan, Republic of Korea.

Hoyle SD, Kolody DS, Nicol SJ. 2013. Analyses of tagging data for tropical tunas, with implications for the structure of WCPO Bigeyestock assessments. Information paper WCPFC-SC9-2013/SA-IP-06 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

Hoyle S, Nicol S, Itano D. 2009. Revised biological parameter estimates for application in Yellowfinstock assessment. Working paper WCPFC-SC5-2009/BI- WP -3 rev 2 presented to the fifth regular session of the Scientific Committee of the Western and Central Pacific Fisheries Commission, 10 – 21 August 2009, Port Vila, Vanuatu.

Hyde JR, Humphreys R, Musyl M, Lynn E, Vetter R. 2006. A central north Pacific spawning ground for Striped Marlin, *Tetrapturus audax*. Bulletin of Marine Science 79: 683 – 690.

Ianelli J, Maunder M, Punt AE. 2012. Independent review of the 2011 WCPO Bigeye Tuna assessment. Working paper WCPFC-SC8-SA-WP-01 presented to the Western and Central Pacific Fisheries Commission Scientific Committee eighth regular session, 7 – 15 August 2012, Busan, Republic of Korea.

Itano DG. 2000. The reproductive biology of Yellowfin Tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: project summary. SOEST 00-01, JIMAR Contribution 00-328. Pelagic Fisheries Research Program, JIMAR, University of Hawaii.

Itano DG, Holland KN. 2000. Movement and vulnerability of Bigeye(*Thunnus obesus*) and Yellowfin Tuna (*Thunnus albacares*) in relation to FADs and natural aggregation points. Aquatic Living Resources 13: 213 – 223.

Itano DG, Wells RJD, Rooker JR. 2008. Origin of Yellowfin Tuna (*Thunnus albacares*) in the Hawaiian islands: preliminary assessment of natal signatures in otoliths. Working paper WCPFC-SC4-2008/BI-WP-2 presented to the Western and Central Pacific Fisheries Commission Scientific Committee fourth regular session, 11 – 22 August 2008, Port Moresby, Papua New Guinea.

Itano DG, Williams PG. 1992. Analyses of Yellowfintagging data and related information collected by the skipjack survey and assessment programme. Tuna and Billfish Assessment Technical Report No. 28. South Pacific Commission, Noumea.

Jones JB. 1991. Movements of Albacore (Thunnus alalunga) in the south Pacific: evidence from parasites. Marine Biology 111: 1 – 9.

Kasapidis P, Magoulas A, García-Cortés B, Mejuto M. 2008. Stock structure of Swordfish (*Xiphias gladius*) in the Pacific Ocean using microsatellite DNA markers. Working paper WCPFC-SC4-2008/BI-WP-4 presented to the Western and Central Pacific Fisheries Commission Scientific Committee fourth regular session, 11 – 22 August 2008, Port Moresby, Papua New Guinea.

Kolody D, Campbell R, Davies N. 2008. A MULTIFAN-CL stock assessment of south-west Pacific Swordfish 1951–2007. Working paper WCPFC-SC4-2008/SA-IP-2 presented to the Western Central Pacific Fisheries Commission Scientific Committee fourth regular session, 11–22 August, Port Moresby.

Kolody D, Hoyle S. 2013. Evaluation of tag mixing assumptions for skipjack, Yellowfinand Bigeye Tuna stock assessments in the western Pacific and Indian Oceans. Information paper WCPFC-SC9-2013/SA-IP-11 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

Kolody DS, Preece AL, Davies CR, Hartog JR, Dowling NA. 2010. Integrated evaluation of management strategies for tropical multi-species long-line fisheries. Final report to the Fisheries Research and Development Corporation. CSIRO Marine and Atmospheric Research, Hobart.

Kopf RK, Davie PS, Bromhead D, Pepperell JG. 2011. Age and growth of Striped Marlin (*Kajika audax*) in the southwest Pacific Ocean. ICES Journal of Marine Science 68: 1884 – 1895. doi:10.1093/icesjms/fsr110.

Kopf RK, Davie PS, Holdsworth JC. 2005. Size trends and population characteristics of Striped Marlin, *Tetrapturus audax* caught in the New Zealand fishery. New Zealand Journal of Marine and Freshwater Research 39: 1145 – 1156. doi:10.1080/00288330.2005.9517381.

Labelle M, Hampton J. 2003. Stock assessment of Albacore in the south Pacific Ocean. Working paper ALB-1 presented to the sixteenth meeting of the Standing Committee on Tuna and Billfish, 9 – 15 July 2003, Mooloolabah, Australia.

Langley A, Hampton J. 2005. Stock assessment of Albacore in the south Pacific Ocean. Working paper SA WP-3 presented to the Western and Central Pacific Fisheries Commission Scientific Committee first regular session, 8 – 19 August, Noumea, New Caledonia.

Langley A, Hoyle S, Hampton J. 2011. Stock assessment of Yellowfin Tuna in the western and central Pacific Ocean. Working paper WCPFC-SC7-2011/SA-WP-03 presented to the Western and Central Pacific Fisheries Commission Scientific Committee seventh regular session, 9 – 17 August 2011, Pohnpei, Federated States of Micronesia.

Langley AD. 2004. An examination of the influence of recent oceanographic conditions on the catch rate of Albacore in the main domestic longline fisheries. Working paper SA-4 presented to the seventeenth meeting of the Standing Committee on Tuna and Billfish, 9 – 18 August 2004, Majuro, Republic of the Marshall Islands.

Langley AD. 2006. The south Pacific Albacore fishery management issues of relevance to Pacific island countries and territories. Working paper WCPFC-SC2-2006/SA WP-3 presented to the Western and Central Pacific Fisheries Commission Scientific Committee second regular session, 7 – 18 August 2006, Manila, Philippines.

Langley A, Hoyle S, Hampton J. 2011. Stock assessment of Yellowfin Tuna in the western and central Pacific Ocean/ Working paper WCPFC-SC7-2011/SA-WP-03 presented to the Western and Central Pacific Fisheries Commission Scientific Committee seventh regular session, 9 – 17 August 2011, Pohnpei, Federated States of Micronesia.

Larcombe J, Kirby D, Leatherbarrow A, Patterson H, Hormis M. 2011. Eastern tuna and billfish fishery. Pages 325 – 348 in Woodhams J, Stobutzki I, Viera S, Curtotti R, Begg G (eds.). Fishery status reports 2010. Status of fish stocks and fisheries managed by the Australian government. Australian Government Department of Agriculture, Fisheries and Forestry, Bureau of Rural Sciences and Australian Bureau of Agricultural and Resource Economics, Canberra.

Grall C, De Silva DP, Houde ED. 1983. Distribution, relative abundance and seasonality of Swordfish larvae. Transactions of the American Fisheries Society 112: 235–246.

Leroy B, Evans K, Scutt Phillips J, Patterson T, Caillot S, Usu T, Kumasi B, Davies C, Nicol S, Kumoru L. 2014. Progress report on archival tagging within the Papua New Guinea Tagging Program. Working paper WCPFC-SC10-2014/RP-PTTP-05 presented to the seventeenth meeting of the Standing Committee on Tuna and Billfish, 6 – 14 August 2014, Majuro, Republic of the Marshall Islands.

Lawson T. 2008. Factors affecting the use of species composition data collected by observers and port samplers from purse seiners in the western and central Pacific Ocean. Working paper WCPFC-SC4-2008/ST-WP-3 presented to the Western and Central Pacific Fisheries Commission Scientific Committee fourth regular session, 11 – 22 August 2008, Port Moresby, Papua New Guinea.

Lawson T. 2009. Selectivity bias in grab samples and other factors affecting the analysis of species composition data collected by observers on purse seiners in the western and central Pacific Ocean. Working paper WCPFC-SC5-2009/ST-WP-03 presented to the Western and Central

Pacific Fisheries Commission Scientific Committee fifth regular session, 10 – 21 August 2009, Port Vila, Vanuatu.

Lawson T. 2010. Update on the estimation of selectivity bias based on paired spill and grab samples collected by observers on purse seiners in the western and central Pacific Ocean. Working paper WCPFC-SC6-2010/ST-WP-02 presented to the Western and Central Pacific Fisheries Commission Scientific Committee sixth regular session, 10 – 19 August 2010, Nuku'alofa, Tonga.

Lehodey P, Hampton J, Leroy B. 1999. Preliminary results on age and growth of Bigeye Tuna (Thunnus obesus) from the western and central Pacific Ocean as indicated by daily growth increments and tagging data. Working paper BET-2 presented to the twelfth meeting of the Standing Committee on Tuna and Billfish, 16 – 23 July 1999, Tahiti, French Polynesia.

Leroy B, Nicol S, Lewis A, Hampton J, Kolody D, Caillot S, Hoyle S. In Press. Lessons learned from implementing three large-scale tuna tagging programmes in the western and central Pacific Ocean. Fisheries Research. doi:10.1016/j.fishres.2013.09.001.

Leroy B, Scutt Phillips J, Nicol S, Pilling GM, Harley S, Bromhead D, Hoyle S, Allain V, Hampton J. 2012. A critique of the ecosystem impacts of drifting and anchored FADs use by purse-seine tuna fisheries in the western and central Pacific Ocean. Aquatic Living Resources 26: 49 – 61. doi:10.1051/alr/2012033.

Lu H-J, Lee K-T, Lin H-L, Liao C-H. 2001. Spatio-temporal distribution of Yellowfin Tuna Thunnus albacares and Bigeye Tuna Thunnus obesus in the tropical Pacific Ocean in relation to large-scale temperature fluctuation during ENSO episodes. Fisheries Science 67: 1046 – 1052.

McDonald JI, Farley JH, Clear NP, Williams AJ, Carter TI, Davies CR, Nicol SJ. 2013. Insights into mixing and movement of south Pacific Albacore *Thunnus alalunga* derived from trace elements in otoliths. Fisheries Research 148: 56 – 63. doi:10.1016/j.fishres.2013.08.004.

McDowell JR, Graves JE. 2008. Population structure of Striped Marlin (*Kajikia audax*) in the Pacific Ocean based on analysis of microsatellite and mitochondrial DNA. Canadian Journal of Fisheries and Aquatic Science 65: 1307 – 1320. doi:10.1139/F08-054.

McPherson GR. 1988. A possible mechanism for the aggregation of Yellowfinand Bigeye Tuna in the north western Coral Sea. Technical Report No. FRB 88/8, Northern Fisheries Research Centre, Queensland Department of Primary Industries, Cairns.

McPherson GR. 1991. Reproductive biology of Yellowfin Tuna in the eastern Australian fishing zone, with special reference to the north-western Coral Sea. Australian Journal of Marine and Freshwater Research 42: 465 – 477.

Mejuto J, García-Cortés B, Ramos-Cartelle A. 2008. Reproductive activity of Swordfish (*Xiphias gladius*) in the Pacific Ocean on the basis of different macroscopic indicators. Working paper WCPFC-SC4-2008/BI-WP-6 presented to the Western Central Pacific Fisheries Commission Scientific Committee fourth regular session, 11–22 August, Port Moresby.

Melo-Barrera FN, Felix-Uraga R, Quinonez-Velazquez C. 2003. Growth and length weight relationship of the Striped Marlin *Tetrapturus audax*, in Cabo San Lucas, Baja California Sur, Mexico. Ciencias Marinas 29: 305 – 313.

Miyabe N. 1994. A review of the biology and fisheries for Bigeye Tuna, *Thunnus obesus*, in the Pacific Ocean. Pages 244 – 295 in Shomura RS, Majkowski J, Langi S (eds.). Interactions of Pacific tuna fisheries. Volume 2. Papers on biology and fisheries. Proceedings of the first FAO expert consultation on interactions of Pacific tuna fisheries, 3 – 11 December 1991, Noumea, New Caledonia. FAO Fisheries Technical Paper 336/2. FAO, Rome.

Miyake MP, Miyabe N, Nakano H. 2004. Historical trends of tuna catches in the world. FAO Fisheries Technical Paper 467. FAO, Rome.

Miyake MP, Miyabe N, Nakano H. 2004. Historical trends of tuna catches in the world. FAO Fisheries Technical Paper 467. FAO, Rome.

Montes I, Iriondo M, Manzano C, Arrizabalaga H, Jiménez E, Pardo MÁ, Goñi N, Davies CA, Estonba A. 2012. Worldwide genetic structure of Albacore *Thunnus alalunga* revealed by microsatellite DNA markers. Marine Ecology Progress Series 471: 183 – 191. doi:10.3354/meps09991.

Murray T. 1994. A review of the biology and fisheries for Albacore, *Thunnus alalunga*, in the south Pacific Ocean. Pages 188 – 206 in Shomura RS, Majkowski J, Langi S (eds.). Interactions of Pacific tuna fisheries. Volume 2. Papers on biology and fisheries. Proceedings of the first FAO expert consultation on interactions of Pacific tuna fisheries, 3 – 11 December 1991, Noumea, New Caledonia. FAO Fisheries Technical Paper 336/2. FAO, Rome.

Musyl MK, Brill RW, Boggs CH, Curran DS, Kazama TK, Seki MP. 2003. Vertical movements of Bigeye Tuna (*Thunnus obesus*) associated with islands, buoys and seamounts near the main Hawaiian Islands from archival tagging data. Fisheries Oceanography 12: 1–18.

Nakamura I. 1983. Systematics of billfishes (Xiphiidae and Istiophoridae). Publications of the Seto Marine Biological Laboratory 28: 255 – 396.

Nakamura I. 1985. FAO species catalogue. Vol. 5 Billfishes of the world. An annotated and illustrated catalogue of marlins, sailfishes, spearfishes and Swordfishes known to date. FAO Fisheries Synopsis No. 125, Volume 5. FAO, Rome.

Narum SR, Banks M, Beacham TD, Bellinger MR, Campbell MR, Dekoning J, Elz A, Guthrie CM, Kozfkay C, Miller KM, Moran P, Phillips R, Seeb LW, Smith CT, Warheit K, Young SF, Garza JC 2008. Differentiating salmon populations at broad and fine geographical scales with microsatellites and single nucleotide polymorphisms. Molecular Ecology 17: 3464–3477.

Nicol S, Hoyle S, Farley J, Muller B, Retalmi S, Sisior K, Williams A. 2011. Bigeye tuna age, growth and reproductive biology (Project 35). Working paper WCPFC-SC7-2011/SA-WP-01 presented to the Western and Central Pacific Fisheries Commission Scientific Committee seventh regular session, 9 – 17 August 2011, Pohnpei, Federated States of Micronesia.

Nielsen EE, Hemmer-Hanson J, Poulsen NA, Loeschcke V, Moen T, Johansen T, Mittelholzer C, Taranger G-L, Ogden R, Carvalho GR. 2009. Genomic signatures of local directional selection in a high gene flow marine organism: the Atlantic cod (*Gadus morhua*). BMC Evolutionary Biology 9: 276. doi:10.1186/1471-2148-9-276.

Nikolic N, Bourjea J. 2013. Differentiation of Albacore stock: review by oceanic regions. Paper SCRS/2013/126 presented to the International Commission for the Conservation of Atlantic Tunas Standing Committee of Research and Statistics meeting, September 30 – October 4 2013, Madrid, Spain.

Nishikawa Y, Honma M, Ueyanagi S, Kikawa S. 1985. Average distribution of larvae of oceanic species of scombrid fishes, 1956 – 1981. Far Seas Fisheries Research Laboratories S Series 12: 1 – 99.

NSW DPI. 2005. NSW DPI game fish tagging program. Program summary and report to July 2005. New South Wales Department of Primary Industries. Downloaded on 16 January 2013 from: http://www.dpi.nsw.gov.au/fisheries/recreational/saltwater/gamefish-tagging/program-summaries-and-reports.

Oritz M, Prince ED, Serafy JE, Holts DB, Davy KB, Pepperell JG, Lowry MB, Holdsworth JC. 2003. A global overview of the major constituent-based billfish tagging programs and their results since 1954. Marine and Freshwater Research 54: 489 – 507. doi:10.1071/MF02028.

Ortega-Garcia S, Klett-Traulsen A, Ponce-Diaz G. 2003. Analysis of sportfishing catch rates of Striped Marlin, *Tetrapturus audax*, at Cabo San Lucas, Baja California Sur, Mexico and their relation to sea surface temperatures. Marine and Freshwater Research 54: 483 – 488.

Otsu T, Uchida RN. 1959. Sexual maturity and spawning of Albacore in the Pacific Ocean. Fishery Bulletin 148: 287 – 305.

Palko BJ, Beardsley GL, Richards WJ. 1981. Synopsis of the biology of the Swordfish, *Xiphias gladius* Linnaeus. NOAA Technical Report NMFS Circular 441. US Department of Commerce, Seattle.

Parrish CC, Pethybridge H, Young JW, Nichols PD. 2015. Spatial variation in fatty acid trophic markers in Albacore from the southwestern Pacific Ocean – a potential 'tropicalization' signal. Deep Sea Research II 113: 199 – 207. doi:10.1016/j.dsr2.2013.12.003.

Patterson H, Sahlqvist P, Larcombe J. 2013. Annual report to the Western and Central Pacific Fisheries Commission. Part 1: Information on fisheries, research and statistics 2012 Australia. Paper WCPFC-SC9-AR/CCM-01 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

Pepperell JG, Diplock JH. 1989. Seasonal migration of Yellowfin Tuna *Thunnus albacares* off south-eastern Australia. Evidence for possible localised stock. New South Wales Agriculture and Fisheries, Fisheries Research Institute, Cronulla

Polacheck T, Eveson JP, Laslett GM, Pollock KH, Hearn WS. 2006. Integrating catch-at-age and multiyear tagging data: a combined Brownie and Petersen estimation approach in a fishery context. Canadian Journal of Fisheries and Aquatic Science 63: 534 – 548. doi:10.1139/F05-232.

Pollock KH, Hoenig JM, Hearn WS, Calingaert B. 2001. Tag reporting rate estimation: 1. An evaluation of the high reward tagging method. North American Journal of Fisheries Management 21: 521 – 532.

Ramon D, Bailey K. 1996. Spawning seasonality if Albacore, *Thunnus alalunga*, in the south Pacific Ocean. Fishery Bulletin 94: 725 – 733.

Reeb CA, Arcangeli L, Block BA. 2000. Structure and migration corridors in Pacific populations of the Swordfish *Xiphias gladius*, as inferred through analyses of mitochondrial DNA. Marine Biology 136: 123 – 131.

Rooker JR, Secor DH, DeMetrio G, Schloesser R, Block BA, Neilson JD. 2008. Natal homing and connectivity in Atlantic bluefin tuna populations. Science 322: 742 – 744. doi:10.1126/science.1161473.

Rooker JR, Secor DH, Zdanowicz VS, De Metrio G, Orsi Relini L. 2003. Identification of Atlantic bluefin tuna (*Thunnus thynnus*) stocks from putative nurseries using otoliths chemistry. Fisheries Oceanography 12: 75 – 84.

Rosel PE, Block BA. 1996. Mitochondrial control region variability and global population structure in the Swordfish, *Xiphias gladius*. Marine Biology 125: 11 – 22.

Sakagawa GT, Bell RR. 1980. Swordfish, *Xiphias gladius*. Pages 43 – 55 in Shomura RS (ed.). Summary report of the billfish stock assessment: Pacific resources. NOAA technical Memorandum NMFS-SWC5. US Department of Commerce, Seattle.

Sands A, Summerson R, Viera S, Wilson D. 2009. Eastern tuna and billfish fishery. Pages 283 – 305 in Wilson D, Curtotti R, Begg G, Phillips K (eds.). Fishery status reports 2008. Status of fish stocks and fisheries managed by the Australian government. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Schaefer KM. 1992. An evaluation of geographic and annual variation in morphometric characters and gill-raker counts of Yellowfin Tuna, *Thunnus albacares*, from the Pacific Ocean. Bulletin of the Inter-American Tropical Tuna Commission 20: 135 – 163.

Schaefer KM. 1998. Reproductive biology of Yellowfin Tuna (*Thunnus albacares*) in the eastern Pacific Ocean. Inter-American Tropical Tuna Commission Bulletin 21(5): 205 – 272.

Schaefer KM. 2001. Reproductive biology of tunas. Pages 225 – 270 in Block BA, Stevens ED (eds.). Tuna: physiology, ecology and evolution. Academic Press, San Diego.

Schaefer KM, Fuller DW. 2002. Movements, behaviour, and habitat selection of Bigeye Tuna (Thunnus obesus) in the eastern equatorial Pacific, ascertained through archival tags. Fishery Bulletin 100: 765 – 788.

Schaefer KM, Fuller DW, Block BA. 2007. Movements, behavior and habitat utilization of Yellowfin Tuna (*Thunnus albacares*) in the northeastern Pacific Ocean, ascertained through archival tag data. Marine Biology 152: 503 – 525.

Schaefer KM, Fuller DW, Miyabe N. 2005. Reproductive biology of Bigeye Tuna (*Thunnus obesus*) in the eastern and central Pacific Ocean. Inter-American Tropical Tuna Commission Bulletin 23: 1 – 31.

Schloesser RW, Neilson JD, Secor DH, Rooker JR. 2010. Natal origin of Atlantic bluefin tuna (*Thunnus thynnus*) from Canadian waters based on otolith $\delta^{13}C$ and $\delta^{18}O$. Canadian Journal of Fisheries and Aquatic Science 67: 563 – 569. doi:10.1139/F10-005.

Scoles DR, Graves JE. 1993. Genetic analysis of the population structure of Yellowfin Tuna, *Thunnus albacares*, from the Pacific Ocean. Fishery Bulletin 91: 690 – 698.

Scutt Phillips J, Patterson T, Pilling G, Hoyle S, Leroy B, Nicol S. 2013. Species-specific vertical habitat utilisation by tunas in the tropical WCPO, and the impacts of FADs in vertical behaviour. Paper WCPFC-SC9-2013/RP-PTTP-03 presented to the Western and Central Pacific Fisheries Commission Scientific Committee ninth regular session, 6 – 14 August 2013, Pohnpei, Federated States of Micronesia.

Shiao J-C, Wang S-W, Yokawa K, Ichinokawa M, Takeuchi Y, Chen Y-G, Shen C-C. 2010. Natal origin of Pacific bluefin tuna *Thunnus orientalis* inferred from otoliths oxygen isotope composition. Marine Ecology Progress Series 420: 207 – 219. doi:10.3354/meps08867.

Shiao J-C, Yui T-F, Høie H, Ninnemann U, Chang S-K. 2009. Otolith O and C stable isotope compositions of southern bluefin tuna Thunnus maccoyii (Pisces: Scombridae) as possible environmental and physiological indicators. Zoological Studies 48: 71 – 82.

Sippel TJ, Davies PS, Holdsworth JC, Block BA. 2007. Striped Marlin (*Tetrapturus audax*) movement and habitat utilization during a summer and autumn in the southwest Pacific Ocean. Fisheries Oceanography 16: 459 – 472. doi:10.1111/j.1365-2419.2007.00446.x.

Sippel T, Eveson JP, Galuardi B, Lam C, Hoyle S, Maunder M, Kleiber P, Carvalho F, Tsontos V, Teo SLH, Aires-de-Silva A, Nicol S. 2015. Using movement data from electronic tags in fisheries stock assessment: a review of models, technology and experimental design. Fisheries Research 163: 152 – 160. doi: 10.1016/j.fishres.2014.04.006.

Sippel T, Holdsworth J, Dennis T, Montgomery J. 2011. Investigating behaviour and population dynamics of Striped Marlin (*Kajikia audax*) from the southwest Pacific Ocean with satellite tags. Plos One 6: e21087. doi:10.1371/journal.pone.0021087.

Skillman RA, Yong MYY. 1976. Von Bertalanffy growth curves for Striped Marlin *Tetrapturus audax* and blue marlin *Makaira nigricans* in the central north Pacific Ocean. Fishery Bulletin 74: 553 – 566.

Smith AK, Dixon PI, Black M. 1988. Population structure of Yellowfin Tuna (*Thunnus albacares*) in eastern Australian waters. University of New South Wales, Centre for Marine Science Technical Report.

SPC-OFP. 2014. Implementing the recommendations from the Bigeye Tuna assessment review. Working paper WCPFC-SC10-2014/SA-WP-02 presented to the Western and Central Pacific

Fisheries Commission Scientific Committee tenth regular session, 6 – 14 August 2014, Majuro, Republic of the Marshall Islands.

Squire J, Suzuki Z. 1990.Migration trends of Striped Marlin (*Tetrapturus audax*) in the Pacific Ocean. In Stroud RH (ed.). Planning the future of billfishes: research and management in the 90s and beyond. Proceedings of the second international billfish symposium, Kailua-Kona, Hawaii, August 1-5, 1988. Part 2: Contributed papers. Marine Recreational Fisheries 13: 67 – 80.

Sun C-L, Chu S-L, Yeh S-Z. 2006. Reproductive biology of Bigeye Tuna in the western and central Pacific Ocean. Working paper WCPFC-SC2-2006/BI WP-1 presented the Western and Central Pacific Fisheries Commission Scientific Committee second regular session, 7 – 18 August 2006, Manila, Philippines.

Sun C-L, Wang W-R, Yeh S. 2005. Reproductive biology of Yellowfin Tuna in the central and western Pacific Ocean. Working paper BI WP-1 presented to the first meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, Noumea, New Caledonia, 8 – 19 August 2005.

Sun CL, Yeh SZ, Chang YJ, Chang HY, Chu SL. 2013. Reproductive biology of female Bigeye Tuna *Thunnus obesus* in the western Pacific Ocean. Journal of Fish Biology 83: 250 – 271. doi:10.1111/jfb.12161.

Sund PN, Blackburn M, Williams F. 1981. Tunas and their environment in the Pacific Ocean: a review. Oceanography and Marine Biology Annual Review 19: 443 – 512.

Takagi M, Okamura T, Chow S, Taniguchi N. 2001. Preliminary study of Albacore (*Thunnus alalunga*) stock differentiation inferred from microsatellite DNA analysis. Fishery Bulletin 99: 697 – 701.

Ueyanagi S. 1969. Observations on the distribution of tuna larvae in the Indo-Pacific Ocean with emphasis on the delineation of the spawning areas of Albacore, *Thunnus alalunga*. Far Seas Research Laboratories Bulletin 2: 177 – 256.

Ueyanagi S, Shomura RS, Watanabe Y, Squire JL. 1990. Trends in fisheries for billfishes in the Pacific. In Stroud RH (ed.). Planning the future of billfishes: research and management in the 90s and beyond. Proceedings of the second international billfish symposium, Kailua-Kona, Hawaii, August 1-5, 1988. Part 1: Fishery and Stock Synopses, Data Needs and Management. Marine Recreational Fisheries 13: 31 – 45.

Viñas J, Alvarado Bremer JR, Pla C. 2004. Inter-oceanic genetic differentiation among Albacore (*Thunnus alalunga*) populations. Marine Biology 145: 225 – 232. doi:10.1007/s00227-004-1319-5.

Wang CH, Lin YT, Shaio JC, You CF, Tzeng WN. 2009. Spatio-temporal variation in the elemental compositions of otoliths of southern bluefin tuna Thunnus maccoyii in the Indian Ocean and its ecological implication. Journal of Fish Biology 75: 1173 – 1193. doi:10.1111/j.1095-8649.2009.02336.x.

Ward P. 2007. Eastern tuna and billfish fishery. Pages 65 – 84 in Larcombe J, McLoughlin K (eds.). Fishery status reports 2006: status of fish stocks managed by the Australian government. Bureau of Rural Sciences, Canberra.

Ward P. Porter JM, Elscot S. 2000. Swordfish: status of established fisheries and lessons for developing fisheries. Fish and Fisheries 1: 317 – 336.

Ward RD, Elliott NG, Grewe PM, Smolenski AJ. 1994. Allozyme and mitochondrial DNA variation in Yellowfin Tuna (Thunnus albacares) from the Pacific Ocean. Marine Biology 118: 531 – 539.

Ward RD, Reeb CA, Block BA. 2001. Population structure of Australian Swordfish, *Xiphias gladius*. Final report to the Australian Fisheries Management Authority. CSIRO Marine Research, Hobart.

Wells RJD, Rooker JR, Itano DG. 2012. Nursery origin of Yellowfin Tuna in the Hawaiian Islands. Marine Ecology Progress Series 461: 187 – 196. doi:10.3354/meps09833.

Williams AJ, Allain V, Nicol SJ, Evans KJ, Hoyle SD, Dupoux C, Vourey E, Dubosc J. 2015. Vertical behavior and diet of Albacore (*Thunnus alalunga*) vary with latitude in the south Pacific Ocean. Deep Sea Research II 113: 154 – 169.

Williams AJ, Farley JH, Hoyle SD, Davies CR, Nicol SJ. 2012. Spatial and sex-specific variation in growth of Albacore (*Thunnus alalunga*) across the south Pacific Ocean. Plos One7: e39318. doi:10.1371/journal.pone.0039318.

Wirgin I, Kovach AI, Maceda L, Roy NK, Waldman J, Berlinsky DL. 2007. Stock identification of Atlantic cod in U.S. waters using microsatellite and single nucleotide polymorphism DNA analyses. Transactions of the American Fisheries Society 136: 375–391. doi:10.1577/T06-068.1

WPRFMC. 2005. Excerpt from "Background paper for amendment 14 to the pelagic fishery management plan" – Chapter 1: Bigeye Tuna (*Thunnus obesus*) general description of the species within the Pacific Ocean. Information paper WCPFC-SC1 BI IP-1 presented to the Western and Central Pacific Fisheries Commission Scientific Committee first regular session, 8 – 19 August, Noumea, New Caledonia.

WPRFMC. 2014. Workshop on Pacific Bigeyemovement and distribution. Western Pacific Regional Fishery Management Council, Honolulu, Hawaii, USA, April 22 – 24 2014.

Yabe H, Ueyanagi S, Kikawa S, Watanabe H. 1959. Study on the life-history of the Swordfish, *Xiphias gladius* Linneaeus. Reports of the Nankai Regional Fisheries Research Laboratory 10: 107 – 150.

Young JW, Bradford R, Lamb TD, Clemenston LA, Kloser R, Galea H. 2001. Yellowfin Tuna (*Thunnus albacares*) aggregations along the shelf break off south-eastern Australia: links between inshore and offshore processes. Marine and Freshwater Research 52: 463 – 474.

Young J, Drake A. 2002. Reproductive dynamics of Swordfish, *Xiphias gladius*, in the domestic longline fishery off eastern Australia. Final report 1999/108 to the Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Young J, Drake A. 2004. Age and growth of Swordfish (*Xiphias gladius*) from Australian waters. Final report 2001/014 to the Fisheries Research and Development Corporation. CSIRO Marine Research, Hobart.

Young J. Drake A, Brickhill M, Farley J, Carter T. 2003. Reproductive dynamics of Swordfish, *Xiphias gladius*, in the domestic longline fishery off eastern Australia. Marine and Freshwater Research 54: 1 – 18. doi:10.1071/MF02011.

Appendix 5: Summary of ETBF Harvest Strategy Workshop

Summary of ETBF Harvest Strategy Workshop

The workshop was held on the 2nd and 3rd of June at CSIRO in Hobart. The attendess were:

Rich Hillary, Karen Evans, Campbell Davies, Ann Preece, Rob Campbell, and Cathy Dichmont (CSIRO)

Trent Timmiss and Stephanie Johnson (AFMA)

Kelly Buchanan, James Larcombe and Jenny Baldwin (DAg)

Julian Pepperill (independent scientist)

Keith Sainsbury and Sean Tracey (IMAS)

Sandra Diamond (UWS)

Key topics on the agenda were:

- Updated Management Strategy Evaluation work for the tuna and billfish
- Connectivity and stock structure work
- Cost and benefits of reducing the current major uncertainties
- State of play of a Harvest Strategy initiative at the level of the Western and Central Pacific Fishery Commission
- Summary of gamefish information
- Strategies for future engagement and research priorities

Management Strategy Evaluation work

Currently, the ETBF Harvest Strategy (HS) is implemented for Swordfish and Striped Marlin only. Given recent updates in both the stock assessments used previously to condition the original Management Strategy Evaluation (MSE) models, and a slight change in the index used in the HS, the billfish (Striped Marlin, Swordfish) MSE models were rerun to assess whether the original expected performance of the HS had changed.

For Swordfish, there are a number of general issues that came forth. In terms of the current stock assessment, the migratory and general population (and productivity) structure does not cover the whole range of likely spatial uncertainties. If the current assessment understanding is correct, and the recently increased level of international effort is maintained, the HS will act to strongly reduce catches in the ETBF, albeit ensuring the limit spawning stock biomass (SSB) level is not breached with significant probability. If international effort doubled there is little chance of the HS avoiding SSB limit violations, even with effective closure of the ETBF by the HS. There was also an apparent mismatch between the target Catch Per Unit Effort (CPUE) level in the HS and the target SSB depletion level (48% of the unfished level), both taken from a single year and assessment configuration.

For Striped Marlin, key issues still outstanding from the previous MSE work were (a) scenarios where the HS did not function (i.e. no apparent feedback in the system); (b) scenarios where the HS did function, but the economic losses arising from catch reductions did not lead to any apparent conservation gain; and (c) levels of international effort, conditional on connectivity scenarios, at which the HS failed to function satisfactorily. The issue of HS functionality and adverse economic impact, and the potential to increase risk to the stock, was seen to be resolved with the limit level breached at levels well below the current stipulations of the Commonwealth Harvest Strategy Policy and CPUE being able to be maintained at the target level. With respect to international effort, for lower connectivity scenarios between ETBF and non-ETBF areas, the HS would actually still allow for increased catches at target level catch rates but not necessarily for higher connectivity scenarios.

Issues common to both billfish MSEs were:

- Impact of recent inclusion of large amounts of “Eastern” Pacific catch and effort (that is those catches in the far north east of the Western and Central Pacific Fishery Commission area), and whether catches in that region are from the same stocks as the ETBF species
- Continued limited understanding of migration, stock structure and regional productivity
- Potential mismatch between the target CPUE and SSB depletion level used in the revised HS
- Better summary statistics for demonstrating whether the HS is “working” or not
- Perhaps some additional graphical work to better explain the mechanics of the HS

For the tropical tuna, “localised” operating models (OMs) were conditioned for Yellowfin Tuna and Bigeye Tuna using the catch composition and long-line CPUE data. For Yellowfin Tuna, while the data were very noisy and the resultant fits similarly noisy, there is no strong evidence that the current ETBF is having any notable impact on the stock. This reinforces the original decision not to implement the HS for this species given there will be no feedback in the system. For Bigeye Tuna the data are so noisy and, at times, contradictory that no stable estimates of local population abundance could be obtained. It was therefore not possible to judge whether the HS would be effective or not for Bigeye Tuna in the ETBF region.

Connectivity and structure

The project has compiled an in-depth summary of the available information on this topic for the main target species. For the billfish, localised movement across the ETBF and eastern zones around New Zealand and the Pacific are observed, but with some fairly clear evidence of apparent residence in this areas. Currently a single spawning stock is assumed in both Swordfish and Striped Marlin assessments but genetic analyses of the wider Pacific region have shown structure below the levels assumed currently.

For the tropical tuna the vast majority of the tag recaptures released in the ETBF area are recaptured in the same general region and not moving into the equatorial zone to the North. Of the tens of thousands of tags released in the equatorial zone a miniscule fraction have been recaptured in the ETBF zone – even accounting for lower effort levels and attrition over time this is strongly suggestive of little movement between these zones. Satellite tags released on Yellowfin Tuna in the PNG region have also shown very localised movement of Yellowfin Tuna within this region. The most recent genetic work on Yellowfin Tuna is perhaps the most revealing to date: for three sample locations (eastern Pacific, Tokolau in the South Pacific, the ETBF region) there was effectively complete separation between all locations suggesting that, even for a limited number of sites within the WCPO, the current assessment configuration is both spatially and reproductively incorrect, and that there might well be several spawning sub-populations within the WCPO.

Cost and benefits of reducing uncertainty

For the billfish the major remaining uncertainties are life-history parameters (particularly Swordfish) and spatial dynamics; for the tropical tuna these are estimates of local abundance and a wider understanding of stock structure. A current AFMA funded project is underway to resolve current uncertainty in Swordfish growth and in association hopefully maturity metrics.

With respect to tuna abundance three methods that could be used to reduce uncertainty were presented: conventional tagging, gene tagging and close-kin mark-recapture (CKMR) – the final method uses matches between parents and offspring or half-siblings to estimate absolute abundance. While gene tagging addresses many of the issues associated with conventional tagging (variable reporting rates, tag shedding etc.), the prohibitive cost of sampling and releasing the 'tagged' fish made it far more costly than the CKMR half-sibling option, in terms of obtaining the same precision in abundance. The meeting also touched on the difference between connectivity (where electronic tags are the best tool) and stock structure (where genetics are the standout method) and what questions they related to in a management context. It was generally agreed that no one factor really has precedence and that we need to know both better to achieve more representative assessment (and operating) models at present. At least in relation to stock structure though, there was clear agreement that current genetic technology was both powerful and cost-effective enough to permit the kind of pan-WCPO study that would deliver a huge improvement to the current state of knowledge about all the stocks and should be explored.

Harvest strategy initiative at WCPFC

Key attendees at the WCPFC Scientific Committee and Commission from the Department of Agriculture discussed the state of the current initiative to develop a harvest strategy framework for managing the WCPFC target species. While the political challenges were acknowledged, the meeting did focus in more on what such a framework might look like operationally, and how current (and future) research being discussed at the workshop might best be disseminated to assist in the process. For the tropical tuna species (including skipjack) the multispecies element was considered to be central to any approach for it to be implementable. It was also noted that the various fisheries and members often have quite different priorities that a harvest strategy framework might have to accommodate – this led to the notion of there being an over-arching harvest strategy with potentially quite different harvest control rules (HCRs) depending on the context (species, fishery etc.). Clearly, some of the stock structure work (both current and likely in the near future) has the potential to complicate both the assessment and general management advice system at the WCPFC for some species. In acknowledgement of this the group considered if someone could attend, or at least prepare information papers for example, for upcoming meetings to mitigate this risk as much as possible.

Gamefish data

An in-depth summary of the various data sets coming from the recreational fishing sector was given to the group. There are a wide array of tagging (conventional, electronic), catch weights and CPUE data for various ETBF and non-ETBF species. Most notably for Striped Marlin, these data represent an underused but clearly informative additional resource, relative to the commercial data. Continuation of some of the data sets was in doubt due to funding and the group agreed that it would be good to maintain these kinds of (largely) uninterrupted time-series if at all possible.

General summary

For the HS as currently applied to the billfish species in the ETBF, the key influences are still spatial: connectivity, regional productivity, reproductive structure, inclusion of eastern regions catch and effort. However, there is also the issue of the revised CPUE targets (and limits) as currently calibrated (via a single year and assessment realisation) to stock assessment SSB depletion estimates. For Yellowfin Tuna: new derived “local” abundance estimates show little apparent effect of the ETBF catches on the population, confirming previous work that showed little to no feedback in the HS system and therefore little point in applying it. For Bigeye Tuna the data are not informative enough and far too noisy to estimate local abundance so it is not feasible to assess whether the HS would illicit feedback if applied for this species. Cost-benefit analyses focussed on connectivity, stock structure and local abundance. The connectivity picture is still not entirely clear, but it is hard to gauge exactly how one couches the benefits associated with further electronic tagging work. For stock structure, given the initial Yellowfin Tuna results, genetic techniques are now at the point of making a WCPO-wide structure analysis for the major species affordable, albeit with some requirement for practical design in terms of sample locations. In terms of local abundance, when comparing conventional, genetic and close-kin mark-recapture methods, the clear winner in terms of cost-effectiveness and ability to provide robust estimates was CKMR, given it both obviates the need to tag juveniles and release them (and the associate high cost thereof) and permits estimation of the spawning population not the exploitable one. The summary of the gamefish data also emphasised the additional data not currently being used perhaps as much as it could be in relation to the billfish species in the ETBF in particular.

The workshop discussed a lot of the practical challenges involved in establishing a HS framework within the WCPFC. The array of different priorities apparent for various members and/or fisheries suggested that perhaps one might have several different harvest control rules in place for the various fisheries/species under one overarching framework. The dependence of the MSE work in decisions made at the WCPFC assessment level, as well as the potential for more localised research like the current genetic structure work to strongly affect the assessment process, reinforces the idea that continued engagement at all levels of the WCPFC is essential for assessing the efficacy of the current HS as applied at the national level in the ETBF.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

AT CSIRO WE SHAPE THE FUTURE

We do this by using science to solve real issues. Our research makes a difference to industry, people and the planet.

As Australia's national science agency we've been pushing the edge of what's possible for over 85 years. Today we have more than 5,000 talented people working out of 50-plus centres in Australia and internationally. Our people work closely with industry and communities to leave a lasting legacy. Collectively, our innovation and excellence places us in the top ten applied research agencies in the world.

WE ASK, WE SEEK AND WE SOLVE

FOR FURTHER INFORMATION

Oceans and Atmosphere Flagship
Rich Hillary
t +61 3 6232 5222
e Rich.Hillary@csiro.au
w www.csiro.au