Australian Government

Australian Fisheries Management Authority

Harvest Strategies for the Torres Strait Finfish fishery

Project No. 2016/0824

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Project completed by:

Trevor Hutton (CSIRO), Michael O'Neill (DAF), George Leigh (DAF), Matt Holden (UQ), Roy Deng (CSIRO) and Eva Plaganyi (CSIRO)

On behalf of CSIRO authors:

Important disclaimer

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Version	Updates	Approver
V1. 14th June 2019.	Modified reflecting 2 meetings at end of June and comments on draft submitted.	
V2.	Submitted (this version)	

Executive Summary

The project has provided a foundation and framework for a Harvest Strategy for both Spanish mackerel and coral trout, with both fish species supported within the project by stock assessments.

An update to the Spanish mackerel assessment was conducted with direct feedback between the outputs and diagnostics of the assessment informing the process of harvest strategy development. Similarly, for coral trout the initial harvest strategy resourced the first preliminary assessment of the coral trout, also funded as part of the project.

Project staff worked closely with management agencies and stakeholders, using formal committee meetings inputs and advice, which fulfilled the requirements of the guidelines for developing harvest strategies. The versions of the harvest strategies presented herein are correct up the date of the submission of the report. The current versions of the harvest strategies are adaptive, as various components need checking based on updated assessments and any new information. The project team have made a series of recommendations for future updates required to progress to the full and complete harvest strategies.

Spanish mackerel

The Torres Strait Spanish mackerel harvest strategy (HS) sets out the management actions to achieve the agreed fishery objectives. The HS describes the performance indicators used for monitoring the condition of the stock, the stock assessment procedures and the rules applied to determine the recommended biological catch (RBC). The total allowable catch (TAC) can then be allocated for each fishing season.

The HS uses an age-structured stock assessment model that is dependent on a standardised annual catch rate index (CPUE) from the TVH sector. The RBC is based on the best available scientific advice on what the fishing mortality should be for the stock. In application, the RBC is split based on catch sharing decisions between the fishing sectors, and a TAC (an enforced limit on total commercial catches) is calculated.

The HS herein meets the requirements of the Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries (June 2018) (HSP). This was by applying a precautionary approach to the reference points and measures to be implemented in accordance with the reference points. This is reflected in the use of reference points that are appropriate for Torres Strait fisheries, to protect traditional livelihoods and cultural values.

The Harvest Control Rule (HCR) is designed to decrease harvests as the stock size decreases below the target reference point. The HS uses a biomass target reference point (set initially low in the short term) to account for leased fish to TVH operators. The reference points are biologically and economically acceptable. The longer-term BTARG is 60% of B0. This is seen to be the ‘aspirational’ target, given the estimated current status of the resource. The HS reference points are BLIM equal to 20% of B0, and BTARG (interim) equal to 48% of B0.

Given the current status (BCURRENT) of the stock in 2018 was around 32% of B0, the recommendation was for the stock assessment to be undertaken every year until the stock is above B40. The scope of this working document outlines preliminary HS procedures for setting RBCs from 2020/21 onwards. The procedure settings and documentation will advance in time based on further FFRAG and FWG review. Previous RBC settings did not follow this HS or the HCR herein.

Coral Trout

The Torres Strait Finfish Fishery Coral Trout Harvest Strategy (HS) sets out the management actions needed to achieve the agreed Fishery objectives. The Fishery HS describes the performance indicators used for monitoring the condition of the stock, the stock assessment procedures and the rules applied to determine the recommended biological catch (RBC) and the total allowable catch (TAC) each fishing season.

The HS uses a stock assessment (age-structured model) that is very dependent on a single abundance index at this stage (standardised Catch Per Unit Effort – CPUE) from the TVH (Sunset) fleet daily fishing logbooks. The RBC is the best available scientific advice on what the total fishing mortality should be for the stock.

The HS meets the requirements of the Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries (June 2018) (HSP) by applying a precautionary approach to the reference points and measures to be implemented in accordance with the reference points. This is reflected in the use of proxy reference points that are more precautionary than those specified in the HSP in line with stakeholder advice in the formation of this HS. The Harvest Control Rule (HCR) is designed to decrease exploitation rate as the stock size decreases below the target reference point. The HS uses a biomass target reference point (set in the short-term) that takes account of the fact that the resource is important for the traditional way of life and livelihood of traditional inhabitants and must be biologically and economically acceptable. The target reference point also takes account of the fact that the coral trout stock is underutilised at present by the TIB commercial sector and is mainly leased to TVH (sunset sector) fishers. The HS proxies are BLIM is 20% of B0, BTARG is 60% of B0.

In the interim and given the current status of the stock (based on catch data to 2018) is in the region of BCURRENT is 80% of B0, the recommendation is for the stock assessment to be undertaken every three years; with a recommendation to trigger a stock assessment based on two empirical rules to be examined annually. This approach would likely suit the needs of the fishery with increased participation of TIB commercial fishers or increased leasing of access to non-traditional inhabitant fishers (TVH sunset fishers).

1 Background

Research is required to deliver harvest strategy (HS) options as described in the project outline established by the PZJA consultative forums, TSSAC 2016 research call and the TSSAC operational plan. Since 2008 the Torres Strait Finfish Fishery has been reserved for Traditional Inhabitants, on whose behalf the Torres Strait Regional Authority (TSRA) leases out fishing licences to non-Traditional Inhabitants. The leasing process is based on consideration of estimates of sustainable total allowable catches (TAC) for coral trout and Spanish mackerel, with the aim to generate revenue for the benefit of Torres Strait (TS) communities.

A HS framework for the finfish fishery is sought to guide future TAC decisions, support leasing arrangements and expansion of the fishery using new stock status indicators; and to achieve ecological, economic and social management objectives consistent with the Torres Strait Fisheries Act 1984, TSFFF management plan 2013, the Commonwealth Fisheries Harvest Strategy Policy and Guidelines and Torres Strait FinFish Action Plan. HS options will also assist and guide future investment on finfish research and data collection to ensure the shared interests of Torres Strait Islanders, AFMA, TSRA and DAF are balanced in developing sustainable and economic fishing opportunities.

Current management of the fishery involves TACs based on historical catch which have remained unchanged since 2008. A clear contrast between under-utilisation of coral trout and over-subscription to Spanish mackerel exists. Lack of data and rules to set effective allowable harvests may impede the returns to islanders and put the fishery at risk, unless there is a clear set of harvest control rules (within a harvest strategy framework) agreed to by the custodians of the resource. This has been the subject of some discussion at management forums (e.g. FFWG) and community meetings for some time. A new harvest strategy process will provide the platform for an agreed and transparent strategy for managing, monitoring and information gathering into the foreseeable future.

2 Need

The Torres Strait Finfish Fishery consists of a mix of commercial, traditional and recreational sectors. The commercial allocation is held by Torres Strait Islanders and is fished by islander owner-operators and non-islander lease-fishing operators. The leased allocation provides income and market certainty to communities; the islander operators provide important local employment and income opportunities, and local food security and health benefits. The strategy for overseeing each sector and their joint fishing impact is relatively *ad hoc*, with a Total Allowable Catch (a separate TAC for Spanish mackerel and coral trout) the primary point of reference for capping fishing pressure at a level which meets sustainability targets. Under the current management approach there is considerable risk of under or overfishing in some situations and no process of formalising harvest control rules to control fishing pressure.

A major impediment to defensible and robust management decisions is the development of a clear understanding of management arrangements including the potential mechanisms for fishery expansion and potential co-management, the knowledge underpinning current management strategies and fishery risk. Much of the rationale for current management arrangements are immersed in consultative meeting minutes, scientific reports or in various stages of ratification through a complex administrative framework. The development of a HS document that is ratified by management agencies and Islanders will guide and demonstrate sustainable fishing, in a clear consultative fashion for future development of the fishery. Adding some additional urgency is the fact that the current strategic assessment for the fishery includes a commitment for the development of “harvest strategies to include meaningful performance indicators, performance measures and responses”.

3 Objectives

1. Collate and analyse available coral trout and Spanish mackerel fishery data to estimate variability and assess whether there is sufficient information to develop time-series indicators of stock status. (data links and sampling methodology).

2. Summarise and assess utility of updated stock assessments and reference points for coral trout and Spanish mackerel.

3. Present results and HS guidelines (including Harvest Control Rules) to the Finfish working group, with fishery managers and representative stakeholders to develop and evaluate key elements of the draft HS. It is the responsibility of the FFWG to take the recommended draft HS and formally adopt it as the HS.

The project will develop and ratify a clear and concise draft harvest strategy for the Torres Strait Finfish Fishery. It will include clear guidance for sustainable fishing, the data requirements that underpin management strategies, options for flexibility to suit market and community needs, targets and limits and guidance for situations where these targets and/or limits are reached, and data requirements for potential fishery expansion.

4 Harvest Strategies for each fishery

4.1 Spanish mackerel

The Spanish Mackerel harvest strategy is presented in Appendix A (draft working document) – with a summary described below in sections (). The most recent stock assessment is presented in Appendix B. Appendix C provides a single table summary of the Spanish mackerel Harvest Strategy.

The HS has been developed in consultation with the FFRAG (meeting no. 1 on 9-10 November 2017; meeting no. 2 on 22-23 March 2018; meeting no. 3 on the 19-20 of November 2018; and meeting no. 4 on 13 and 14 March 2019) and FFWG (meeting no. 1 on 16-17 March 2017 and meeting no 2. on 22-23 March 2018). The HS will be endorsed in the future. This HS is the working document and does not replace any previous HS.

Further updates to this report and particularly the Spanish mackerel harvest strategy were made on the basis of recommendations from two dedicated stakeholder harvest strategy meetings (Torres Strait Finfish Harvest Strategy Meeting, 11-12th June 2019 and Torres Strait Finfish Harvest Strategy Meeting: Combined Finfish Resource Assessment Group and Working Group Meeting, 27th-28th June 2019).

4.1.1 STOCK ASSESSMENT MODEL

The stock assessment model was first developed in 2006 (Begg et al. 2006) and updated (O'Neill & Tobin 2018), with the most recent assessment including data up to the 2017-18 fishing season. The model is an age-structured model based on similar application to the Queensland East Coast stock (see Begg et al. 2005, Campbell et al. 2012, O'Neill et al. 2018). It is a widely used approach for providing RBC advice and the associated uncertainties and has been reviewed and accepted by the FFRAG and has been adopted by the PZJA to support decision making on sustainable catch limits.

The model integrates all available information into a single framework to assess resource status and provide a RBC. The model is fitted to TVH (Sunset) catch per unit effort (CPUE) data which has been standardised. The growth relationships used in the model were based on the previous stock assessment models to ensure that the modelled individual mass at age more closely resembled field measurements (collected over a three year period).

The stock assessment model is non-spatial and assumes (conservatively) that the Torres Strait Spanish mackerel Fishery stock is independent of the Spanish mackerel Queensland East Coast Fishery stock (and other stocks in the Gulf of Carpentaria and Northern Territory waters). A spatial version of the model could be developed as part of a MSE project, and can be used to investigate plausible linkages between these stocks (as per method for Tropical Rock Lobster – see Plagányi et al. 2012, 2013).

A stock-recruitment relationship is used allowing for annual fluctuation about the average value predicted by the recruitment curve. The model is fitted to the available abundance indices by maximising the likelihood function. The model estimation process was conducted in Matlab®

(MathWorks, 2018) and consisted of a maximum likelihood (ML) step followed by Markov Chain Monte Carlo sampling (MCMC).

4.1.2 HARVEST CONTROL RULE

The harvest control rule (HCR) recommended by the FFRAG sets a harvest level (as a recommended biological catch - RBC) on the basis of evaluating the resource status. The resource status is estimated using an assessment (that is fitted to the standardised catch rate (CPUE) indices from the TVH sector).

The basic HCR formula is:

- The biomass lower bound of the 'hockey stick' HCR is B_{LIM} (20% of B_0). For biomasses less than 20%, F is zero and the calculated RBC is zero.
- The initial (interim) biomass upper bound of the HCR is set at B_{TARG} (48% of B_0). An increasing linear relationship between F and biomasses between B_{LIM} and B_{TARG} calculate the RBC.
- The HCR takes the current-status ($B_{CURRENT}/B_0$) of the resource into account. On this basis, the HCR determines the exploitation rate as a fraction of F_{MSY} and the RBC to achieve B_{TARG}.
- The HCR is applied to a stock assessment, or is the median HCR for a set of stock assessment scenarios. For example, in the 2018 assessment this was a median RBC estimate of 35 model scenarios, taking into account a range of uncertainty.

4.1.3 REFERENCE POINTS

The HS reference points are:

a) The unfished biomass B_0 is the model-estimate of spawning stock biomass in 1940 (start of the commercial operations in the Fishery). $B_0 = B_{1940} = 100\%$.

b) The short-term interim target biomass B_{TARG} is the spawning biomass level equal 48% of B_0. A longer-term B_{TARG} of 60% of B_0 is aspirational and will be the goal once the stock reaches the initial TRP of 40% (subject to RAG endorsement).

  - The current B_{TARG} of 48% is less than B_{MEY} (biomass at maximum economic yield). The FFRAG noted a B_{TARG} less than B_{60} was initially needed because the setting of the RBC 'moved' to a dynamic assessment of the current status of the resource in 2019, rather than using the potential equilibrium RBC.

c) The limit biomass B_{LIM} is the spawning biomass level below which the ecological risk to the stock is unacceptable and the stock is defined as 'overfished'. In certain circumstances B_{LIM} is agreed to be half of B_{TARG}, $B_{LIM} = 0.20\ B_0$. In this case – it is more a case that it is set to the agreed level accepted in other fisheries where there is uncertainty.

  - The agreed B_{LIM} is set to the default HSP B_{LIM} of 20% of B_0.

d) The target fishing mortality rate F_{TARG} is the estimated level of fishing mortality rate that maintains the spawning biomass around B_{TARG}. Ideally, F_{TARG} is the target fishing mortality rate that corresponds to an optimal level in terms of economic, biological and social considerations.

4.1.4 HCR AND ASSESSMENT CYCLE

A stock assessment should be conducted each year until the biomass is greater than B_{40}. It is assumed that the stock will take approximately 10 years to build to B_{40} at the current biomass level and given the RBC that was agreed to.

The ongoing frequency of stock assessments will be set once B_{40} has been reached, with every three years as one suggested time schedule.

4.2 Coral trout

The Coral trout harvest strategy is presented in Appendix D (draft working document) – with a summary described below in sections (). The most recent stock assessment is presented in Appendix E. Appendix F provides a single table summary of the Coral trout Harvest Strategy.

The HS has been developed in consultation with the FFRAG (meeting no. 1 on 9-10 November 2017; meeting no. 2 on 22-23 March 2018; meeting no. 3 on the 19-20 of November 2018; and meeting no. 4 on 13 and 14 March 2019) and FFWG (meeting no. 1 on 16-17 March 2017 and meeting no 2. on 22-23 March 2018). The HS will be endorsed in the future. This HS is the working document and does not replace any previous HS.

Further updates to this report and particularly the Coral trout harvest strategy were made on the basis of recommendations from two dedicated stakeholder harvest strategy meetings (Torres Strait Finfish Harvest Strategy Meeting, 11-12th June 2019 and Torres Strait Finfish Harvest Strategy Meeting: Combined Finfish Resource Assessment Group and Working Group Meeting, 27th-28th June 2019).

4.2.1 STOCK ASSESSMENT MODEL

The stock assessment model was first developed in 2018 (it is preliminary) and is an age-structured model based on similar application to the Queensland East Coast stock (see Leigh *et al*. 2014). It is a widely used approach for providing RBC advice and the associated uncertainties.

The model integrates all available information into a single framework to assess resource status and provide a RBC. The model is fitted to TVH catch per unit effort (CPUE) data which has been standardised. A stock-recruitment relationship is used, allowing for annual fluctuation about the average value predicted by the recruitment curve. The model is fitted to the available abundance indices by maximising the likelihood function. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (using the package AD Model Builder™) (Fournier *et al*. 2012).

4.2.2 HARVEST CONTROL RULE

The harvest control rule (HCR) recommended by the FFRAG sets a harvest level (as a recommended biological catch -RBC) on the basis of evaluating the resource status. The resource status is estimated using an assessment (that is fitted to the standardised catch rate (CPUE) indices from the TVH sector).

The basic formula is:

- The FFRAG recommended that the current constant RBC of 134.9 tonnes be adopted as the interim RBC until the stock assessment is updated. The current preliminary assessment indicates the stock is greater than 80% of B_0.

4.2.3 REFERENCE POINTS

The HS reference points are:

a) The unfished biomass B_0 is the model-estimate of spawning stock biomass in 1950 (start of the Fishery). $B_0 = B_{1950}$.

b) The target biomass B_{TARG} is the spawning biomass level equal to 60% of B_0 to take account of the fact that the resource is important for the traditional way of life and livelihood of traditional inhabitants, is leased to sunset licence holders and the target biomass level must be biologically and economically acceptable.

c) The current agreed B_{TARG} is based on the assumption that B_{MSY} is 50% of B_0 for this species and B_{TARG} should be set at 1.2 B_{MSY}.

d) The limit biomass B_{LIM} is the spawning biomass level below which the risk to the stock is unacceptably high and the stock is defined as 'overfished'. B_{LIM} is agreed to be half of B_{TARG}, $B_{LIM} = 0.20\ B_0$. In this case –it is set to the agreed proxy accepted in other fisheries where there is uncertainty.

    a. The agreed B_{LIM} is set to the default proxy HSP B_{LIM}.

e) If the limit reference point (B_{LIM}) is triggered then the Fishery will be closed.

f) The target fishing mortality rate F_{TARG} is the estimated level of fishing mortality rate that maintains the spawning biomass around B_{TARG}. This current F is estimated to be approximately 0.02 (average over the two regions).

4.2.4 HCR AND ASSESSMENT CYCLE

The stock assessment is only preliminary and at this stage it is planned that it will be updated three years from now. A decision was made and endorsed such that a stock assessment should be conducted in three years provided additional data available (during the 2021-22 season ahead of setting catch limits for the 2022-23 season). Postponing the stock assessment for three years would allow enough time for additional data to be included. The additional data priorities are:

a) the 1994-95 CSIRO fish survey data which may form a valuable baseline datum;

b) improved catch and effort data from TIB fishers; and

c) fishery independent data such as an underwater survey or biological sampling.

The use of empirical trigger reference points was recommended for the years between stock assessments. The agreed trigger reference points will use standardised CPUE data as a proxy for biomass and the yearly fishery catch data to ensure the maximum yield of the fishery zones are not being exceeded.

The specific trigger reference points are:

a) In line with the recommended target reference point (B TARG = B60) and taking into account the conservative approach preferred by industry, if the biomass of coral trout is less than B60 (B TARG) then an integrated stock assessment will be conducted. To determine the biomass level, this trigger will use CPUE data as a proxy for biomass. It was agreed that the average CPUE from 2012 until 2017 (inclusive) would be used as an indicative reference point of the CPUE at B80 (average = 120.8 kg per vessel per day) from which the CPUE at B60 can be calculated and used as the trigger reference point. Given the ratio of 80:60 is equal to 0.75 then the trigger reference point which would activate the rule that an assessment must be undertaken is: *if the standardised CPUE falls below 90.6 kg per (primary) vessel per day* (computed as 0.75*120.8 = 90.6).

b) If the combined yearly total catch of the four coral trout species from both commercial sectors is greater than 90 tonnes. Ninety tonnes was agreed because this 2/3 of the current constant RBC of 134.9 tonnes.

If either (a) or (b) above occurs, the stock assessment must be repeated the following year in order to monitor the condition of the stock.

5 Conclusions & Recommendations

The project has provided a foundation and framework for a Harvest Strategy for both Spanish mackerel and coral trout, with both fish species supported within the project by stock assessments. An update to the Spanish mackerel assessment was conducted with direct feedback between the outputs and diagnostics of the assessment informing the process of harvest strategy development. Likewise, the initial harvest strategy resourced the first preliminary assessment of the coral trout. Project staff worked closely with management agencies and stakeholders, using formal committee meetings inputs and advice, which fulfilled the requirements of the guidelines for developing harvest strategies. These being that they are *pragmatic and easy to understand*. The project provided extensive summaries of the component and key elements of harvest strategies (e.g. establishing indicators, reference points, and decision rules). Moreover, the project provided the theoretical basis for the underlying principles and concepts. The initial harvest strategies were cognisant of the need for their designs to be *cost-effective* and where possible suggested data collection regimes which met that principle.

A critical principle of the guidelines was to be *transparent and inclusive*. Project documentation included all technical terms, methodology and assumptions. All stakeholders, as much as possible through AFMA, contributed to the HS review, so far as possible to make the framework *unambiguous*. The principle that the HS process needed to be *precautionary* was within the draft management procedures, and staff raised when relevant the different types of uncertainty faced when managing multiple species with limited data. The current version of the harvest strategy is adaptive, as various components need checking based on updated assessments and any new information.

The project suggests that the FFRAG and FFWG give due consideration to the following recommendations:

- While the initial reference points were set, the decision rules relating to harvest rates depend on the current-status of each stock. Target reference points require may require more research, discussion and change (for example away from F_{MSY}). Further discussions should be within each management forum (RAG and WG). This is especially true for coral trout where the assessment was only preliminary and had spatial considerations.
- In order to be meet the guidelines of “easy to understand”, RAG and WG members need to know all concepts and the HS differences between fish species. For example, different technical definitions, where stock spawning-biomasses was as tonnes of mature fish for coral trout and for Spanish mackerel female spawning egg production.
- Harvest Strategy performance metrics (target future: catches, catch rates, and annual variation in catch) are yet to be established and future research (MSE) efforts should outline candidate options. Preliminary TIB and TVH values for target catch rates of Spanish mackerel require sector conversions. The conversion factor needs updating based on more time-location comparable TIB–TVH catch rate data.
- Data limitations are posing a risk to the predictions from stock assessment methodology of both species in their respective fisheries. Although, new data collection programs are proposed and some projects initiated, without meaningful fish catch-effort and age-length data from the TIB and TVH sectors, the ability to monitor the fishery stocks is compromised.
- In addition, future stock assessments need information on species ratios for coral trout assemblages. Coral trout density surveys are also required, to accurately scale stock assessment dynamics, like completed on the Great Barrier Reef (Leigh et al., 2014).

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Appendices A-F:

Appendix A

Torres Strait Spanish mackerel Fishery

Harvest Strategy

June 2019

Australian Government
Australian Fisheries Management Authority

Torres Strait Finfish Fishery: Spanish mackerel

Harvest Strategy Working Document - draft

June 2019

Box 7051, Canberra Business Centre, ACT 2610 / Ph (02) 6225 5555 / Fax (02) 6225 5500 / AFMA Direct 1300 723 621 afma.gov.au

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GLOSSARY

Types of reference points:

Reference points	Description
Metarule	A rule that describes how the RBCs obtained from an assessment should be adjusted in calculating a recommended TAC
Target	The desired state of the stock or fishery (for example, MEY or B_{TARG})[1]
Limit	The level of an indicator (such as biomass or fishing mortality) beyond which the risk to the stock is regarded as unacceptably high[1]
MEY	The sustainable catch or effort level for a commercial fishery that allows net economic returns to be maximised. In this context, maximised equates to the largest positive difference between total revenue and total cost of fishing[1]
MSY	Maximum Sustainable Yield - the maximum average annual catch that can be removed from a stock over an indefinite period under prevailing environmental conditions[1]

Abundance indicators:

Symbols	Description
B	Spawning biomass - the total weight of all adult (reproductively mature) fish in a population[1] (sometimes designated with a S)
B_0	The unfished spawning biomass (determined from an appropriate reference time point)
F or U	Fishing harvest rate
B_{LIM}	Biomass limit reference point - the point beyond which the risk to the stock is regarded as unacceptably high[1]
B_{TARG}	Biomass target reference point - the desired biomass of the stock[1]
$B_{CURRENT}$	The estimated biomass in the last year of the most recent assessment.

Other terms:

Acronym	Description
CPUE	Catch Per Unit Effort or Catch rate, e.g. number of fish caught per day. Often standardised.
Change Limiting Rule	(Definition required).
HCR	Harvest Control Rule - pre-determined rules that control fishing activity according to the biological and economic conditions of the fishery (as defined by monitoring or assessment). Also called 'decision rules'. HCR are a key element of a harvest strategy[1]

[1] Definition sourced from the *Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018)

HSP	*Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018)
HS	Harvest Strategy
Median	Midpoint of a frequency distribution of results. This is the middle value separating the higher half from the lower half of results.
PZJA	Protected Zone Joint Authority – government body responsible for decision making in Torres Strait Fisheries.
RBC	Recommended Biological Catch, also referred to as 'total kill' which is the maximum harvest that should be taken from a fishery by all users e.g. commercial fishers, recreational fishers, traditional fishing.
FFRAG	Protected Zone Joint Authority Finfish Fishery Resource Assessment Group, advisory group to the PZJA
FFWG	Protected Zone Joint Authority Finfish Fishery Working Group, advisory group to the PZJA
TAC	Total Allowable Catch- the annual catch limit set for a stock, species or species group. May be referred to as Total Allowable Commercial Catch (TACC). Used to control commercial harvests and fishing pressure[1]
Tiered approach	A framework that uses different control rules to cater for different levels of uncertainty about a stock
TIB, TIB sector	Traditional Inhabitant Boat Licence holders – Torres Strait Islander commercial fishers operating in the Torres Strait Protected Zone
TVH	Transferrable vessel holder, also referred to as Sunset Licence Holders or Sunset Sector. These fishers lease access to the fishery from Traditional Inhabitants under a yearly 'Sunset' licence
Sunset Sector	(see TVH)

OVERVIEW

The Torres Strait Spanish mackerel harvest strategy (HS) sets out the management actions to achieve the agreed fishery objectives. The HS describes the performance indicators used for monitoring the condition of the stock, the stock assessment procedures and the rules applied to determine the recommended biological catch (RBC). The total allowable catch (TAC) can then be allocated for each fishing season.

The HS uses an age-structured stock assessment model that is dependent on a standardised annual catch rate index (CPUE) from the TVH sector. The RBC is based on the best available scientific advice on what the fishing mortality should be for the stock. In application, the RBC is split based on catch sharing decisions between the fishing sectors, and a TAC (an enforced limit on total commercial catches) is calculated.

The HS herein meets the requirements of the *Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018) *(*HSP). This was by applying a precautionary approach to the reference points and measures to be implemented in accordance with the reference points. This is reflected in the use of reference points that are appropriate for Torres Strait fisheries, to protect traditional livelihoods and cultural values.

The Harvest Control Rule (HCR) is designed to decrease harvests as the stock size decreases below the target reference point. The HS uses a biomass target reference point (set initially low in the short term) to account for leased fish to TVH operators. The reference points are biologically and economically acceptable.

The longer-term B_{TARG} is 60% of B_0. This is seen to be the 'aspirational' target, given the estimated current status of the resource. The HS reference points are B_{LIM} equal to 20% of B_0, and B_{TARG} (interim) equal to 48% of B_0.

Given the current status ($B_{CURRENT}$) of the stock in 2018 was around 32% of B_0, the recommendation was for the stock assessment to be undertaken every year until the stock is above B_{40}.

The status of the stock, against the HS, is reported to the Finfish Resource Assessment Group (FFRAG), Finfish Working Group (FFWG) and the Protected Zone Joint Authority (PZJA). The stock assessment is conducted to evaluate stock status relative to the reference points and, in doing so, calculate the HCR. The stock assessment includes considerations of the catch rates in current and previous fishing seasons, how the harvests compare to the RBCs, and the levels of the status indicators in relation to the reference points. This information produces an RBC for the upcoming fishing season.

The scope of this working document outlines preliminary HS procedures for setting RBCs from 2020/21 onwards. The procedure settings and documentation will advance in time based on further FFRAG and FWG review. Previous RBC settings did not follow this HS or the HCR herein.

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1 BACKGROUND

The Torres Strait Finfish Fishery Spanish mackerel Harvest Strategy (HS) has been developed in accordance with the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines* (HSP, 2018). This is consistent with objectives of the *Torres Strait Fisheries Act 1984* (the Act).

Importantly the HS has been designed to have regard for traditional knowledge and the ability of communities to manage fishery resources locally, through acknowledging and incorporating customary and traditional laws, recognising; Malo Ra Gelar, Gudumalulgal Sabe Maluailgal Sabe Kulkalgal Sabe.

The strategy takes into account key fishery attributes including:

a) Commercial fishing by traditional inhabitants is important for local employment, economic development and for the passing down of traditional knowledge and cultural lore. Enough fish needs to be left in the water for fishers to make money and to protect the traditional way of life and livelihoods and cultural values.

b) Torres Strait Spanish mackerel stock are assumed separate from other regional stocks. They do not mix with the Queensland East Coast and the Gulf of Carpentaria stocks (see Buckworth *et al.* 2007 and Newman *et al.* 2009).

c) There is potential for variations in availability and abundance of Spanish mackerel, due to their movement, schooling and aggregation patterns for feeding and spawning.

d) Spanish mackerel are a shared resource important for subsistence, commercial, traditional, charter and recreational sectors.

e) Spanish mackerel are a shared resource with Papua New Guinea listed under the *Torres Strait Treaty 1978*.

1.1 COMMONWEALTH FISHERIES HARVEST STRATEGY POLICY

The objective of the HSP is the ecologically sustainable and profitable use of Australia's AFMA managed fisheries.

To pursue this objective, the Australian Government, through AFMA, implements harvest strategies that:

a) ensure exploitation of fisheries resources and related activities are conducted in a manner consistent with the principles of ecologically sustainable development, including the exercise of the precautionary principle

b) maximise net economic returns to the Australian community from management of Australian fisheries - always in the context of maintaining commercial fish stocks at sustainable levels

c) maintain key commercial fish stocks, on average, at the required target biomass to produce maximum economic yield from the fishery

d) maintain all commercial fish stocks, including byproduct, above a biomass limit where the risk to the stock is regarded as unacceptable (B_{LIM}), at least 90 per cent of the time

e) ensure fishing is conducted in a manner that does not lead to overfishing - where overfishing of a stock is identified, action will be taken immediately to cease overfishing

f) minimise discarding of commercial species as much as possible

g) are consistent with the *Environment Protection and Biodiversity Conservation Act 1999* and the *Guidelines for the Ecologically Sustainable Management of Fisheries (2nd Edition)*.

The HSP provides for the use of proxy settings for reference points when there is no other information to base them on. It is important to cater for different levels of information available and to be able to create a HS that addresses unique fishery needs. This balance between prescription and flexibility encourages the development of innovative and cost effective strategies to meet key policy objectives. Proxies, including those that exceed the minimum standards, must be demonstrated to be compliant with the HSP objective.

With a harvest strategy in place, communities, fishers, fishery managers and other stakeholders are able to operate with pre-defined rules, management decisions are more transparent, and there are likely fewer unanticipated outcomes necessitating hasty management responses. However, due to the inherent variability of mackerel abundance, there may be a need for significant changes in recommended harvest on an annual basis based on the current level of stock biomass.

1.2 DEVELOPMENT OF THE TORRES STRAIT FINFISH FISHERY SPANISH MACKEREL HARVEST STRATEGY

The HS was developed in consultation with the FFRAG and FFWG through several meetings held through 2017 to 2019[2]. Further updates to this report were made on the basis of recommendations from two dedicated stakeholder harvest strategy meetings (Torres Strait Finfish Harvest Strategy Meeting, 11-12th June 2019 and Torres Strait Finfish Harvest Strategy Meeting: Combined Finfish Resource Assessment Group and Working Group Meeting, 27th -28th June 2019).

[2] FFRAG Meeting no. 1 on 9-10 November 2017; Meeting no. 2 on 22-23 March 2018; Meeting no. 3 on the 19-20 of November 2018; and Meeting no. 4 on 13 and 14 March 2019 and FFWG Meeting no. 1 on 16-17 March 2017 and Meeting no 2 - 22-23 March 2018.

2 TORRES STRAIT FINFISH FISHERY SPANISH MACKEREL HARVEST STRATEGY

2.1 SCOPE

This HS applies to Torres Strait managed waters, and includes potential catch sharing arrangements between Australia and Papua New Guinea (PNG) under the *Torres Strait Treaty 1978.*

The HS outlines the control rules used to develop advice on the recommended biological catch (RBC) and to recommend total allowable commercial catches (TAC) (an enforced limit on total commercial catches). The HS sets the criteria that pre-agreed management decisions will be based on achieving the HS objectives.

2.2 OBJECTIVES

The operational objectives of the SM Harvest Strategy are to:

a) maintain the stock at (on average), or return to, a target biomass point B_{TARG} equal to the stock size that aims to protect the traditional way and life and livelihood of traditional inhabitants and is biologically and economically acceptable (fishers can make money)

  - The default proxy for B_{MEY} was agreed as an interim B_{TARG} to allow for stock building whilst minimising potential economic impacts on the fishery. Once the interim B_{TARG} is reached further consideration of a longer-term target will be undertaken (for example B_{60}).

b) maintain stocks above the limit biomass level (B_{LIM}), or an appropriate proxy, at least 90 per cent of the time;

c) reduce fishing levels if a stock is below B_{TARG} but above B_{LIM}; and

d) implement rebuilding strategies, if the stock moves below B_{LIM}.

Broader fishery level objectives are outlined in the *Torres Strait Finfish Fishery Management Plan 2013* (Australian Government 2013).

2.3 RECOMMENDING TACs FROM RBCs

The RBC is the recommended biological catch (or total kill) of Spanish mackerel that can be taken by all users of the Fishery. The HS states that when setting the TAC for the next fishing season the HS should take into account all sources of mortality on the stock, including the fishing sectors operating in the Torres Straits.

The HS includes harvests taken by non-commercial fishing sectors, for example traditional Islander harvest mainly taken for subsistence, recreational/charter catches, and commercial TIB harvest catches. The estimates of these catches over a time series are included in the stock assessment model.

The HS may be updated to account for changing circumstances in the fishery (e.g. increased participation from TIB sector) and catch allocation priorities. The review provisions are described in Section 2.12.

In setting the Australian TAC, regard must be had for Australia's obligations under the Treaty. Spanish mackerel catch sharing arrangements are in place however have not been implemented to date.

2.4 MONITORING

Data for the fishery are collected and monitored by a range of methods. The current and desired types are listed below. Currently there is no ongoing monitoring strategy in place to collect economic information.

Fishery independent surveys

No current independent surveys for Spanish mackerel.

Catch and effort information

Fishers in the transferrable vessel holder (TVH or Sunset) sector are required to record catch and effort information in the Torres Strait Finfish Daily Fishing Log[3]. The following data is recorded for each TVH fishing operation: the port and date of departure and return, fishing area, fishing method, hours fished and the weight of retained fish.

All commercial catch taken by fishers in the Traditional Inhabitant Boat (TIB) sector must be unloaded to a licensed Torres Strait Fish Receiver and weighed and reported at the point of unload through the Torres Strait Catch Disposal Record. Effort reporting through this Fish Receiver System remains voluntary.

Fish aging

The Queensland Government (QDAF) conducted monitoring of Torres Strait Spanish mackerel between 2000 and 2002 to obtain biological data and parameters on fish age and length (McPherson, unpublished). Research projects are ongoing to update this data (age, sex and length frequency data collection in 2019-20); and a technical review within the RAG will evaluate the stock assessment after more recent data has been added to the existing time series

2.5 STOCK ASSESSMENT MODEL

The stock assessment model was first developed in 2006 (Begg *et al.* 2006) and updated (O'Neill & Tobin 2018), with the most recent assessment including data up to the 2017-18 fishing season. The model is an age-structured model based on similar application to the Queensland East Coast stock (see Begg *et al*. 2005, Campbell *et al.* 2012, O'Neill *et al.* 2018). It is a widely used approach for providing RBC advice and the associated

[3] Copies of Torres Strait reporting forms are available here: https://www.afma.gov.au/fisheries-services/logbooks-and-catch-disposal

uncertainties and has been reviewed and accepted by the FFRAG and has been adopted by the PZJA to support decision making on sustainable catch limits.

The model integrates all available information into a single framework to assess resource status and provide a RBC. The model is fitted to TVH (Sunset) catch per unit effort (CPUE) data which has been standardised. The growth relationships used in the model were based on the previous stock assessment models to ensure that the modelled individual mass at age more closely resembled field measurements (collected over a three year period).

The stock assessment model is non-spatial and assumes (conservatively) that the Torres Strait Spanish mackerel Fishery stock is independent of the Spanish mackerel Queensland East Coast Fishery stock (and other stocks in the Gulf of Carpentaria and Northern Territory waters). A spatial version of the model could be developed as part of a MSE project, and can be used to investigate plausible linkages between these stocks (as per method for Tropical Rock Lobster – see Plagányi *et al.* 2012, 2013).

A stock-recruitment relationship is used allowing for annual fluctuation about the average value predicted by the recruitment curve. The model is fitted to the available abundance indices by maximising the likelihood function. The model estimation process was conducted in Matlab® (MathWorks, 2018) and consisted of a maximum likelihood (ML) step followed by Markov Chain Monte Carlo sampling (MCMC).

2.6 HARVEST CONTROL RULE

The harvest control rule (HCR) recommended by the FFRAG sets a harvest level (as a recommended biological catch - RBC) on the basis of evaluating the resource status. The resource status is estimated using an assessment (that is fitted to the standardised catch rate (CPUE) indices from the TVH sector).

The basic HCR formula is:

- The biomass lower bound of the 'hockey stick' HCR is B_{LIM} (20% of B_0). For biomasses less than 20%, F is zero and the calculated RBC is zero.
- The initial (interim) biomass upper bound of the HCR is set at B_{TARG} (48% of B_0). An increasing linear relationship between F and biomasses between B_{LIM} and B_{TARG} calculate the RBC.
- The HCR takes the current-status ($B_{CURRENT}/B_0$) of the resource into account. On this basis, the HCR determines the exploitation rate as a fraction of F_{MSY} and the RBC to achieve B_{TARG}.
- The HCR is applied to a stock assessment, or is the median HCR for a set of stock assessment scenarios. For example, in the 2018 assessment this was a median RBC estimate of 35 model scenarios, taking into account a range of uncertainty.

2.7 REFERENCE POINTS

The HS reference points are:

a) The unfished biomass B_0 is the model-estimate of spawning stock biomass in 1940 (start of the commercial operations in the Fishery). $B_0 = B_{1940} = 100\%$.

b) The short-term interim target biomass B_{TARG} is the spawning biomass level equal 48% of B_0. A longer-term B_{TARG} of 60% of B_0 is aspirational and will be the goal once the stock reaches the initial TRP of 40% (subject to RAG endorsement).

   - The current B_{TARG} of 48% is less than B_{MEY} (biomass at maximum economic yield). The FFRAG noted a B_{TARG} less than B_{60} was initially needed because the setting of the RBC 'moved' to a dynamic assessment of the current status of the resource in 2019, rather than using the potential equilibrium RBC.

c) The limit biomass B_{LIM} is the spawning biomass level below which the ecological risk to the stock is unacceptable and the stock is defined as 'overfished'. In certain circumstances B_{LIM} is agreed to be half of B_{TARG}, B_{LIM} = 0.20 B_0. In this case – it is more a case that it is set to the agreed level accepted in other fisheries where there is uncertainty.

   - The agreed B_{LIM} is set to the default HSP B_{LIM} of 20% of B_0.

Decision rules have yet not been established for utilization related performance metrics such as future 'target' catches or 'target' catch rates per primary vessel or per TIB dory day.

Rational for reference points

The Commonwealth HS Policy recognises that each stock/species/fishery will require an approach tailored to the fishery circumstances, and species life history characteristics. The HS identifies that the selection of reference points within harvest strategies need to be realistic with respect to the scale or nature of the fishery, and the capacity to manage it. Reference points should be set at levels appropriate to the biology of the species and the proper functioning of the broader marine ecosystem. Further, stocks that fall below B_{LIM} will be subject to the recovery measures stipulated in the HS. A number of adaptive management approaches may be used to deal with this.

The Fishery is characterised by temporal and spatial variability, where in the last few years 2010–2018 catch rates have declined. Hypotheses have been presented as to potential environmental anomalies influencing fish catchability or recruitment.

Stakeholders have expressed the need for B_{TARG} to be set between 48 and 60 per cent of the unfished biomass to account for the importance of the stock for the traditional way of life and livelihood of traditional inhabitants (social objectives) and the need to achieve biological and economic objectives. The HS's higher target biomass level (referring to 60%), would increase catch rates and improve profits in the fishery over other lower RP, such as B_{48}.

The unfished biomass (B_0) is calculated within the stock assessment model, the value of unfished biomass and target biomass have therefore varied over time in response to annual data updates and model parameter settings and estimates. Estimates of unfished biomass and target biomass are particularly sensitive to changes to data, which determines the steepness of the stock-recruit relationship.

2.8 HCR AND ASSESSMENT CYCLE

A stock assessment should be conducted each year until the biomass is greater than B_{40}. It is assumed that the stock will take approximately 10 years to build to B_{40} at the current biomass level and given the RBC that was agreed to.

The ongoing frequency of stock assessments will be set once B_{40} has been reached, with every three years as one suggested time schedule.

2.9 DATA SUMMARY

The annual data summary reviews the catch per unit effort (CPUE) from the TVH sector, as well as total catch from all sectors, and size information provided from a sub-sample of fish. The data summary is used as an indicator to identify if catches correspond to the TAC, and to monitor CPUE.

2.10 DECISION RULES

The decision rules for the HS are:

Biomass target reference point triggered

- The HCR takes the current status of the resource into account and on the basis of this determines the exploitation rate (and corresponding RBC) to achieve the TRP.
    - From the 2020-21 season, the TAC will be set to allow the stock to build to B48. The FRAG will consider the number of years it should take to reach B_{TARG} prior to setting the 2020-2021 TAC. The scientists and industry noted that in determining the number of years for it to rebuild the social/economic impacts of a low RBC would need to be weighed against building the stock quickly. The rate of rebuilding to the TRP is still to be agreed. Twelve (12) years was discussed by the RAG as an option (based on 3 times the average age of maturity (Australian Government, 2007; Sainsbury, 2008). The current median RBC (94 tonnes) expects to achieve B_{MSY} in ~6years, B_{40} in 10 years, and B_{48} in 17 years.

Biomass limit reference point triggered

- If the HCR limit reference point is triggered, the fishery is closed and subject to a rebuilding strategy.
    - The nature of the rebuilding strategy will be determined on the basis of the stock assessment (to be applied immediately) and the rate of recovery (i.e. number of years to achieve a biomass greater than B_{LIM}).
- If the HCR limit reference point is triggered two years (or more) in a row, a stock assessment must be conducted annually.

Fishery closure rules

- If the stock assessment determines the stock to be below the biomass limit reference point, the Fishery will be closed to fishing. Previous analyses have indicated the potential risk that this occurs (see stock assessment Report).

Re-opening the Fishery

- Following closure of the Fishery, the Fishery can only be re-opened when a stock assessment determines the Fishery to be above the biomass limit reference point. Given the model produces a set of agreed scenarios, the exact technical specification of this rule is yet to be determined.

Based on the decision rules, there are a number of alternative possible scenarios that may occur under the application of the HCR as to the number of years for the stock to rebuild to the reference points. This will be determined when the next assessment is undertaken.

In provided advice on the formation of this strategy, industry stakeholders gave their full support that if the stock is below the target reference point, catches should be set at a level aiming to build the stock towards the target within 12 years (with 12, 10 and 8 year scenarios to be explored for future RBC setting).

Industry agreed that if the stock assessment outcomes suggested increases in RBCs (and in turn the TACs), these increases should only occur slowly through some kind of change limiting rule, noting that an increased TAC would likely not affect the TIB sector with a low present level of utilisation. Industry advised a preference for 'banking' these fish to contribute to the biomass and future catch rates rather than harvesting this extra stock. FFRAG will be well placed to continue working with industry on the development of a change limiting rule in line with the implementation of the harvest strategy.

2.11 GOVERNANCE

The status of the SM Fishery and how it is tracking against the Harvest Strategy Framework (HSF) is reported to the FFRAG, FFWG who advise the PZJA as part of the yearly TAC setting process.

2.12 REVIEW

Under certain circumstances, it may be necessary to amend the harvest strategy. For example if:

a) there is new information that substantially changes the status of a fishery, leading to improved estimates of indicators relative to reference points; or

b) drivers external to management of the fishery increase the risk to fish stock/s; or

c) it is clear the strategy is not working effectively and the intent of the HSP is not being met; or

d) alternative techniques are developed (or a more expensive but potentially more cost-effective harvest strategy that includes surveys and annual assessments is agreed) for assessing the fishery, the HS may be amended to incorporate decision rules appropriate for those assessments.

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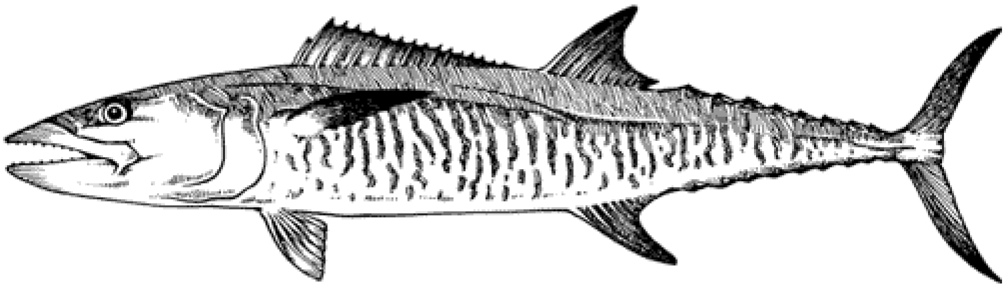
Appendix B

Torres Strait Spanish mackerel Assessment

June 2019



Scomberomorus commerson

Torres Strait Spanish mackerel

Stock assessment 2019

Results for harvest strategy development

Torres Strait AFMA Project Number: 2016/0824

Queensland Government

This publication has been compiled by Dr M. F. O'Neill of Agri-Science Queensland, Department of Agriculture and Fisheries.

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Summary

The fishery for Torres Strait Spanish mackerel is by line and troll fishing from ocean waters between Cape York Peninsula (northeast Australia) and the western province of Papua New Guinea. Spanish mackerel are an important economic and traditional food source. The fishery is seasonal with harvests mostly taken between September and November from eastern Torres Strait and Bramble Cay waters, when notable aggregations form to spawn and feed.

Management of the fishery covers six fishing sectors: 1) commercial licensed islander boats (aka TIB), 2) commercial operators who annually lease portions of quota (TVH), 3) non-commercial islander fishers , 4) recreational, 5) charter, and 6) commercial Papua New Guinea fishers (PNG), which thus far have not requested quota to fish.

Normally, TVH fishers caught more Spanish mackerel than other sectors. Recent 2017–2018 annual harvests (and catch share percentages) were around 2 tonnes (t) for TIB (2%), 67 t for TVH (80%), 10 t for islander non-commercial take (12%), 2–5 t for recreational and charter (6%), and no PNG harvest (0%). TVH harvests ranged 106–256 t per year between 1989 and 2006, and 64–105 t between 2007 and 2018. By definition July 2017-June 2018 is labelled through-out document as 2017 – fishing year.

The more prominent TVH sector's data computed the annual mean catch rates of fish abundance. Generalised linear models standardised the catch rates of Spanish mackerel (for legal sized fish). Results signalled a 50% decline between 2009 and 2018 (labelled 2017). Catch rates were lowest in 2017–2018 and similar to the low in 1999. The signal of decline was stronger when standardised for different fishing behaviours between TVH operations. The longer series of 1989–2018 catch rates revealed a cyclic pattern over years.

The age-structured population analyses of Spanish mackerel assessed annual data on fish harvests, catch rates and age-length. The assessment analysed 44 different combination of data. This included:

- four annual series of fish catch rates,
- five rates of fish natural mortality per year, and
- two series of annual harvest, considering line fishing 1940–2018 and suspected Taiwanese gill netting between 1979 and 1986.
- All 40 analyses above (4x5x2) assumed a logistic shaped pattern of fish vulnerability-at-age. Four domed analyses were included to explore different vulnerability effects on results; they were unremarkable, had higher variance and within the range of the logistic results.

Across population analyses, estimated spawning biomasses of Spanish mackerel in 2017/2018 were 14–43% of original estimates for the start of the fishery in 1940. Lower results in the

range were associated with including Taiwanese harvests. No rational evidence was available to narrow the range of results. The broad percentage signified a classification status at or below the biomass level for maximum sustainable yield. Estimates of fishing pressure in 2017/2018 were sustainable at less than maximum sustainable levels ($u_{2018} < u_{MSY}$).

The declining biomass results relate to the downturn in Spanish mackerel standardised catch rates 2009–2018. The decline had a biomass ratio midpoint, across analyses, at around 28% of virgin levels in 2017/2018. We caution that catch rates, and fish age-length data, may indicate localised patterns, as more data were from Bramble Cay than other locations in the Torres Strait.

Management should consider the variance in results and set recommended biological harvests at appropriate levels following a harvest strategy. Median reference points for Spanish mackerel harvests, based on the downturn to 2017/2018 population size, were F_{BMSY} = 94 t, F_{B40} = 81 t, F_{B48} = 63 t, F_{B50} = 60 t and F_{B60} = 43 t. Median equilibrium measures, potential harvests at their reference population sizes, were F_{BMSY} = 138 t, F_{B40} = 135 t, F_{B48} = 129 t, F_{B50} = 125 t, and F_{B60} = 107 t.

At this time, a safeguard approach for management procedures is to allow for lower biomass (i.e. base decisions on current population estimates, not equilibrium measures), and a down cycle which may be caused by unknown environmental or fishery conditions. Recent levels of reported fishery harvest and fishing pressure alone do not explain the downturn.

This report was prepared to update the stock assessment with the latest data, and to inform new harvest strategy design. It will be important to assess how Spanish mackerel are responding to any further down cycle or change. Initiating sampling of Spanish mackerel ages is critical to support future age-structured stock assessments and management procedures. Further data on fish harvests (commercial and non-commercial) and catch rates are required.

Table of contents

Introduction

Torres Strait Spanish mackerel, *Scomberomorus commerson*, are large pelagic fish that are harvested by line and troll fishing from ocean waters between Cape York Peninsula (north-east Australia) and the western province of Papua New Guinea. Australia and Papua New Guinea share fishery management in the Torres Strait, through the Protected Zone Joint Authority (PZJA) (Figure 1).

Torres Strait waters connect to the Coral Sea in the east and Great Barrier Reef to the south, and the Arafura Sea and the Gulf of Carpentaria to the west. Separate stocks of Spanish mackerel reside in these surrounding waters, with the most recent stock structure research recommending that Torres Strait Spanish mackerel be regarded as a discrete meta-population for management (Buckworth et al., 2007). This recommendation formed the spatial boundary for stock assessment.

The Australian sector for Spanish mackerel is an important economic and traditional food source for all Torres Strait communities (Begg et al., 2006). Historically, the Australian commercial sector have harvested in order of 200 t of Spanish mackerel per year, with lesser harvests taken by Torres Strait and Papua New Guinea communities (Begg et al., 2006; Busilacchi et al., 2015).

The inaugural stock assessment for Torres Strait Spanish mackerel was completed using data up to the 2003 fishing year (Begg et al., 2006). The assessment described the biological parameters, management and research histories and estimated the stock as being fully fished with annual harvests (mean = 173 t and standard deviation = 31 t) judged to be nearing or exceeding maximum sustainable levels (146–264 t) (Begg et al., 2006). The Australian Government fishery status reports have monitored nominal harvest trends since 2003 and in 2015 classified Torres Strait Spanish mackerel as not overfished and not subject to overfishing (Patterson et al., 2015).

In 2014 the Torres Strait Scientific Advisory Committee, on behalf of the Protected Zone Joint Authority, funded the need to revisit and update the previous 2006 stock assessment (Begg et al., 2006). Results signalled the Spanish mackerel population to be sustainable, but near maximum sustainable levels. Results were reviewed by a technical working group, and realigned expectations of sustainable levels of harvests around 125–150 t per year.

This new 2018–2019 stock assessment delivers updated results for consideration in defining future management objectives and harvest strategies. A surprising downturn in catch rates drives results. The research contract was managed by the Torres Strait Scientific Advisory Committee – AFMA project number RR2016/0824.

Figure 1. Area of the Torres Strait Fisheries. The management area for the Australian (Torres Strait) component is shaded blue. The map was sourced from the ABARES Fishery status report 2015.

Methods

Harvest and catch rate data

The Australian Fisheries Management Authority (AFMA) supplied the Spanish mackerel harvest data. The project Principal Investigator signed the AFMA 'deed of confidentiality' to cover project staff data analyses. This included the authority for the project co-investigators (Queensland Department of Agriculture and Fisheries – DAF, and The University of Queensland) to analyse the data for stock assessment under the project.

The raw data tables were imported and stored in the MS Access database 'spanish_ts_catch_afma'. The database location was in the computer directory for 'spanish_mackerel_ts\HarvestStrategyProject'. The directory was a part of the 'Stock Assessment Security Group' on the Queensland Government DAF server. The security group ensured access only by approved staff and confidentiality, integrity and backup of the data. A copy of the 'spanish_ts_catch_afma' database is available to AFMA under the 'deed' agreement.

The data on Torres Strait Spanish mackerel harvests were from two sources: 1) AFMA compulsory logbook (Log) database and 2) AFMA docket (Doc) book records. The commercial licence and endorsement conditions for logbooks was compulsory for TVH fishing operations (Australian Government, 2013). This is a condition of all commercial endorsement holders fishing for Spanish mackerel to ensure that the information required by the logbook about fish taken and effort expended in the fishery is accurately and fully recorded in accordance with the instruction (Australian Government, 2013). The docket (Doc) book records are important information for harvest reporting through community processor/freezer establishments. At the time of this report, the Doc data recorded mostly harvests from Islander commercial fishers. Historically, docket book reporting was non-compulsory and database maintenance was not frequent (French et al., 2015).

The following data tables were created and linked in the MS Access database for the purpose of summarising total harvests and fishing efforts and modelling to standardise catch rates (* indicates non AFMA data sourced and created by DAF):

- LogOperation – logbook client, vessel, fishing date and location data.
- LogEffort – number of crew, tenders and the fishing method.
- LogCatch – tender number, species harvested, numbers and weights (kilograms: kg)
- LogBoat – grouping factors for different vessels and operators.
- LogSpp – defines species categories / families.
- LogWtConversions – for different product forms (e.g. kg of fillets to kg whole fish).
- Regions* – latitude and longitude borders for the five fishing regions; see Figure 3.
- DayYear* – daily sinusoidal data for modelling within year fishing seasons.
- LeapYear* – binary factor identifying leap years; links with DayYear.
- Winds* – daily mean wind speed, direction and components (NS and EW).

- LunarPhases* – continuous moon phase data.
- Setup_meanwt – mean fish weights by species (kg).
- DocOperation – Docket book records of processed harvest by island and fisher/seller.
- DocCatch – species weights (kg) and prices (AUD$).
- DocSpp – defines species categories / families.

The Torres Strait wind data was from the Bureau of Meteorology (BOM, Australian Government; www.bom.gov.au). The wind data encompassed Horn and Coconut Islands weather stations. The recorded measures of wind speed (km $hour^{-1}$) and direction (degrees from where the wind blew) was converted to an average daily reading. From this data, the north-south (NS) and east-west (EW) wind components were calculated:

$$NS = km\ hr^{-1} \times \cos(radians(degrees)), \text{ and}$$

$$EW = km\ hr^{-1} \times \sin(radians(degrees)).$$

The Torres Strait wind components showed a predominant southeast wind pattern. Any missing wind components were assumed equal to the overall average values (NS = -10.4334 and EW = 9.9282). The wind components standardised Spanish mackerel catch rates for different wind directions and strengths. The component functions considered the BOM defined wind directions as degrees measured clockwise from true north (0 degrees = North, 90 degrees or $\pi/2$ radians = East, 180 degrees or π radians = South, and 270 degrees or $3\pi/2$ radians = West.

The lunar phase (luminance) data was a calculated measure of the moon cycle with values ranging between 0 = new moon and 1 = full moon for each day of the year (Courtney et al., 2002; Begg et al., 2006; O'Neill and Leigh, 2006). The data were from the Department of Agriculture and Fisheries (DAF), Queensland Government. The luminance measure (lunar) followed a sinusoidal pattern and was copied and advanced 7 days (≈ ¼ lunar cycle) into a new variable (lunar_adv) to quantify the cosine of the lunar data (O'Neill and Leigh, 2006); Figure 2. The two variables were modelled together to estimate the variation of Spanish mackerel harvest according to the moon phase (i.e. contrasting waxing and waning patterns of the moon).

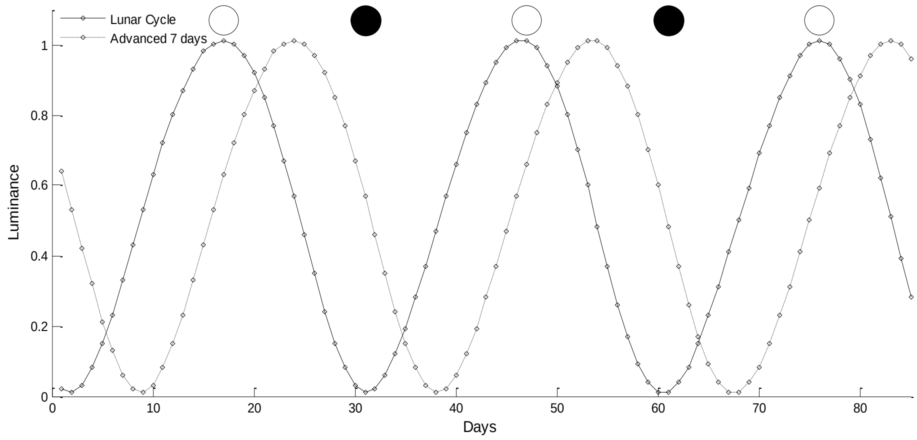

Figure 2. The lunar phase cycle (solid line) illustrated over 85 days. The dashed line illustrates the lunar cycle advanced by seven days. Together these lines modelled catch rates allowing for new moon, waxing moon, full moon, and waning moon effects.

The seasonality of Spanish mackerel catch rates was modelled using sinusoidal data (DayYear) to identify the time of year. The data was calculated and used to minimise the number of model parameters with the purpose to reduce temporal confounding with the regional and/or vessel parameters. For Torres Strait Spanish mackerel, parameter confounding was a concern given the limited temporal and spatial patterns of fishing by some vessels; particularly if more parameters were used to model the explicit monthly or weekly factorisations of the data. In total four trigonometric covariates were used, which together modelled an average monthly pattern of catch (Marriott et al., 2013): $s_1 = \cos\left(2\pi d_y / T_y\right)$, $s_2 = \sin\left(2\pi d_y / T_y\right)$, $s_3 = \cos\left(4\pi d_y / T_y\right)$, $s_4 = \sin\left(4\pi d_y / T_y\right)$, where d_y was the cumulative day of the year and T_y was the total number of days in the year (365 or 366). The reason for using both sine and cosine functions together was similar to modelling lunar phases, where the functions together identify the seasonal patterns of catch rates corresponding to autumn, winter, spring and summer periods.

The merged data tables were analysed to standardise catch rates of Spanish mackerel. The analysis data formed records of each vessel's daily harvest, together with the associated variables for the main vessel name (anonymous codes were used), date, number of specified tenders, numbers and weight of Spanish mackerel harvested, lunar phase and wind components. Analysing harvests at the primary vessel unit aimed to match the daily recording format, avoid correlation between tenders, and to use appropriate sample sizes for estimating confidence intervals. The following aspects were for creating the daily catch rate data:

- The Log Boat and LogOperation data grouped each vessel, day and record number, and filtered for only Spanish mackerel vessels, gear code TR and logbook types SM02 and TSF01. This included the corresponding location data.

- The LogCatch and LogEffort data, linked with the selected LogOperation data based on the record number. The merged data was for the LogSpp codes for Spanish mackerel.

- In addition, the lunar phase, day-year and wind components data were merged based on the fishing dates.

- The region areas were calculated as follows:

  calculate z1 = (lat2.ge.-9.3)

calculate z2 = (lat2.lt.-10.0)

calculate z3 = (lat2.ge.-10.0)

calculate z4 = (long2.ge.143.5)*(long2.le.144.0)

calculate z5 = (long2.ge.143.75)

calculate z6 = (long2.lt.143.75)

calculate zone5 = (z1*z4) + (z3*z6)*2*((z1*z4).eq.0) + (z3*z5)*3*((z1*z4).eq.0) + (z2*z6)*4*((z1*z4).eq.0) + (z2*z5)*5*((z1*z4).eq.0)

groups [redefine=yes] zone5; see Figure 3. The five area stratification was defined by the FFRAG sub-technical group in 2018.

- Some client/fisher names and their fishing regions were inconsistent (Dr A. Tobin pers. comm.). The degree of this problem was unknown. Catch rates were therefore analysed by vessel name (also called a boat), which accurately grouped the clients.

- The recorded harvests of Spanish mackerel were in three different data fields: 1) number of fish *n*, 2) weight of whole fish in kilograms w_{old}, calculated based on different product forms and 3) number of cartons *c*. The catch rate analysis was based the numbers of fish as this data was the most frequent, complete and matched logbooks. In addition, numbers generally index abundance more accurately than weight, given the average size and weight of fish can vary between different areas, times and schools of fish. Records of zero harvest were not analysed, as they may be inconsistent and under reported (Dr A. Tobin pers. comm.). Table 1 lists the conversions used to fill in missing records.

- The harvest tonnages of Torres Strait Spanish mackerel assumed a mean fish weight of 6.909 kg (Table 1). In the 2006 stock assessment report, Begg et al. (2006) estimated a mean fish weight of 8.5 kg based on logbook data for whole fish only (n = 64). In Table 1, the same calculation method was updated to include both whole and filleted fish; i.e. all available mean weight data was used. This resulted in a mean estimate of 6.909 kg that was more consistent with the mean of 7.145 kg (median = 6.562, std = 2.2797) from the age-length monitoring data. The estimate of 6.909 kg was also near the mean values of 7.229 kg and 7.279 kg from northern Queensland and the Gulf of Carpentaria (Figure 4).

- The final catch rate data grouped record numbers identifying different dories and fishing sessions to form records of each vessel's daily harvest. The data removed vessels that had fished less than 30 days over all years analysed, had fished in only one, and had recorded 'bulk' trip harvests. In total, the filter removed about 2% of the recorded harvests.

- The tallied number of dories/tenders/vessels used each day by each fishing operation was from the listed 'tender number' from the LogCatch data table. The tallied vessel numbers ranged 1–5. The catch rate analysis compared the significance of this covariate data against the categorisation of the data into the groups of 1, 2, and ≥3 vessels; where the results were similar and the covariate data utilised.

- To group the seasonal biology and fishing patterns of Spanish mackerel, the fishing-year was defined for the months from July to June (Begg et al., 2006); i.e. fiscal year, where for example the time period from the 1st July 2014 to 30th June 2015 was labelled as fishing year 2014.

Table 1. Equations for converting numbers of fish and weights (kg).

Equation	Condition
$w_{new} = n \times 6.909$, where 6.909 kg was the mean weight of a whole fish calculated using whole and filleted fish data (n = 86, s.d. = 2.93).	$n > 0$
$w_{new} = (w_{old}/v_{old}) \times v_{new}$, where v_{old} was the original and v_{new} was the corrected product conversion weights (fillets, trunk, gilled and gutted or whole; Begg et al., 2006).	$n = 0, w_{old} > 0$
$w_{new} = c \times 13 \times 1.608$, where 13 kg was the mean carton weight for fillets (≈ 3 fish carton^{-1}; s.d = 1.47, n = 6828) and 1.608 kg was the mean conversion for fillets to whole fish.	$n = 0, w_{old} = 0, c > 0$
$n = w_{new}/6.909$	$n = 0$

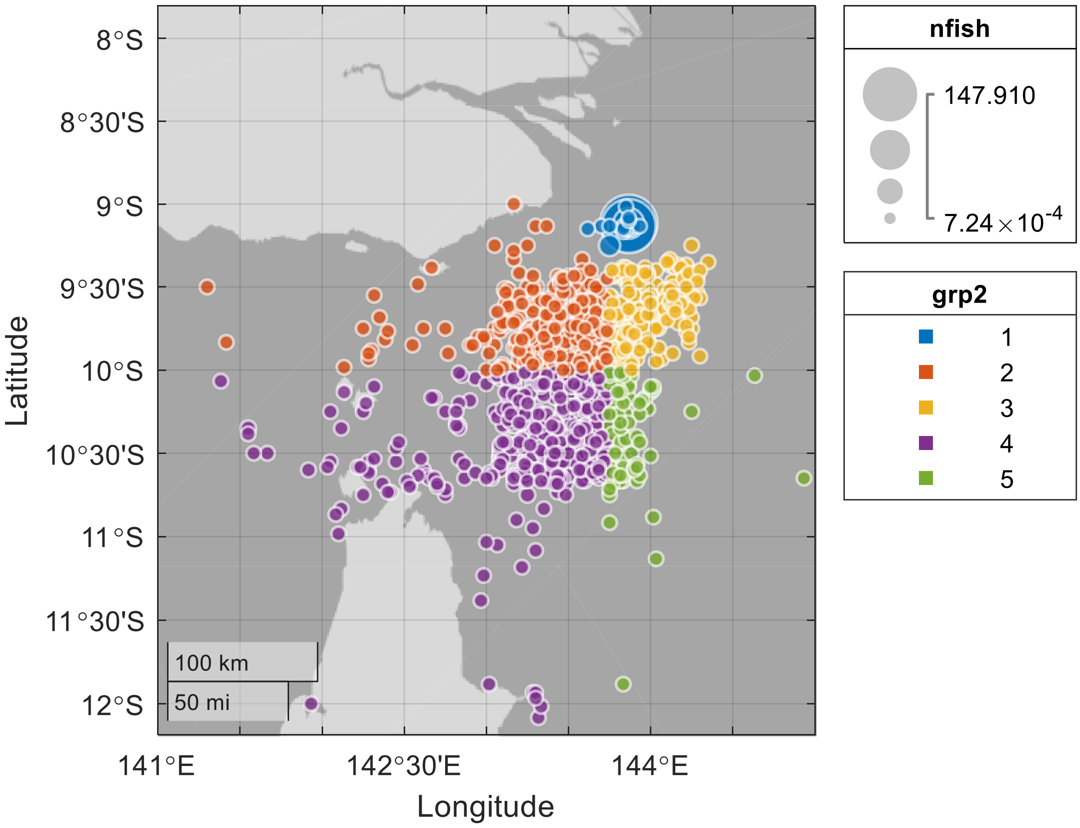

Figure 3. Map of the Torres Strait and regional stratifications illustrated by colour- (Bramble Cay - blue, Ugar - orange, east/anchor - yellow, dugong - purple, and southeast - green). Map circles indicate the numbers of Spanish mackerel harvested per vessel day 1989–2018 at logbook start-latitude and start-longitude coordinates. Larger circles show larger harvests; e.g. see Bramble Cay.

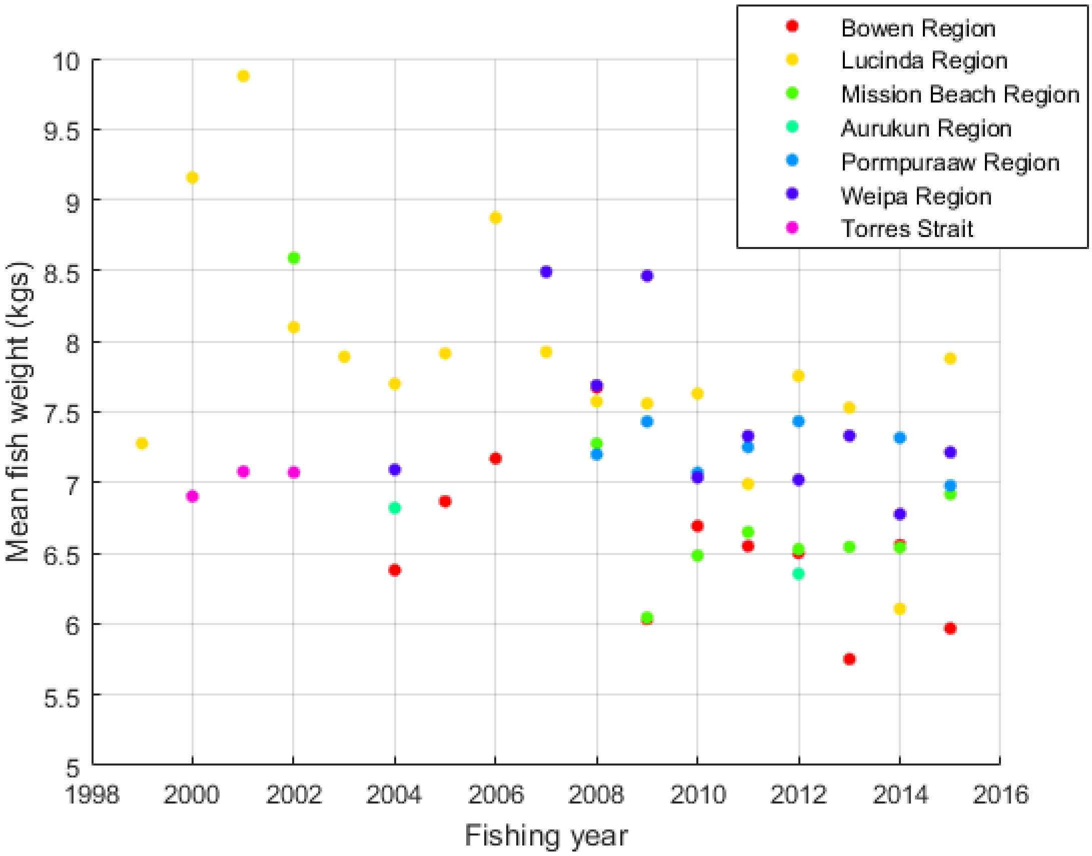

Figure 4. Comparison of the mean weight of Spanish mackerel by fishing years and regions nearby to the Torres Strait. Each mean point had a sample of between 100–2680 fish. The figure illustrates the variability between years and regions, with only a small number of means at or above 8.5 kg.

Fish age-length composition data

The Queensland Government (DAF) conducted monitoring of Torres Strait Spanish mackerel between 2000 and 2002 to obtain biological data and parameters on fish age and length (McPherson, unpublished). The monitoring was through commercial fishing operations, which generally fished within 2 km of Bramble Cay. The sampled fishing locations and times was dependent on the commercial operation of vessels.

In each year, an observer monitored the fish catches of many vessels and days as possible (Table 2). The observer operated from a nominated vessel that provided sample processing and accommodation. Commercial operators were paid a stipend to provide and deliver filleted fish frames (McPherson, unpublished). The observer recorded fish length, otoliths, gonads and genetic samples, with most fish sampled from morning catches. See Begg et al. (2006), Langstreth (2015) and McPherson (unpublished) for more detail.

Queensland Government monitoring ceased after 2002, but a CRC Torres Strait research project (T1.14) adopted the above protocols to sample fish in 2005 (Begg et al., 2006). The 2005 Spanish mackerel data were unable to be found on JCU computer servers or through the past stock assessment author Begg et al. (2006) (emails: A. Tobin 24th August 2015; G. Begg 17th August 2015).

The observed fish-otolith increment counts categorised age (cohort) group based on the otolith edge types (Appendix 2). Fish sampled in October had an age group as follows:

- New edge type (code 0): age group = increment count,
- Intermediate edge type (codes 1 and 2): age group = increment count, and
- Wide edge type (code 3): age group = increment count +1.

The fish aged in the year 2000 samples had no edge type data. To adjust to age groups, 23% of fish were to have a wide edge type. Fish aged 0+ (13 fish) were allocated to the 1+ age group.

As most fish (~90%) were both measured and aged, the age group classifications were used directly to form the age structure proportions for input into the stock model (no age-length key was applied).

Table 2. Number of Spanish mackerel sampled for length and age. The 12 fish sampled (9 were aged) in April 2007 were not used.

Year	Month	Days	Vessels	Number of fish	Number aged
2000	Oct-Nov	15	1	915	827
2001	Oct	11	5	942	860
2002	Oct	8	3	654	579

Catch rate analysis

The Spanish mackerel data consisted of counts of fish (>0) harvested per vessel-operation day. Count data of this form can be analysed as an over-dispersed Poisson-like process (McCullagh and Nelder, 1989; Lee et al., 2006). Analyses that deal with over-dispersion are essential to assess the significance of model parameters and to calculate appropriate confidence intervals on mean predictions. For Spanish mackerel, the over-dispersion arises due to fish aggregating (schooling) with various levels of abundance through time and area.

In total four analyses standardised catch rates and explored different results. These were:

- Including the number of tenders per fishing operation-day, with no fishing power offset.
- Including the number of tenders per fishing operation-day, with fishing power offset.
- Excluding the number of tenders per fishing operation-day, with no fishing power offset.
- Excluding the number of tenders per fishing operation-day, with fishing power offset.

The four analyses investigated the effects of under reported tenders in early years 1988–1991, and fishing power increases according to the Queensland's east coast fishery (O'Neill et al., 2018). This was by substituting each of the data in and out of the analyses.

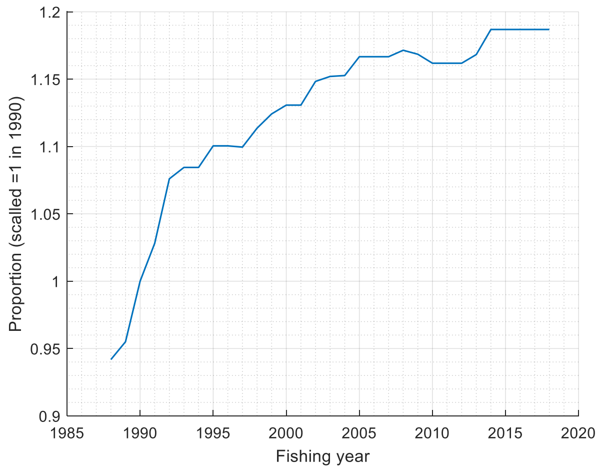

Figure 5. Fishing power adjustment (offset) applied in the catch rate standardisation. This was from Queensland's northeast coast (O'Neill et al., 2018)

The analyses were completed using the statistical software GenStat (VSN International, 2018) and standard errors were calculated for all estimates. The importance of individual model terms was assessed formally using F statistics by dropping individual terms from the full model.

The over-dispersed Poisson models conformed easily to the discrete nature of the count (numbers of fish) data. The Poisson models suitably weighted the data giving greater but no excessive emphasis to harvests with large fitted values, they were consistent with respect to different time scales and it should be noted that the residual plots do not have to appear to be normal (Leigh, 2016).

The calculation of standardised catch rates involved predicting mean catch rates from the different model terms; using GenStat's 'PREDICT' procedures for the GLM (VSN International, 2018). For example, annual standardised catch rates were from the fishing-year model term, keeping all other model terms constant. Standard errors for all predictions were adjusted up according to the sqrt(residual mean deviance); where the residual mean deviance = over dispersion parameter.

Table 3. Example GenStat statistical models used to analyse Spanish mackerel harvests.

```
MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*; offset=logfp2] nfish
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated; \
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
fishyear+zone5+boat+c12+cs12+c6+cs6+tendersn+lunar+lunar_adv+pol(windns;2)+pol(windew;2)

predict fishyear
```

tendersn and logfp2 were substituted in and out of analyses.

The polynomial variables were quadratic model terms.

Population dynamics model

The population dynamic model calculated numbers (N) of Spanish mackerel by yearly (t) time categories and annual age groups (a) from 1+ to the maximum age.

The model accounted for the processes of fish births, growth, reproduction and mortality in every fishing year (time step t). The model operation was in two phases: (i) historical estimation of the Spanish mackerel stock from the fishing years 1940–2018 and (ii) simulations of model values and errors to evaluate reference points and simple constant harvest projections (Figure 7).

The Torres Strait commercial fishery for Spanish mackerel commenced in the 1940's (Begg et al., 2006) and it was unrealistic to start the model in 1989 from an unexploited state (virgin population). An estimated annual harvest from 1940 to 1988, was assumed, with respect to the building trend in harvests reported by McPherson (1986) for the years 1957, 1959, 1960, 1962, 1975-77 and 1979 (Table 4.1 x 1.185, in Begg et al., 2006) up to the average annual harvest 1989–1993 (Figure 6). The method and assumption here was similar to Begg et al. (2006), however a logistic shaped increase was assumed rather than linear or exponential-like. The logistic increase was estimated from a binomial GLM assuming the 1989–1993 harvests were at 100% and the McPherson (1986) data a fraction of the 1989–1993 average annual harvests. The logistic-shape assumption aimed to create a realistic long-term pattern of expansion of the fishery. Begg et al. (2006) used the fishing year 1940 to represent the start time for modelling when fishing pressure was low.

In addition to the historic harvests above, a Taiwanese drift-net harvest was included for 1979–1986. This was after FFRAG discussions in 2018, initiated by Dr R. Buckworth. The net harvests appeared to occur 1979–1986, after review of information held by past projects (McPherson, 1986; O'Neill et al., 2011). No information was available on the tonnage of net Spanish mackerel. FFRAG decided to include a harvest of 100 t (Figure 6), similar to the Australian fishery, to assess what effect it would have on biomass ratios and reference points. It was conceivable that the net fishing would catch a similar amount of mackerel to the troll-line fishery (Dr R. Buckworth. pers. com. email 14/3/2019).

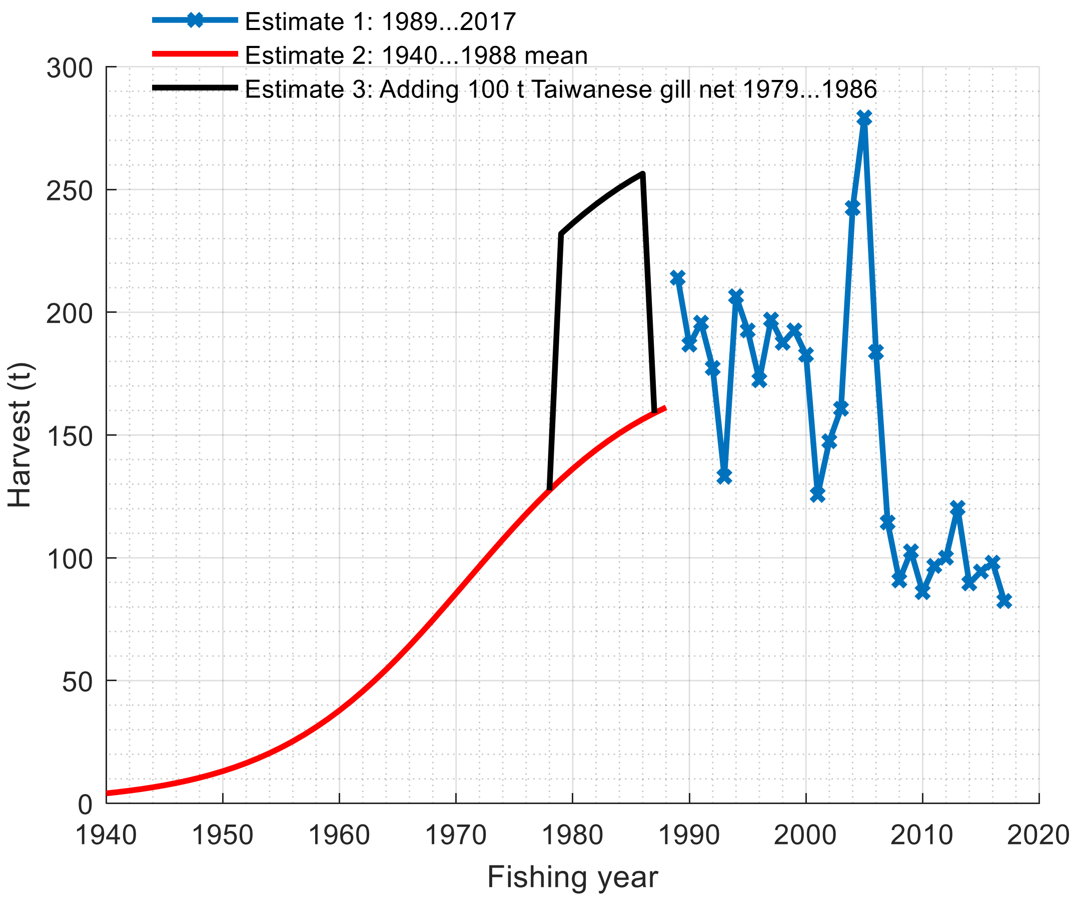

Figure 6. Estimated harvests for stock assessment 1940–2018. This included harvests for all fishing sectors.

Model parameters (**Error! Reference source not found.**) were estimated by calibrating the model to standardised fish catch rates and age composition data. Primary importance was placed on fitting the standardised catch rates (Francis, 2011). Effective sample sizes for scaling multinomial negative log-likelihoods were within the model in order to give realistic weighting to the age composition data. Additional negative log-likelihood functions were considered for predicting natural mortality (M) and annual recruitment variation (η_t).

The model estimation process was conducted in Matlab® (MathWorks, 2018) and consisted of a maximum likelihood (ML) step followed by Markov Chain Monte Carlo sampling (MCMC). The flow of the estimation process is summarised in Figure 7. The maximum likelihood step used Matlab global optimisation (Quasi-Newton method, MathWorks, 2018), followed by a customised simulated annealing program to find and check the parameter solutions and estimate the parameter covariance matrix.

The maximum likelihood step was effective for searching and locating optimal estimates over the negative log-likelihood (combined NLL fitting functions) search space. The simulated annealing started from a NLL scaling factor of 100 and then reduced to 10, 1, 0.1 and then 0.01. For each scaling factor, the annealing process ran for 10000 iterations of each parameter. The covariance matrix measured the differences in the negative log-likelihood with each parameter jump.

The MCMC followed on from the simulated annealing using a NLL scaling factor of 1 with fixed covariance. The MCMC used parameter-by-parameter jumping following the Metropolis-Hastings algorithm described by Gelman et al. (2004). The final parameter distributions were based on 1000 posterior MCMC samples thinned from 1 solution stored per 100 samples. MCMC parameters traces and autocorrelations were assessed for convergence and independence (Plummer et al., 2006).

The calculation of the fishery reference points (equilibrium and for 2017/2018) were based on optimising the population model dynamics through an average harvest rate ($u = 1 - \exp(-F)$). All parameters were included except stochastic recruitment variation (error term $\exp(\eta_t)$ in equation 3) was fixed equal to one.

The age-model reference points were for maximum sustainable yield (B_{MSY}), and biomass ratios 40%, 48%, 50% and 60% being a proxy for maximum economic yield ($B_{MEY} \approx 0.6B_0$). The 60% target level is consistent with the 2027 management goals set in the Queensland Government's Sustainable Fisheries Strategy.

The Australian Government's current proxy for B_{MEY}/B_{MSY} is 1.2 (Australian Government, 2007). The origin of this proxy is not clear (Dr Sean Pascoe, CSIRO, personal communication at the Fisheries Queensland harvest strategy workshop 4-5th August 2015), but likely based on the symmetric surplus production theory of $B_{MSY} \approx 0.5B_0$ (Zhou et al., 2013; Pascoe et al., 2014). This corresponds to $B_{MEY}/B_{MSY} = 1.5$ for the non-symmetric age-model dynamics.

In model development and testing, the estimation of annual recruitment variation was necessary to fit the down cycle of catch rates 2010–2018. This was not required in early assessments. Statistically, this has added a number of parameters for the data.

Before 1985 there was no minimum legal size limit (mls). In 1985 a small 45 cm total length (TL) mls was introduced, and then in 2004 a 75 cm TL mls was enforced (Begg et al., 2006). These management measures appeared to have no influence on the data. Most Spanish mackerel harvested are greater than 75 cm.

For model code see appendix, and equations and theory in (O'Neill et al., 2018; O'Neill and Tobin, 2018; Bessell-Browne et al., 2019). **Error! Reference source not found.** outlined the model parameters.

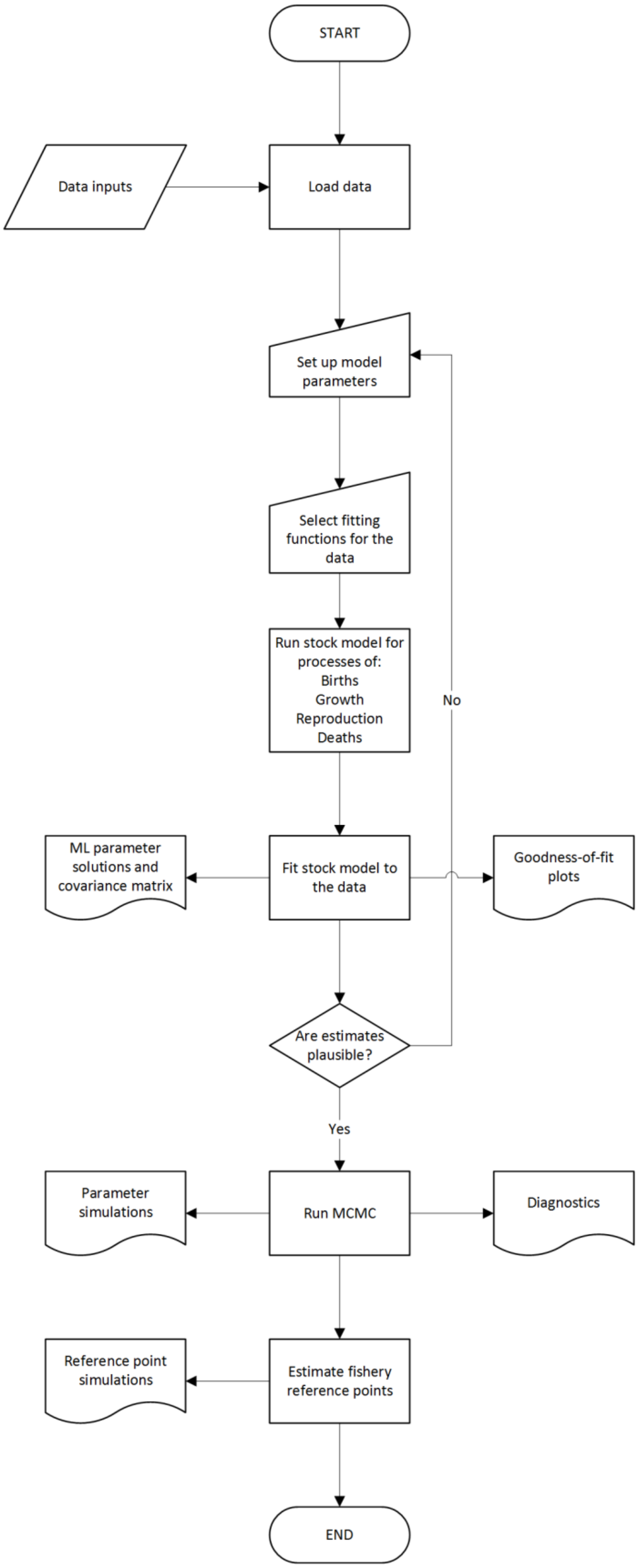

Figure 7. Flow of operations for the stock model from loading the data to evaluating model predictions.

Table 4. Parameter definitions for the Spanish mackerel population dynamics model.

Parameter	Equations and values	Notes
Assumed		
$\mathrm{Max}(a)$	25	Based on considering the maximum fish age recorded from the Torres Strait (12 yrs), the Gulf of Carpentaria (15 yrs) and the Queensland East Coast (26 yrs). Larger values can be set in the model as no plus-group was programmed in the dynamics for combining very old fish.
l	$TL = 4.274 + 1.06 \times l$ $l_s^{\infty}, \kappa_s, a_s^0$	Fish length conversion from fork length (l) to total length (TL) measured in cm (Begg et al., 2006). The estimated von Bertalanffy growth curve parameters for each sex s (Table 5).
w	$w_s = x_s l^{y_s}$	Fish weight (kg) at total length for each sex s, based on the exponential curve parameters x_s and y_s. Females: x = 2.960e-6 and y = 3.148; Males: x = 4.224e-6 and y = 3.068 (Begg et al., 2006).
m	$m_{s,l} = \frac{\exp(\varsigma)}{1+\exp(\varsigma)}$ $\varsigma = -10.349 + 0.0128 \times l$	Logistic maturity schedule $p(\text{mature} \mid l_{s,a})$ by fork length (cm) for female fish (s = 1). The schedule was estimated using binomial regression and logit link (Mackie et al., 2005; Begg et al., 2006). The length-dependent maturity was converted to sex-and-age dependent maturity following the process for length vulnerability (Equation 16).
ϑ	$\vartheta_l = xl + yl^2$	Mature gonad weight (kg as an index of fecundity) at total length for female fish. The relationship was estimated from only mature ripe stage 7 fish using Begg et al. (2006) data. The quadratic curve parameters were: x = -0.008858 and y = 0.000124; R^2 = 0.4906 and n = 83. The length-dependent fecundity was converted to sex-and-age dependent fecundity following the process for length vulnerability (Equation 16).
M		One parameter for instantaneous natural mortality year^{-1}. The prior distribution allowed for a lifespan of about 20 years in the Torres Strait. Begg et al. (2006) considered empirical estimates of 0.37 based on the Hoenig (1983) equation assuming the maximum age of 12 years and 0.28 year^{-1} using the Pauly's (1983) schooling equation. Estimates from east-coast waters of Queensland ranged 0.26 to 0.34 year^{-1} using the same methodology (Campbell et al., 2012). Another estimate of using the age based estimator of Then et al. (2015) was 0.25 year^{-1} assuming a maximum age of 26 years from Queensland east coast waters.
Estimated		
Υ and ξ	$\alpha = S_0(1-h)/(4hR_0)$ $\beta = (5h-1)/(4hR_0)$ $R_0 = \exp(\Upsilon) \times 10^6$ $h = r_{comp} / (4 + r_{comp})$ $r_{comp} = 1 + \exp(\xi)$	Two parameters for the Beverton-Holt spawner-recruitment function, equation, that define α and β (Haddon, 2001). Virgin recruitment (R_0) was estimated on the log scale for the first model year. One estimated value of steepness (h) was assumed for the stock. S_0 was the calculated as the overall virgin egg production in the first model year from equation 4. The r_{comp} parameter is the recruitment compensation ratio (Goodyear, 1977), based on the log scale coefficient ξ.
a_{50} and a_{95}		Two parameters for the logistic vulnerability, equation 7. (Haddon, 2001). a_{50} was the fish age (years) at 50% vulnerability to fishing and a_{95} at 95%.

ζ	$\boldsymbol{\eta} = \boldsymbol{\zeta}\mathbf{e}$
	e = zeros(nparRresid, nparRresid+1);
	for i = 1:nparRresid
	hh = sqrt(0.5 * i ./ (i + 1));
	e(i, 1:i) = -hh ./ i; e(i, i + 1) = hh;
	end; e= e ./ hh;
		Recruitment parameters to ensure log deviations sum to zero with standard deviation σ, equation 15. ζ were the estimated parameters known as barycentric or simplex coordinates, distributed $NID(0,\sigma)$ with number nparRresid = number of recruitment years – 1 (Möbius, 1827; Sklyarenko, 2011). **e** was the coordinate basis matrix to scale the distance of residuals (vertices of the simplex) from zero (O'Neill et al., 2011).

q	Fish catchability parameter measuring the proportion of the exploitable stock taken by one unit of standardised fishing effort. The parameter was derived as a closed-form median estimate of standardised catch rates divided by the midyear biomass form 2 (Haddon, 2001).

Results and discussion

The results and discussion describes notable trends in Spanish mackerel data, predictions from analyses and general conclusions. The key data and results are under two sub-headings for the 'data inputs' into the model and the 'population dynamic model' for estimates and diagnostics. The flow of stock model operations from data inputs to evaluating outputs are in Figure 7.

Data inputs

Harvests

The Torres Strait AFMA finfish logbook data was analysed for the fishing years 1989–2017. The data analyses were summarised to financial or fishing years (e.g. the 2017 fishing year grouped harvests between 1st July 2017 and 30th June 2018). The descriptive terms 'fishing year' or 'year' are synonymous.

From the TVH logbook data, the estimated Spanish mackerel annual harvests ranged 106–256 t between 1989 and 2006 (Figure 8). The estimated annual harvest of Spanish mackerel declined to 64-105 t between 2007 and 2017. The decline was associated with changes in the fishery management, shifting ownership entitlements to the Torres Strait.

The number of TVH vessels reporting Spanish mackerel harvest through logbooks ranged 10–26 between 1989 and 2006. These operations fished in order of 700–1500 days a year. The numbers of operations reporting harvest dropped to 4–7 per fishing year between 2007 and 2017, with less than 500 boat days fished (Figure 9).

The TIB docket database of Spanish mackerel harvests averaged about 9 t each fishing year from 2003–2010 (Figure 10). The harvest tallies from other years were low (Figure 10).

Harvests of 10 t for islander non-commercial take, 2–5 t for recreational and charter, and no PNG harvest were estimated for the other fishing sectors (see FWG and FFRAG meetings notes). The recreational estimate was low based on limited survey participation (Webley et al., 2015).

For data input into the population dynamic model, two scenarios of total Spanish mackerel harvest were considered to cover the range of uncertainty in harvests:

1. Base reported harvests: logbook harvest 1989–2017, docket book harvest 1989–2017, plus 10 t for islander non-commercial take, 2–5 t for recreational and charter, and no PNG harvest. 1940–1988 harvests were model estimated (Figure 6).

2. Inflated harvests: adding a 100 t Taiwanese drift-net harvest 1979–1986 (Figure 6). This scenario considered earlier high harvests and covered the possibility of unaccounted netting across the Torres Strait.

The harvest schedules above included all estimated Spanish mackerel catches for all fishing sectors. Additional unreported catches and fishing effort were possible (Patterson et al., 2015). As reported and assumed by

Patterson et al. (2015) and Begg et al. (2006), the traditional Islander subsistence, recreational, historical foreign fishing and Papua New Guinea harvests were small.

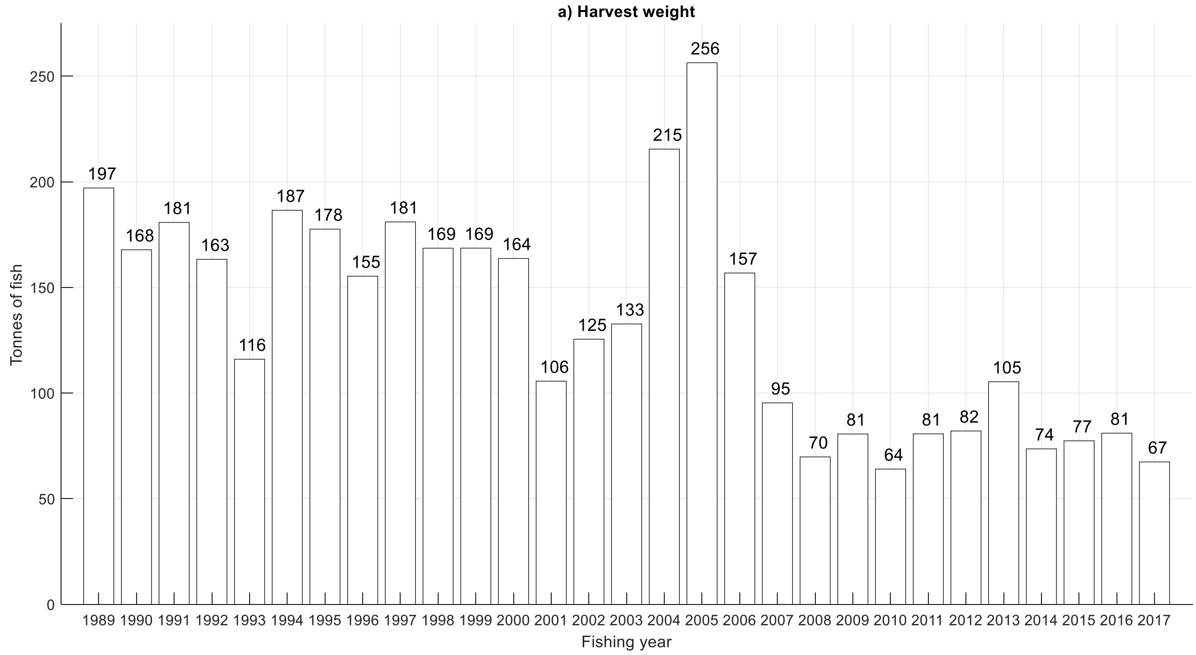

Figure 8. Estimated total harvests of Spanish mackerel by fishing year from TVH logbook data for fish weight measured in tonnes (t).

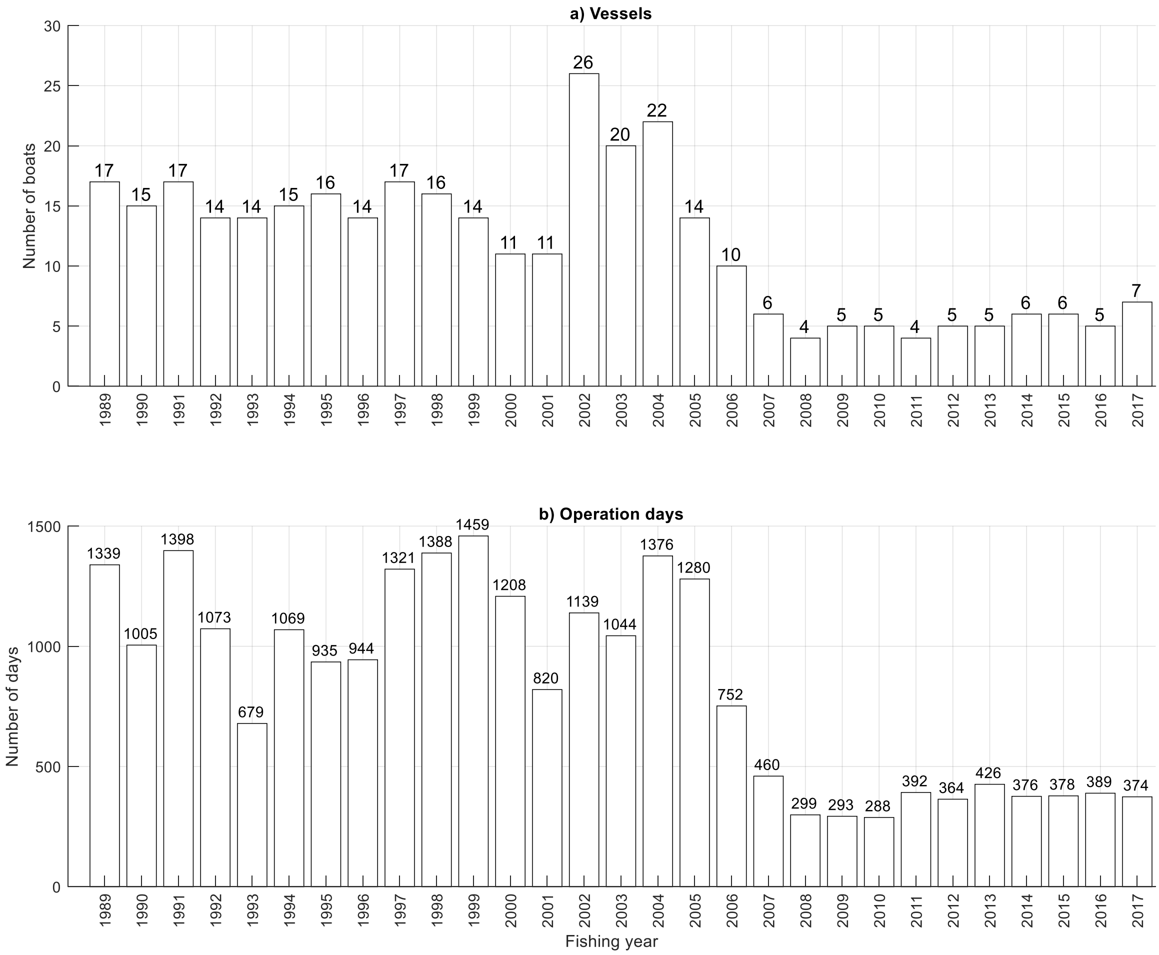

Figure 9. TVH logbook reports of total fishing effort by year for a) number of primary fishing operations (vessels), and b) number of days fished by the operations.

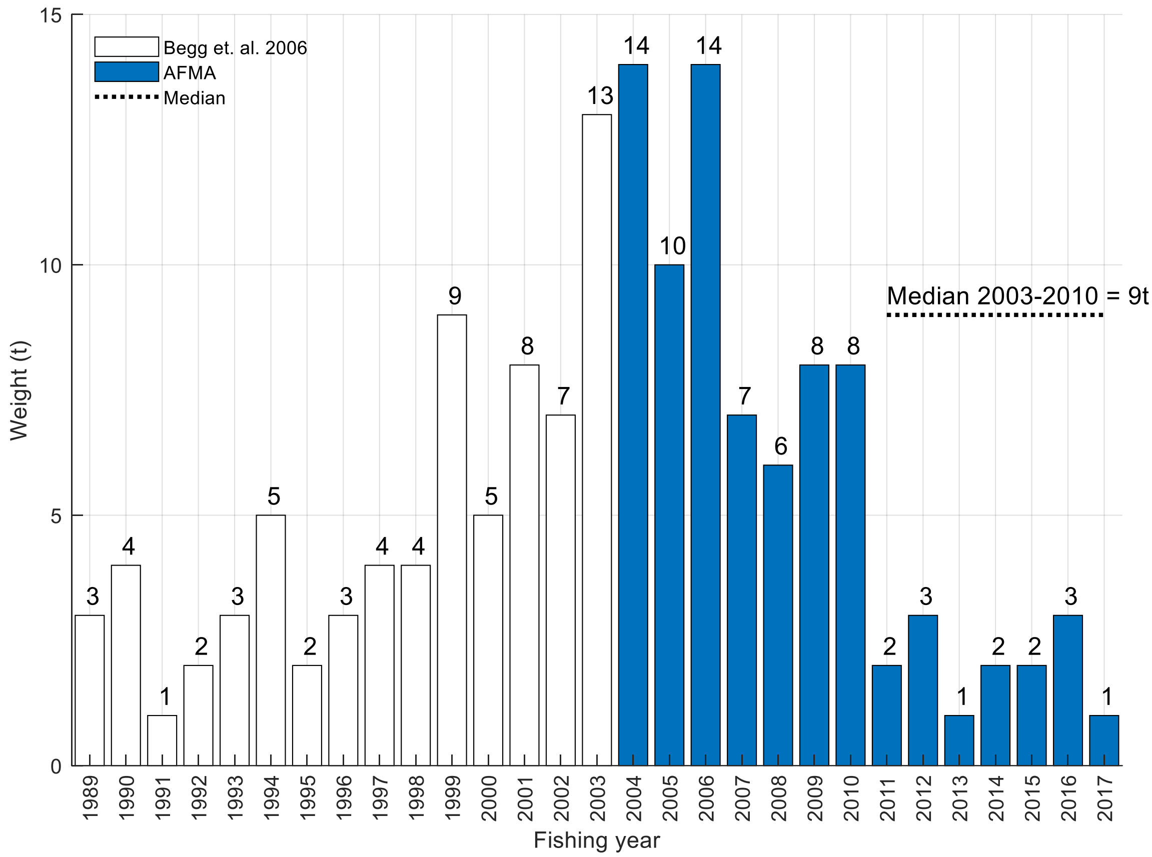

Figure 10. The revised docket database tally of TIB Spanish mackerel harvest (tonnes) by fishing year. The 2003–2010 median = 9 t per year.

Catch rates

Relative trends in Spanish mackerel abundance were from a TVH logbook standardised catch rate. This index was important to the stock assessment as it informed on the magnitude of proportional change in the Spanish mackerel (exploitable) population; this was the primary assumption for the stock model. Full emphasis was on the index as no recent fish age-length or fishery-independent survey data were available.

The assumption of proportionality was made only after employing a regression model (Hilborn and Walters, 1992), in order to standardise the biases or variation in the data by accounting for factors affecting relative fish abundance and fishing efficiency. The result aimed to generate a time series of standardised catch rates that was more representative of trends in the fished population. Standardisation was required to account for efficiency changes in fishing effort and locations fished through time and between fishing vessels.

The catch rate data (numbers of Spanish mackerel harvested per operation day) between 1989 and 2017 was first summarised to understand the distributional properties. The data had high variance and was highly skewed with a nominal median = 15 fish per operation-day, mean = 23 fish and standard deviation = 25 fish (CV = 108%). Most (about 95%) records of harvest were as numbers of fish and not weight. Significant variance in catch rates was evident between fishing operations, with some surprisingly large harvests (> 100 fish per operation day). The variance in catch rates by fishing year is in Figure 11.

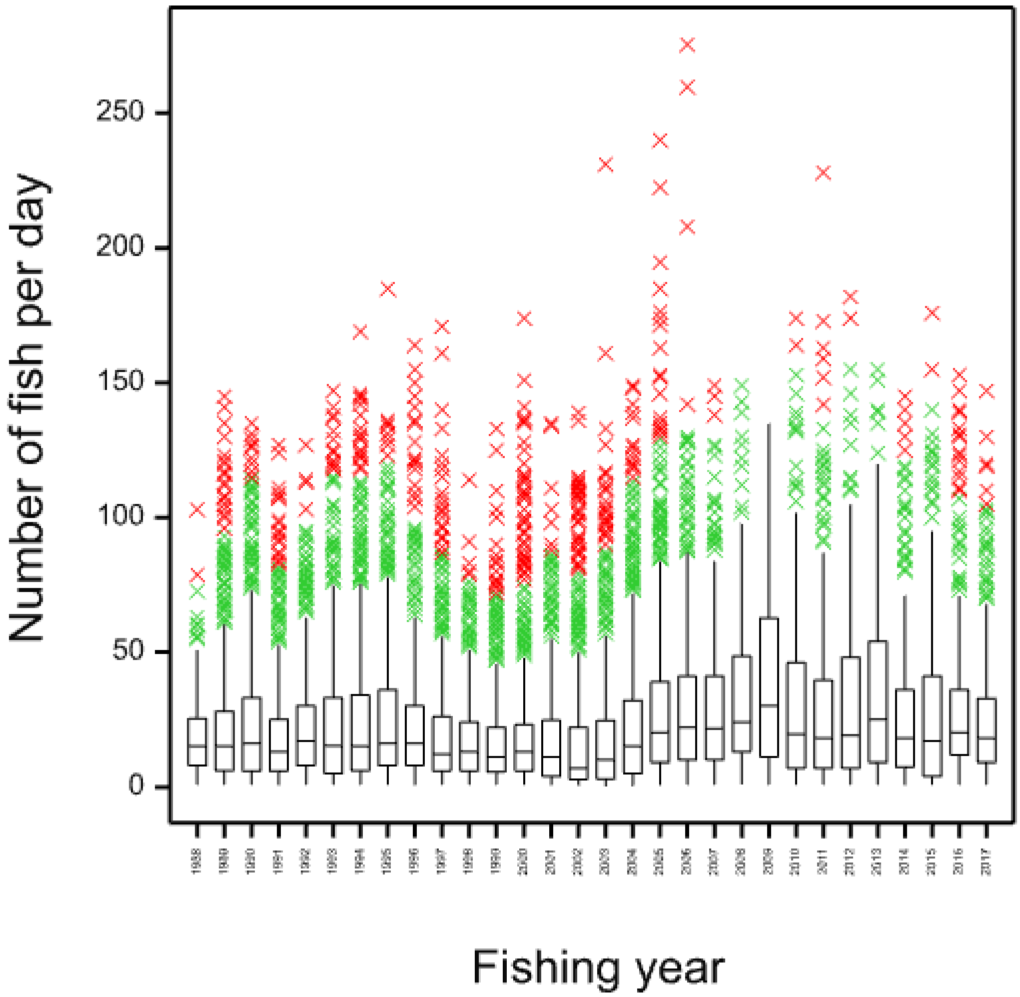

Figure 11. Box plot of reported TVH harvests of Spanish mackerel by fishing year (per primary vessel operation day). The plot displays the skewed distributions of harvest around their medians (line in the middle of each box). The bottom and top of each box were the 25th and 75th percentiles. The whisker lengths indicate the general range of each vessel's harvest in each year, with unusually large harvests drawn as crosses.

Figure 12 compared four different TVH catch rate indices of Spanish mackerel between the fishing years 1989 and 2017 (July 2017-June 2018). The following standardisation results are noted:

- Catch rates illustrated rough 10-year cycles. This started with a down cycle for 1988–1999, then an increase 1999–2009, and a downturn for 2009–2017. The scale (amplitude) of the cycle was about 30–40% from the overall annual mean. The time series indicated significant years of improved and reduced catch rates.
- All indices illustrated a decline of about 50% between 2009 and 2017. This trend was in all operators' data, particularly the declines in 2016 and 2017.
- Scatter plot of the standardised residuals against fitted values is in Figure 17 (Appendix 1). The residual plot showed no lack of model fit. The scatter plot was typical for Poisson models and was similar between the four GLMs.

- Exploratory analysis of the 2003–2017 data (TSF01 logbook) produced indices that were similar and confirmed the 2017–2017 decline (Figure 18, Appendix 1).
- The inclusion of boat-operation and seasonal terms were most important in the standardisation of catch rates (Figure 19 and Table 7, Appendix 1).
- In general, the GLM predicted relationships of increasing catch rates using more tenders, fishing during the spring and autumn months, on the early waxing moon phase and timed with good weather of light SE winds (O'Neill et al., 2018; O'Neill and Tobin, 2018).
- The measures of statistical error on the mean catch rates in Figure 12 were CV ≈ 8%, and 95% confidence intervals about ± 2 fish. This suggests a statistical detection power of change in annual catch rates of about ± 16%, or 4 fish. The standardised catch rates appear sufficient for use in stock assessment and harvest strategies.

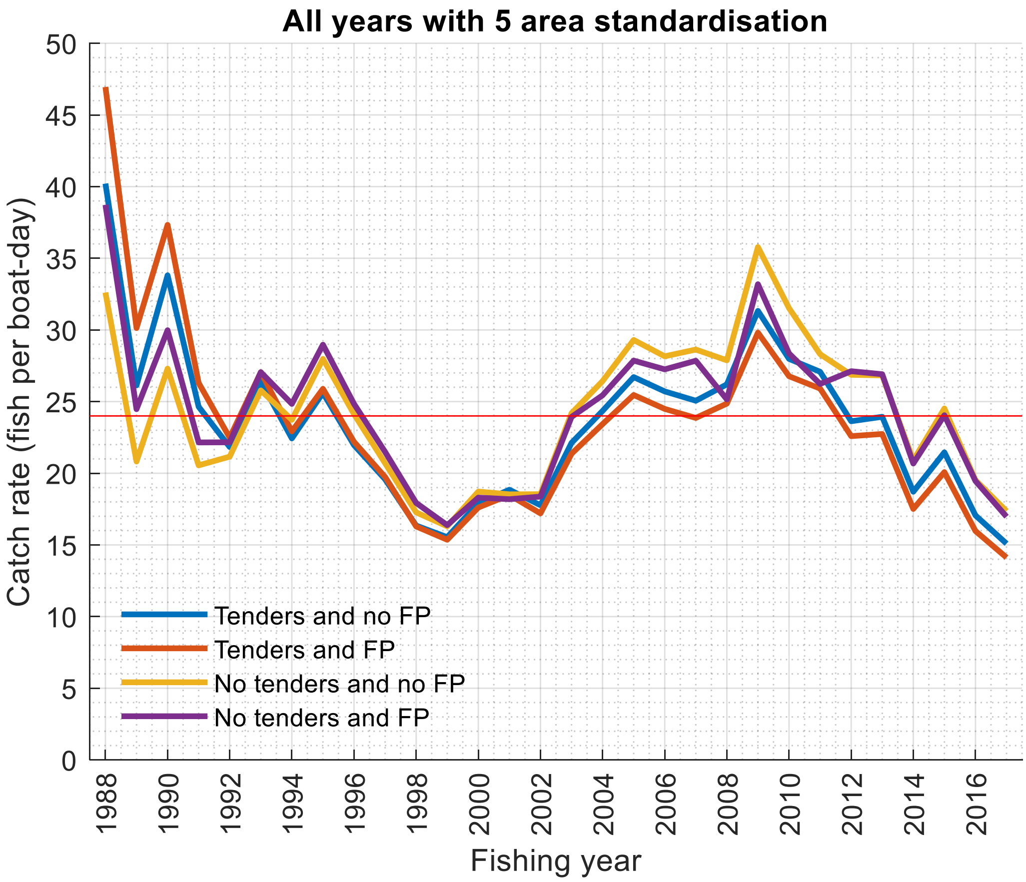

Figure 12. Comparison of Spanish mackerel average catch rates by fishing year 1989–2017. The plot compares four different standardised predictions, with and without the tender and fishing power (FP) data. Note logbook forms changed in 2003.

In 2018, logbooks were setup for TIB operations. Early data indicated a mean catch rate of 10 Spanish mackerel per operation day. The standard error was 1.5 fish. The mean catch rate was for Ugar (zone 2) waters during October and November 2018. The number of reported harvests were only 16.

A direct comparison of TIB and TVH catch rates was not possible at this time. Strictly, the 2018 TVH catch rates are required for the same fishing location and dates. However, for an initial calculation, the TIB catch rate was 63% (CI: 43–89%) of the TVH catch rate. This ratio used a TVH October–November 2016–2017 zone 2 mean catch rate of 16 fish (s.e. = 1.7).

Fish age-length composition data

There has been no sampling for many years of the age-length structure of Torres Strait Spanish mackerel. The available age frequencies show limited numbers of old fish from Bramble Cay waters 2000–2002 (Figure 13). Most of the sampled fish were aged in the 2+ to 4+ cohort-age-groups. The maximum fish age was 10 years, much less, than the maximum age found in waters on the Queensland east coast (26 years; Campbell et al., 2012; Langstreth et al., 2014).

For the 2000–2002 samples, female fish were on average slightly larger (Figure 14; females: overall mean = 109 cm TL and std = 10 cm, males: mean = 102 cm TL and std = 8 cm). The average weight of Spanish mackerel sampled from the Torres Strait was not different to surrounding waters of the Queensland east coast and Gulf of Carpentaria (Figure 4, page 8).

The reason for no old fish in the Torres Strait samples was unclear. The issue may relate to movement patterns of fish, the limited time-frame of sampling within years and the lack of spatial samples across the Torres Strait. Alternatively, the truncated age structures may indicate high fish mortality. In the population model, ranges of natural mortality attempted to explain the lack of old fish.

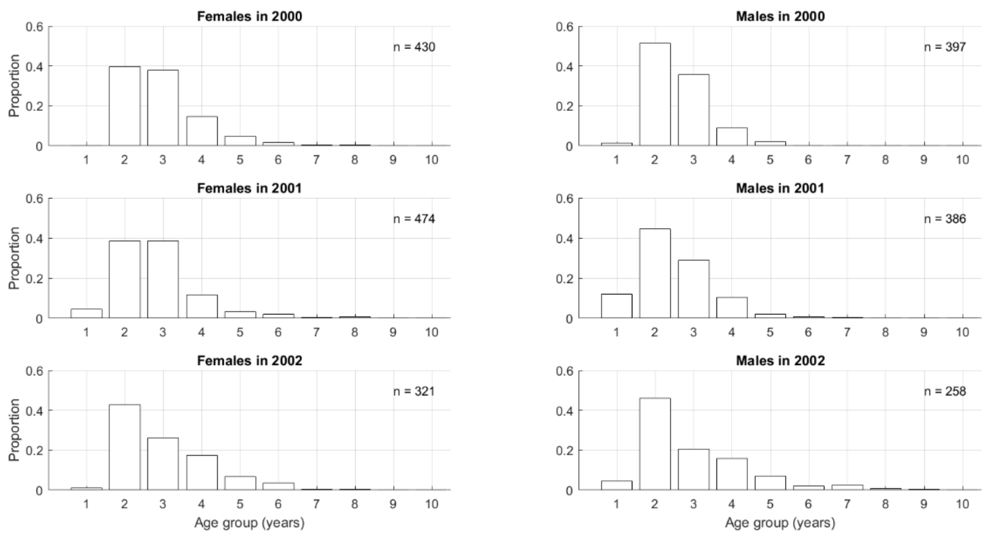

Figure 13. Age group frequencies of Spanish mackerel by fishing year and sex; n is the number of fish sampled.

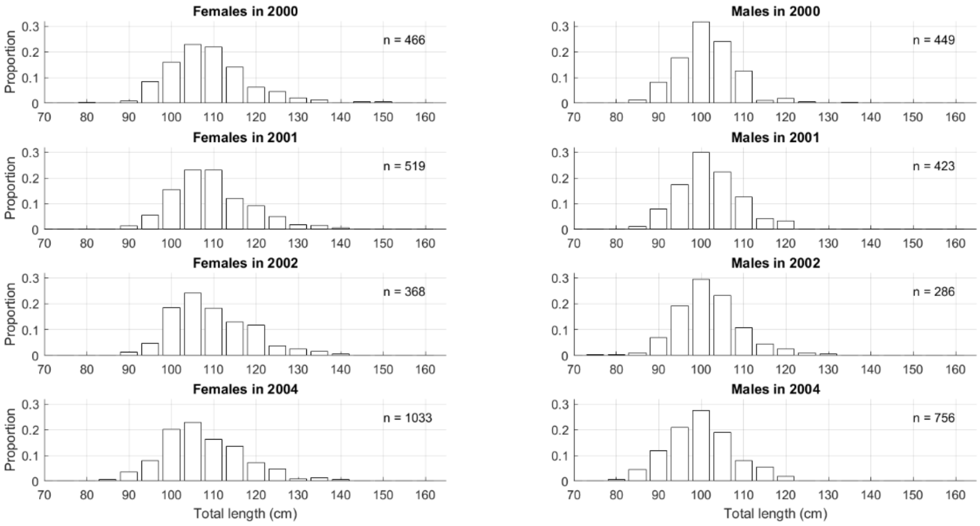

Figure 14. Total length frequencies of Spanish mackerel by fishing year and sex; n is the number of fish sampled. The 2000–2002 data was by DAF monitoring and the 2004 data was from AFMA voluntary fisher recordings.

Table 5. Sex specific von Bertalanffy growth parameters used to predict fish total length (cm) from age group data (years). Parameter standard errors are in brackets.

Parameter	Female	Male
l^{∞}	160.320 (11.697)	159.950 (24.304)
κ	0.133 (0.033)	0.081 (0.034)
a^{0}	-5.781 (0.979)	-9.926 (2.310)
RMSE (std)	6.2	5.2
d.f.	792	644
Adjusted R^2	0.58	0.52

Population dynamics model

The age-structured population analyses of Spanish mackerel assessed annual data on fish harvests, catch rates and age-length. The assessment analysed 44 combinations of data (Table 8, Appendix 3, page 38). This included:

- four annual series of fish catch rates (Figure 12),
- five rates of fish natural mortality per year (0.25, 0.3, 0.35, 0.4, 0.44), and
- two series of annual harvest, considering line fishing 1940–2018 and suspected Taiwanese gill netting between 1979 and 1986 (Figure 6).
- All 40 analyses above (4x5x2) assumed a logistic shaped pattern of fish vulnerability-at-age. Four domed analyses were included to explore different vulnerability effects on results; they were unremarkable, had higher variance and within the range of the logistic biomass ratio results.

All reported analyses resulted in model convergence and sound fits to the input data (Appendix 3). The results differed between model settings and data, and suggested precaution for interpreting stock productivity and setting of annual recommended biological catch (RBC).

Measurement of uncertainty in results, and defining the set of possible population states and reference points, was by comparing maximum likelihood (best) estimates from the 44 analyses. Of the 44, 35 analyses had better fits to the data (Table 8). The nine lesser (disregarded) fits related to domed selectivity and high 0.44 natural mortality matched with Taiwanese harvests. Complex domed selectivity was unnecessary for the data. Matching high natural mortality with extra Taiwanese harvest did not work.

For the 35 analyses, all had adequate fits to the data. MCMC simulations were only for the first four analyses to gauge stability. All MCMC traces appeared adequate (see examples in Appendix 3). Model fits to fish catch rates and age-structures were acceptable. The model results assumed a stochastic stock-recruitment relationship, constant M, logistic age-based vulnerability calibrated on 2000–2002 Bramble Cay data, standardised catch rates were proportional to the exploitable population biomass, and that Torres Strait Spanish mackerel comprise of a single stock.

The estimate of recruitment compensation (r_{comp} = r_{max}) or steepness (h) was not achieved in the first stock assessment due to the limited time series of data (Begg et al., 2006). Begg et al compared values of steepness at 0.38, 0.53 and 0.70 (Tables 2.12 and 6.2, Begg et al., 2006). These settings were based on the reproductive rates for Scombridae species (mackerel and tuna type-species, with median h = 0.52, 20th percentile = 0.3 and 80th percentile = 0.72; Table 1, Myers et al., 1999). Myers et al (1999) concluded that h will vary with species, natural mortality and age-at-maturity, with the number of annual replacement spawners typically ranging 1–7 per spawner per year. Using Myers et al. (1999) generalisation, an expected steepness (h) for Spanish mackerel could range 0.4 to 0.87; noting this range is higher than the values summarised for Scombridae.

The estimation of h in the previous assessment was successful and varied 0.35–0.59 based on four model settings (O'Neill and Tobin, 2018). The values of steepness (h) measure the expected proportion of virgin recruitment at 20% of virgin egg production (Myers et al., 1999; Begg et al., 2005; Begg et al., 2006). The estimated steepness values herein had a median of 0.5 (95% CI: 0.37–0.8) over the 35 analyses.

The estimates of virgin recruitment numbers-of-fish (R_0) correlated with steepness. The last assessment R_0 ranged between 78000 and 259000 fish per year (O'Neill and Tobin, 2018). For the 35 analyses herein, R_0 ranged between 63000 and 201000 per year. The smaller R_0 estimates flow from the decline in catch rates. The median standard deviation of annual log recruitment was 0.24 (95% CI: 0.21–0.3).

The estimates of fish 50% and 95% age-at-vulnerability were consistent between analyses, with $a_{50} \approx 1.8$ years and $a_{95} \approx 2.5$ years. Spanish mackerel aged older than or equal to the 2+ age group were mostly fully vulnerable to fishing. The results were similar to the previous assessments.

The Spanish mackerel age structures had few older fish (Figure 13). Typically, truncated age distributions are indicative of high fishing mortality. This consideration was modelled in analyses with natural mortality (M<=0.3). The other analyses with higher values of M generally improved model fits to the age data. The high values of M were greater than those considered on Australia’s east coast and may indicate the Bramble Cay samples were not representative of the broader Torres Strait waters or that older fish are moving to surrounding areas (e.g. Papua New Guinea and east Queensland waters).

Spatially stratified fish samples are required to test this question and confirm stock boundaries. The sampling of Spanish mackerel along the east coast of Australia was expanded in 2003 to account for spatial biases and variation (Sumpton and O'Neill, 2004; Tobin and Mapleston, 2004). Monitoring options for spatial sampling of Spanish mackerel through Torres Strait waters were modelled in the previous stock assessment and suggested 30 to 40 operation catches were needed from each fishing region per year to approximate the underlying fish length and age structures of the exploited population (Begg et al., 2006).

The previous stock assessment of Spanish mackerel used data up to the end of the 2014-fishing year. The assessment concluded the 2007–2014 harvests and population estimates were sustainable (O'Neill and Tobin, 2018). For this updated assessment, three more years of data have been analysed where catch rates have surprisingly declined (Figure 12). The following estimates were for 2017:

- All 2017 fishing mortality (pressure) indicators were sustainable ($< u_{MSY}$, Figure 15).
- However, the possible mature female spawning stock size was below levels for MSY (Figure 15).
- Across population analyses, estimated spawning biomasses of Spanish mackerel in 2017/2018 were 14–43% of original estimates for the start of the fishery in 1940 (Figure 16). Lower results in the range were associated with including Taiwanese harvests. No rational evidence was available to narrow the range of results. The broad percentage signified a classification status at or below the biomass level for maximum sustainable yield.

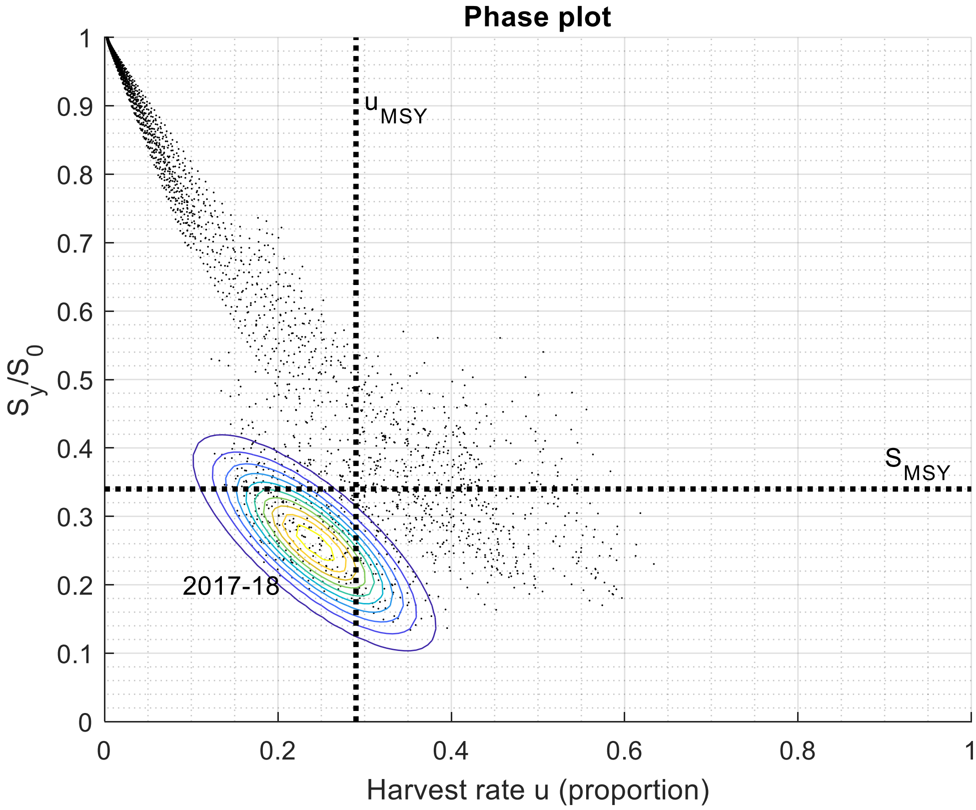

Figure 15. Time series phase plot of fishing harvest rate verse spawning biomass ratio. The contours circle the likely 2017–2018 position. Each dot was a year in each of the 35 analyses.

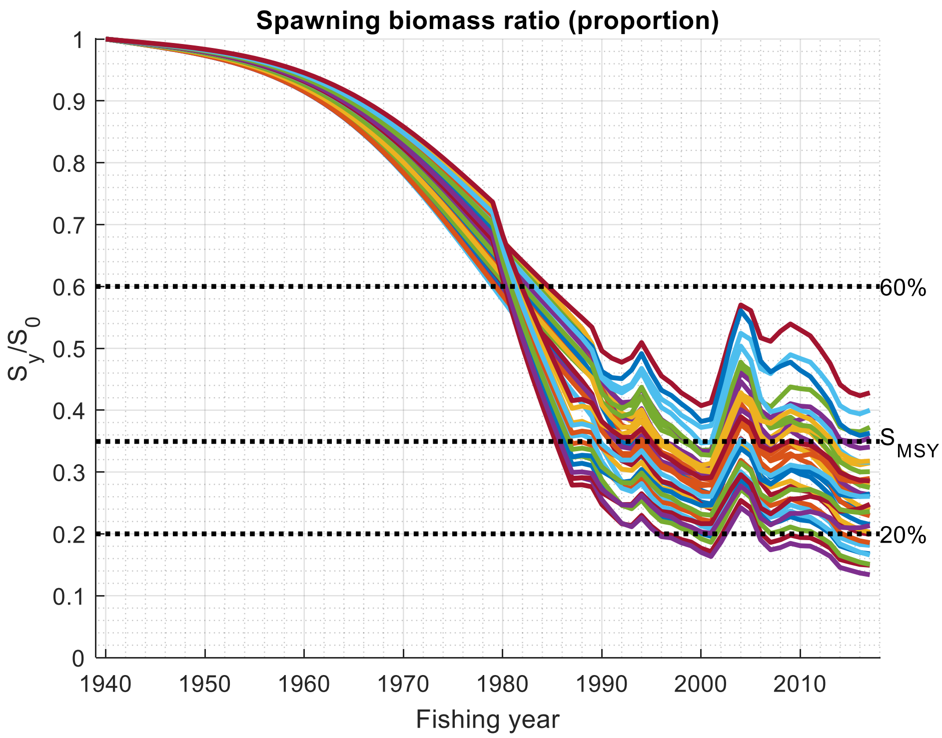

Figure 16. The estimated female spawning egg-production ratio compared against virgin. Each line was for 35 analyses.

As outlined in the methods section, reference points were estimated corresponding to equilibrium (average) and 2017 biomasses. The reference points correspond to the concepts used by the Australian Government (Australian Government, 2007). Before, no formal or other reference points had been set for Torres Strait finfish (Patterson et al., 2015). In the previous draft management plan for Torres Strait finfish only reference is made to ensuring the total catch of target species is at or below agreed annual limits (Australian Government, 2013).

The harvest and catch rate reference points for each analysis are in Appendix 3. The estimates varied with analysis settings and the exact true values remain unclear. Management should consider the variance in results and set recommended biological harvests at appropriate levels following a harvest strategy. The estimates suggest the harvests taken in 2017 were sustainable. Median reference points for Spanish mackerel harvests, based on the downturn to 2017/2018 population size, were u_{BMSY} = 94 t, u_{B40} = 81 t, u_{B48} = 63 t, u_{B50} = 60 t and u_{B60} = 43 t. Median equilibrium measures, potential harvests at their reference population sizes, were u_{BMSY} =138 t, u_{B40} = 135 t, u_{B48} =129 t, u_{B50} =125 t, and u_{B60} = 107 t.

Projection harvest graphs, show harvests at or below about 100 t should promote increases in Spanish mackerel biomass (Appendix 3, Figure 30 and Figure 31).

Average Spanish mackerel catch-rate reference levels are in Table 6. The TIB levels were 63% of TVH.

Table 6. Catch rate reference points (number of fish per operation day). See also Appendix 3.

	Equilibrium	
Reference point	**TVH**	**TIB**
$\mathbf{B_{MSY}}$	28	18
$\mathbf{B_{20}}$	14	9
$\mathbf{B_{40}}$	32	20
$\mathbf{B_{48}}$	39	25
$\mathbf{B_{50}}$	41	26
$\mathbf{B_{60}}$	51	32

Conclusions

The stock assessment analyses of Torres Strait Spanish mackerel conclude that the recent harvests were sustainable. However, across analyses, estimated spawning biomasses of Spanish mackerel in 2017/2018 were 14–43% of original estimates for the start of the fishery in 1940. Lower results in the range were associated with including Taiwanese harvests. No rational evidence was available to narrow the range of results. The broad percentage signified a classification status at or below the biomass level for maximum sustainable yield. The declining biomass results relate to the downturn in Spanish mackerel standardised catch rates 2009–2018. The decline had a biomass ratio midpoint, across analyses, at around 28% of virgin levels in 2017/2018. We caution that catch rates, and fish age-length data, may indicate localised patterns, as more data were from Bramble Cay than other locations in the Torres Strait.

Since 2008, the Torres Strait Finfish Fishery has been reserved for Traditional Inhabitants, on whose behalf the Torres Strait Regional Authority (TSRA) leases out fishing licences to non-Traditional Inhabitants (TVH). Over this time, commercial fishing had eased compared to before 2008. Despite the reduction, the setting of RBCs and leasing quota should consider the revised estimates of sustainable harvests for Spanish mackerel, with the aim to generate sustainable markets and revenue for the benefit of Torres Strait communities. Future management should also consider benchmarking target reference points for fishing to ensure healthy population biomass (above B_{MSY}) and catch rates of Spanish mackerel; in order to achieve and balance sustainability, economic, social and cultural objectives (Australian Government, 2007; Australian Government, 2013; Australian Government, 2015). If future average harvests increase consistently above 120 t, then catch rates of Spanish mackerel may erode long term. In the next few years, quota setting should start to follow a harvest strategy procedure to recommend annual harvests. Settings should be precautionary until improvements in data are addressed.

For quota setting, how does management choose an RBC for 2019-2020? How do we deal with the uncertainty? Suggestions include:

- Use the Commonwealth Harvest Strategy Policy (HSP).
- Confirm the target reference point.
- Choose potential RBCs that increase biomass 95% of the time (Figure 30).
- Study projections! Define the risk levels.
- Define a rebuild time (Figure 31). Typically, recovery times are the minimum of 1) the mean generation time plus ten years, or 2) three times the mean generation time (Australian Government, 2007). Note that the mean generation time is the average age of a reproductively mature animal in an unexploited population.
- For stocks above B_{20} but below the level that will produce maximum sustainable yield (B_{MSY}), it is necessary to rebuild stocks to B_{MSY}. Once stocks are at B_{MSY}, rebuilding shall continue toward B_{TARGET}, however the rate of rebuilding may be slower and shall be determined in a way that considers the appropriate balance between short-term losses and longer-term economic gains.

A harvest strategy framework (Sloan et al., 2014) for the finfish fishery has been sought by the PZJA (Torres Strait Scientific Advisory Committee project call, 2016) to guide decisions on future monitoring, harvests and fishing effort and leasing arrangements. Stock status indicators and reference points calculated herein can support design of a harvest strategy, but further investment in monitoring data is required to reduce indicator variances and biases. A total of nine monitoring data recommendations were listed in the 2006 stock assessment report (Begg et al., 2006). In order to service a future harvest strategy for Torres Strait Spanish mackerel (empirical or stock model based), improvements in the data are required:

- Verify records on fishing effort and harvest through logbook, docket book and electronic reporting systems [*for harvest and/or standardised catch rate assessments*]. This involves recording and validating:
    - trip harvests and average fish weights using unload/sale receipts,
    - number of dories used and hours fished each operation day,
    - the number of and fishing locations of the primary operation and dories; plus utilising VMS/GPS latitude and longitude coordinates in future data recording,

- number of fish caught each operation and dory day,
- zero catches, and
- days when fishing is stopped due to capacity limitations (too many fish).

- Monitor and estimate Spanish mackerel harvests taken by non-commercial sectors [*for stock model assessments*].
- Conduct regular (annual or biennial) long term monitoring of fish age-length structures that are spatially representative of the Torres Strait [*for mortality and/or stock model assessments*].
- Collect fine scale spatially representative genetic fish samples to further examine stock assumptions and boundaries [*for stock model assessments and management*].
- Conduct further investigation with the stock assessment model to consider hyperstability in catch rates and examine domed vulnerability to explain the lack of older fish [*for stock model assessments*].

Review of the stock structure literature is complex and the single stock hypothesis is not completely clear for Torres Strait Spanish mackerel. Buckworth et al. (2007) report distinct management/stock units for Spanish mackerel: a) Queensland east coast, b) Torres Strait and c) Northern Territory and Western Australian waters. Genetic results suggest Spanish mackerel typically exist as localised assemblages (i.e. larger stock areas generally consist of a mix of fine-scale spatial population groups) with the spatial spawning patterns of female fish generally less compared to males (Buckworth et al., 2007). The genetics results also suggest Torres Strait Spanish mackerel are a mixture of surrounding populations (Buckworth et al., 2007). Otolith isotopes suggest some similarity between Torres Strait and Gulf of Carpentaria Spanish mackerel (Newman et al., 2009). No stock structure data have been evaluated from north east Queensland (north of 15°S) or Papua New Guinea waters. Management of Spanish mackerel adjacent to the Torres Strait may impact on the viability of the Torres Strait fishery (Buckworth et al. 2007).

This stock structure uncertainty does not undermine the management and assessment of Torres Strait Spanish mackerel as a single unit and at this time, it would be detrimental to combine Torres Strait data into a larger area with other jurisdictions. This is so because of the seasonal and spatial predictability of Spanish mackerel aggregations and risks of localised overfishing. This risk and event has occurred for spawning aggregations along Queensland's east coast (Tobin et al., 2013; Tobin et al., 2014). The stock structure uncertainty highlights that finer spatial scaled sampling is required to discriminate Spanish mackerel between the Torres Strait and surrounding waters.

If future improvement in data is not cost effective or supported, then use of precautionary reference points to judge abundance (standardised catch rate) indicator signals is essential for mitigation of indicator variance and uncertain management decisions.

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Appendix 1: Catch rate diagnostics

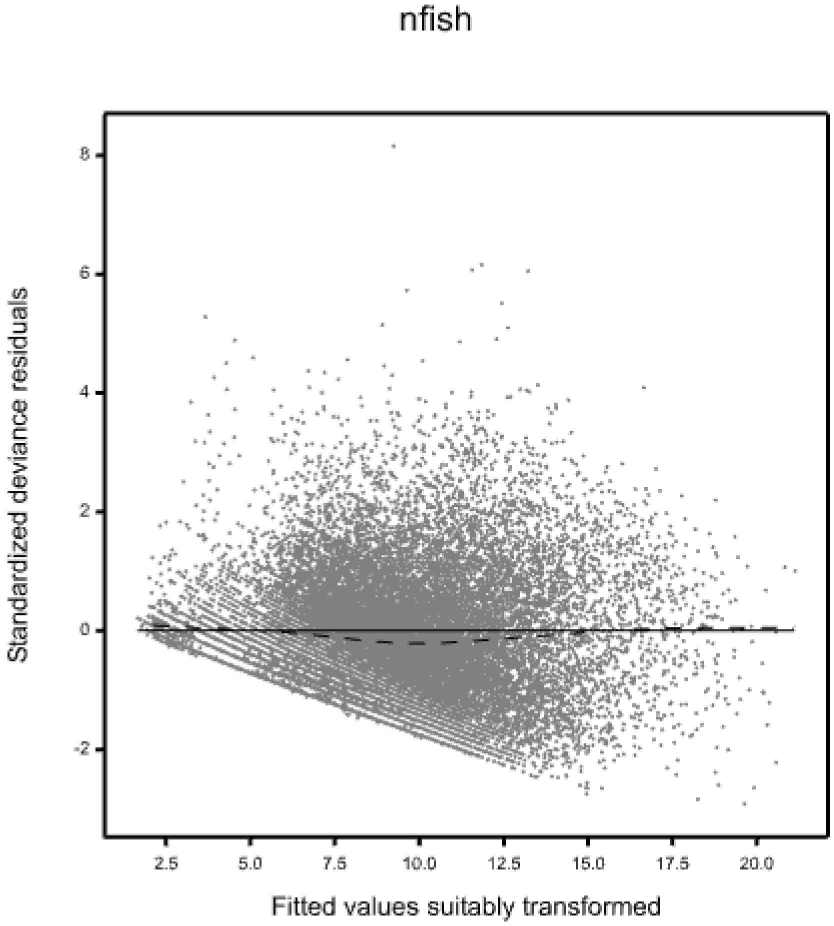


Figure 17. Plot of standardised residuals against fitted values from the Poisson GLM analysing numbers of Spanish mackerel with main effects. The plot shows circle symbols for the goodness-of-fit data, a solid zero reference line and a dashed trend line.

Table 7. Analysis of deviance table for the over-dispersed Poisson model used to standardise catch rates: a) Poisson generalised linear model (GLM) with tenders and no fishing power offset.

a) <u>Poisson GLM with tender effect</u>

Adjusted R^2= 0.375
Residual mean deviance = 13.58
Residual degrees of freedom (d.f.) = 23990

Fixed terms	**d.f.**	**F statistic**	**pr.**
Fishing year	29	41.57	<0.001
Zone 5	4	82.02	<0.001
Vessel	42	75.77	<0.001
s_1	1	1.44	0.23
s_2	1	375.25	<0.001
s_3	1	269.7	<0.001
s_4	1	116.37	<0.001
Number of tenders	1	440.16	<0.001
Lunar phase	1	140.03	<0.001
Lunar phase advanced	1	673.04	<0.001
windns	1	5.41	0.02
windnsQ	1	22.78	<0.001
windew	1	1.47	0.225
windewQ	1	56.35	<0.001

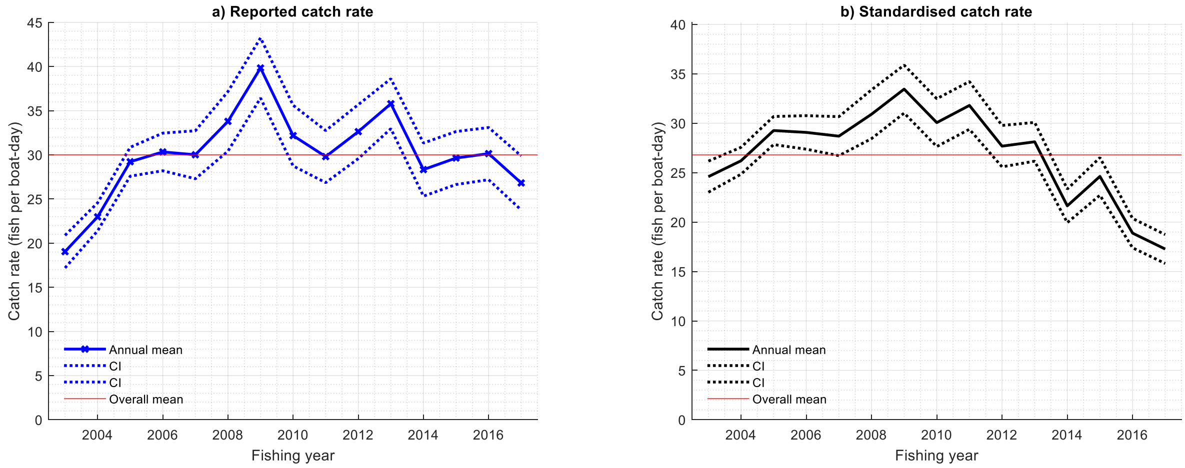


Figure 18. TVH Spanish mackerel average catch rates by fishing year 2003–2017 as predicted from the over-dispersed Poisson GLM. The data included only TSF01 logbook years, including the total hours fished per operation day. The error lines indicate the 95% confidence intervals (CI) on the yearly means.

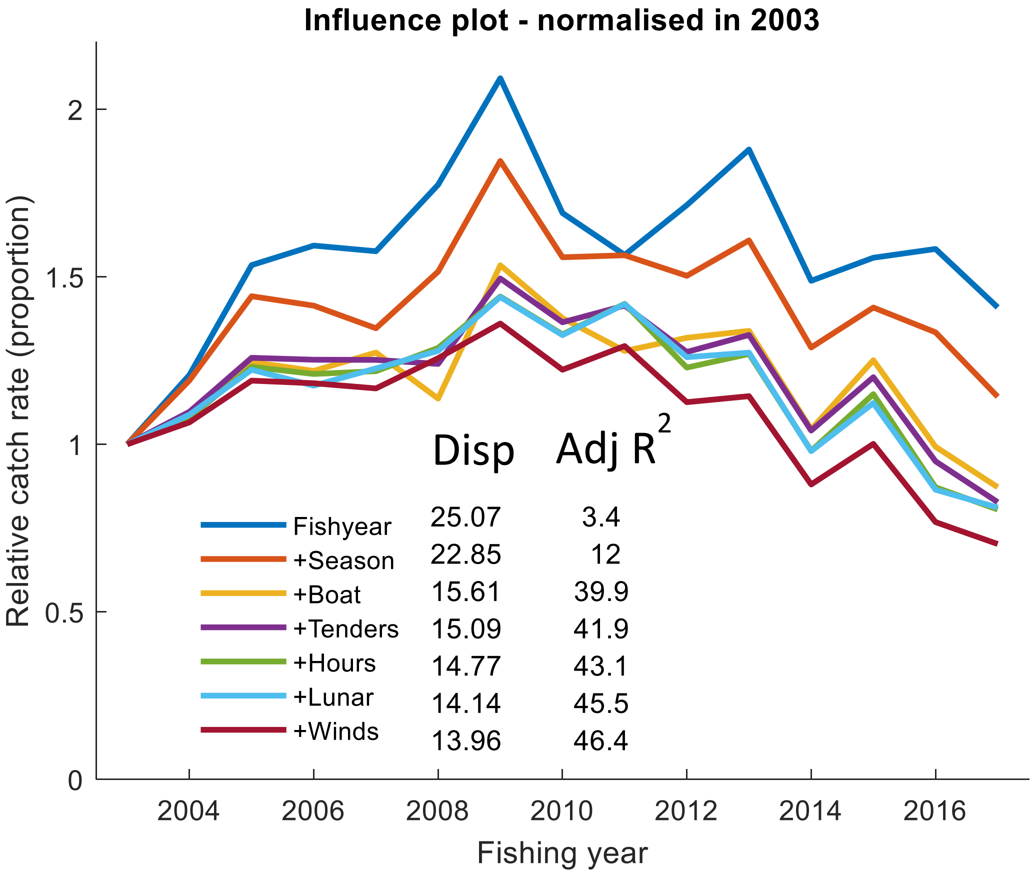


Figure 19. GLM influence plot, illustrating the additive standardisation effect of model terms. The first column of numbers on the figure was the dispersion parameter, and second was the adjusted R^2 as a percentage.

Appendix 2: Calculation of fish age group

J. Langstreth, Fisheries Queensland, 2015

Recommendation on assigning age group to Torres Strait Fish

- **For fish caught in April** (9 fish): age group = increment count. (No adjustment required). However, as April is 6 months after October, if you choose to use them in the ALK, then you should consider adjusting the length as they are likely to have had significant growth from the same cohort of fish caught back in October (possibly in the order of 5-10 cm growth for the main age groups)
- **For fish caught in October :**
    - **New edge types –** age group = increment count
    - **Intermediate edge types (codes 1 & 2) –** age group = increment count
    - **Wide edge types –** age group = increment count **+ 1**

Information to base recommendation

For the GOC & EC Spanish (based on LTMP data), the trend in the timing of edge types being laid down on the otolith are very similar (Figure 20 and Figure 21). (I have plotted EC by fin yr & GOC by calendar year based on our respective LTMP sampling seasons). New edge types are mostly visible on the otolith from June/July, and as spring growth occurs, we can observe intermediate growth (translucent material) on the edge from September.

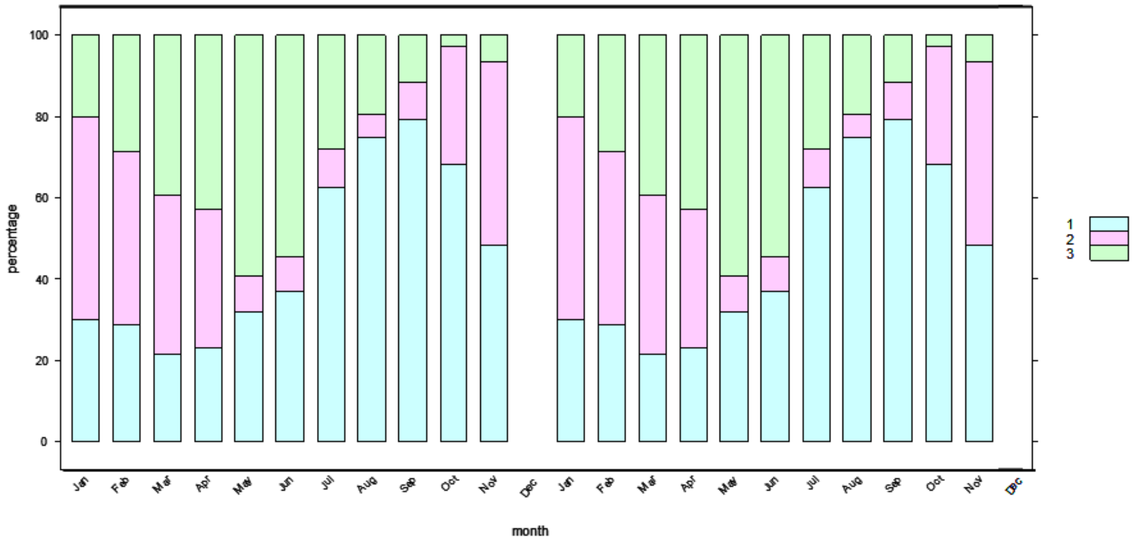


Figure 20. Gulf trend for edge type by month.

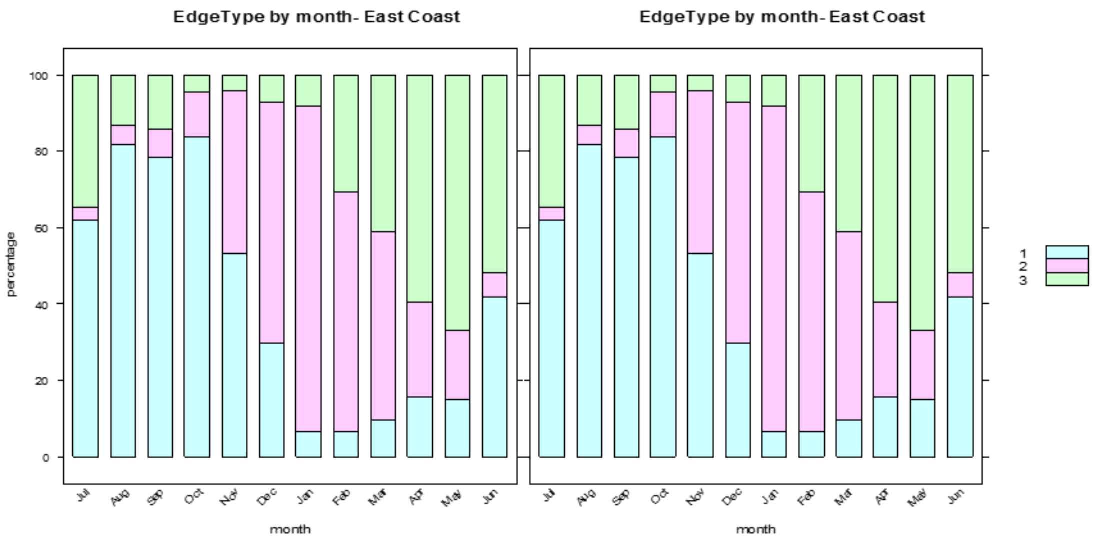


Figure 21. EC trend for edge type by month.

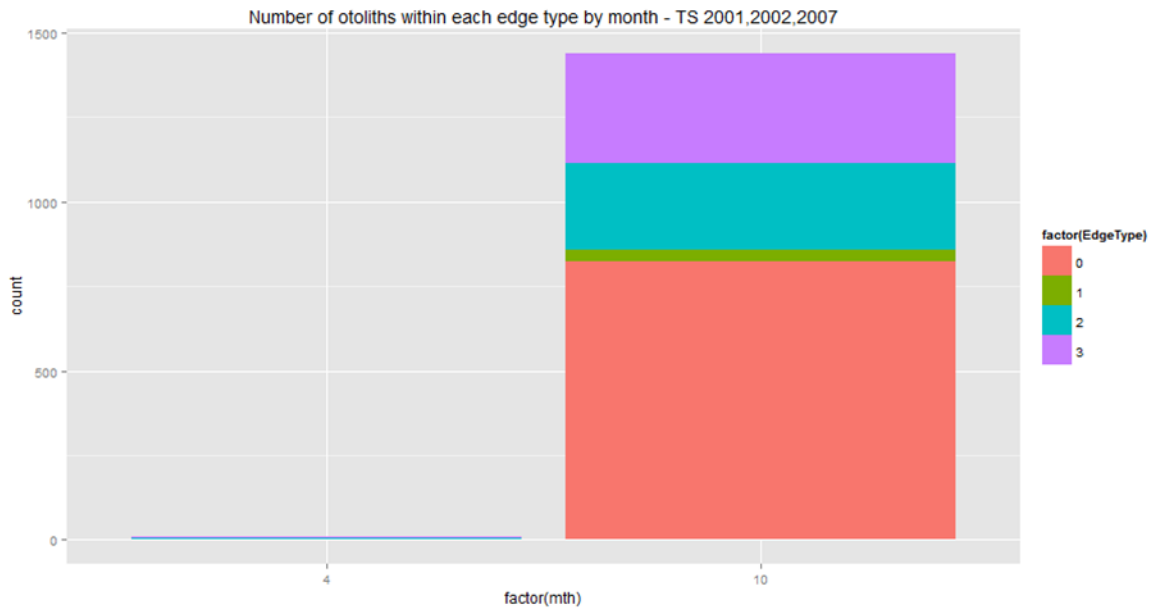


Figure 22. Torres Strait - edge type by month.

Note –edge type was not recorded during the first year of sampling in 2000.

- The majority (57%) of TS fish sampled during October are in the '**New**' Edge type (Figure 22). This suggests that for these, their increment count accurately reflects their age group (i.e. age that these fish will attain in that financial year). E.g. a 2 year old fish with a new increment shows 2 increments and will not show another new increment until the next August-Oct period in the following financial year.
- However, for fish that have a **wide** edge (23%), the increments showing on the otoliths are one less than would be if the fish lasted for the remainder of the financial year. They should be kept in the same cohort with fish that have just shown their 'new' edge type. Therefore the fish would be in one higher

than increment count. This is supported by the fact that there are 13 0-wide fish in the TS data, which have to be in the 1-year age group to have reached minimum legal size (it is highly unlikely these fish are under 4 months old). So we should plus one to the increment count for fish with wide edge types as the age class and age group should be one higher than the otolith shows.

- For **intermediates** (20%), at this time of year, fish have most likely had some significant growth already since “winter” and therefore laid down some translucent material following laying down their opaque increment. This is in line with what occurs on the EC & in GOC fisheries (see plots above). These fish will not lay down another opaque band/increment before the end of the financial year, and are therefore their increment count represents the age group (max. age they will attain in that financial year).
- **For fish caught in April**, they are either intermediates or wides. In April, being near the end of the financial year, fish will have laid down their increment for that financial year already & not go through the cycle to lay down another before the end of June. If there were ‘news’ caught in April (but there aren’t), we would take one increment off to calculate age group.

Code recording the interpretation of the otoliths margin (For Torres Strait Data). This is different for EC & GOC data.

0. Opaque on the margin (New)

1 0-33% of the margin is translucent (Intermediate)

2 34-66% of the margin is translucent (Intermediate)

3 67-100% of the margin is translucent (Wide)

For East Coast – 1 – New, 2 – Intermediate, 3 - Wide

Appendix 3: Stock model diagnostics

Table 8. Settings for the 44 analyses. Harvest 2 include Taiwanese catch. Used, flagged the 35 reported analyses.

Used	negLL	Catch rate	M	Domed	Harvest
1	-74.9535	1	0.25	0	1
1	-79.1797	1	0.3	0	1
1	-82.4628	1	0.35	0	1
1	-86.3509	1	0.4	0	1
1	-88.2054	1	0.44	0	1
1	-76.1613	2	0.25	0	1
1	-80.2675	2	0.3	0	1
1	-83.428	2	0.35	0	1
1	-85.8789	2	0.4	0	1
1	-87.4356	2	0.44	0	1
1	-70.7213	3	0.25	0	1
1	-78.2961	3	0.3	0	1
1	-81.6558	3	0.35	0	1
1	-84.2522	3	0.4	0	1
1	-86.5144	3	0.44	0	1
1	-75.2936	4	0.25	0	1
1	-79.2824	4	0.3	0	1
1	-82.3667	4	0.35	0	1
1	-85.4954	4	0.4	0	1
1	-87.3235	4	0.44	0	1
1	-75.8356	1	0.25	0	2
1	-79.7867	1	0.3	0	2
1	-83.0454	1	0.35	0	2
1	-85.7282	1	0.4	0	2
0	-50.6939	1	0.44	0	2
1	-76.2453	2	0.25	0	2
1	-79.7302	2	0.3	0	2
1	-82.605	2	0.35	0	2
0	-64.2163	2	0.4	0	2
0	-41.7278	2	0.44	0	2
1	-72.2535	3	0.25	0	2
1	-76.3623	3	0.3	0	2
1	-79.8483	3	0.35	0	2
1	-82.673	3	0.4	0	2
0	-35.166	3	0.44	0	2
1	-74.3732	4	0.25	0	2
1	-78.1803	4	0.3	0	2
1	-81.2754	4	0.35	0	2
1	-83.731	4	0.4	0	2
0	-58.5118	4	0.44	0	2
0	-78.0894	1	0.3	1	1
0	-77.4697	2	0.3	1	1
0	-77.5541	3	0.3	1	1
0	-78.2656	4	0.3	1	1

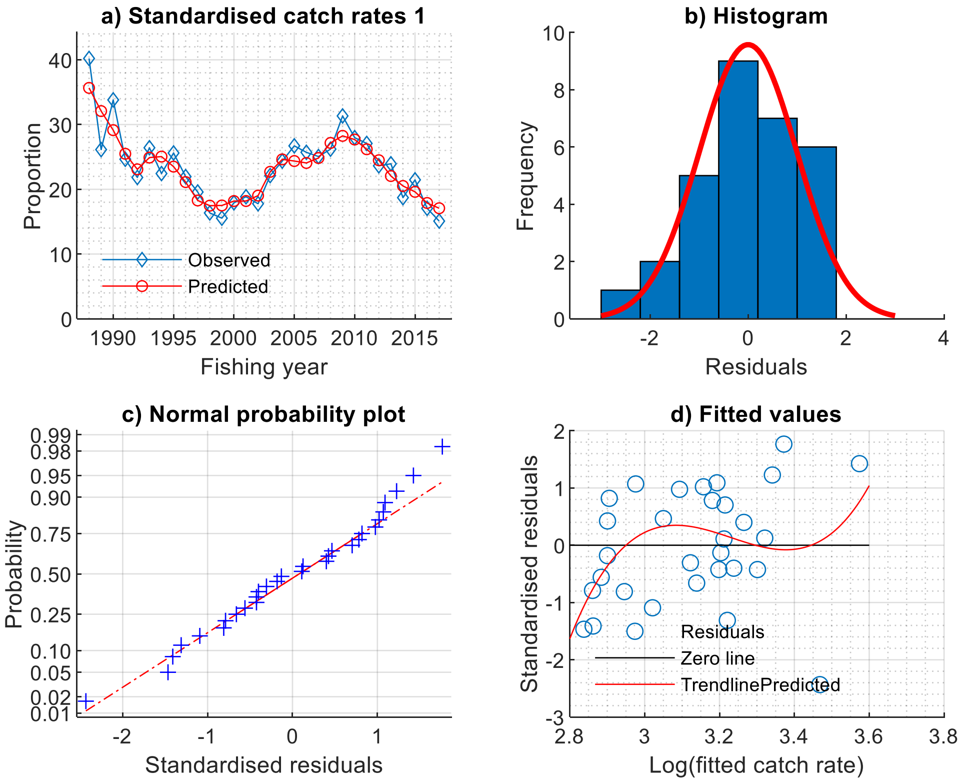


Figure 23. Example stock analysis fit to catch rate 1 (tenders and no fishing power); analysis 5. The level of fit was similar between analyses for catch rates 1–4.

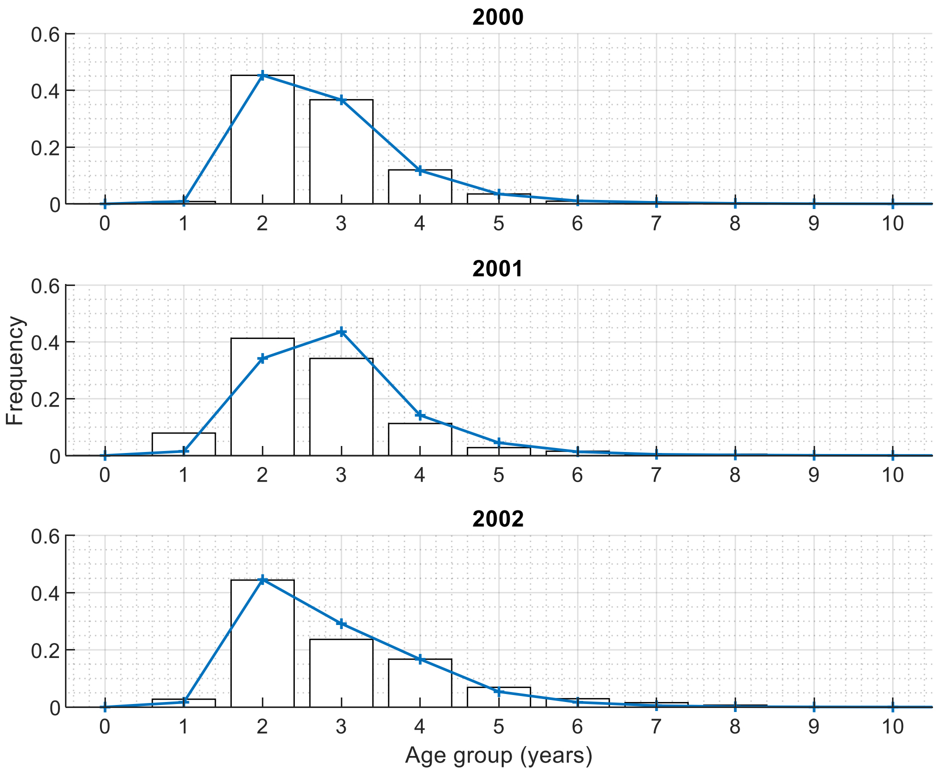
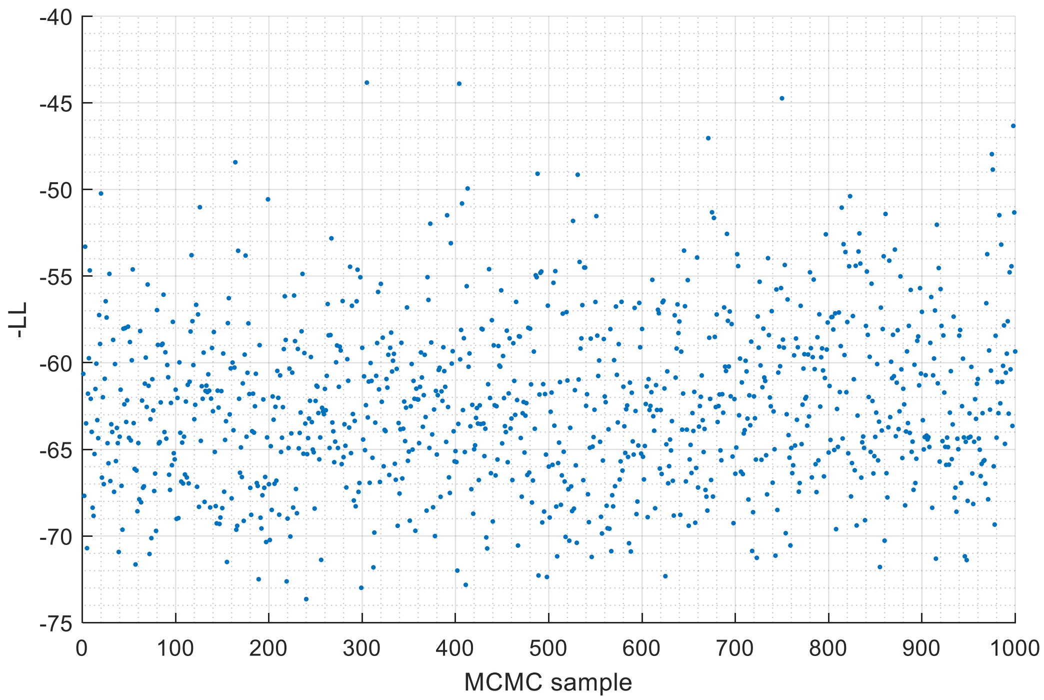
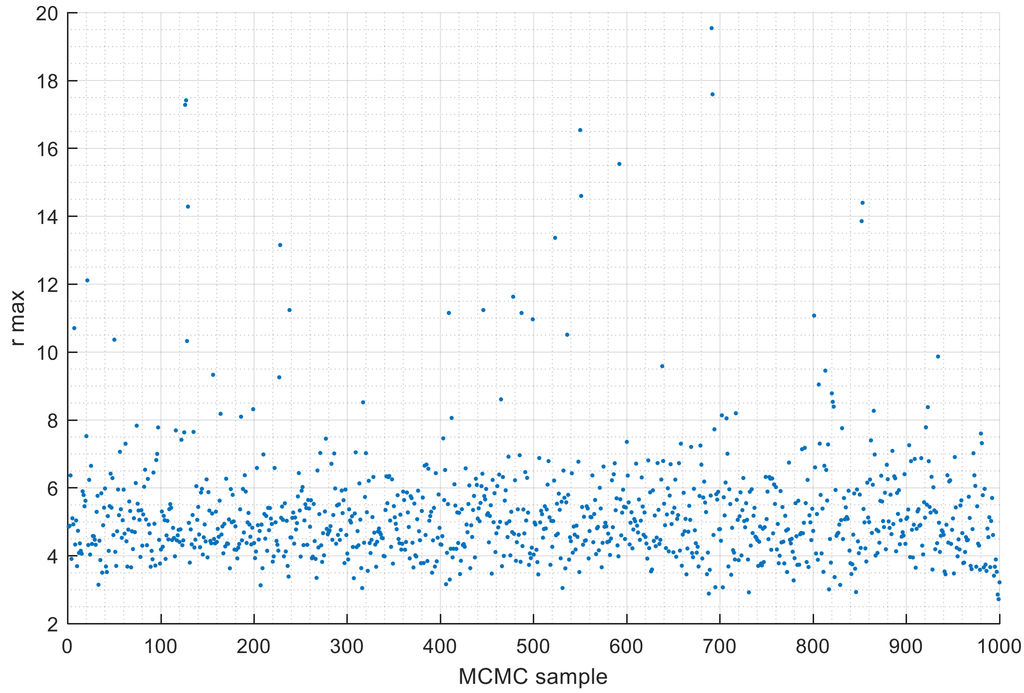
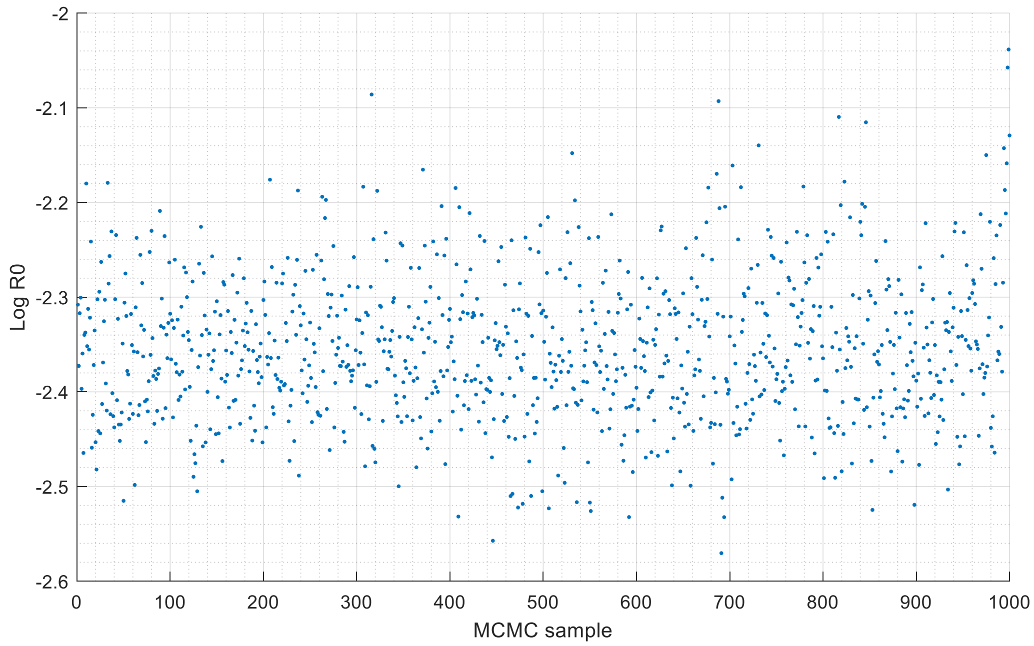
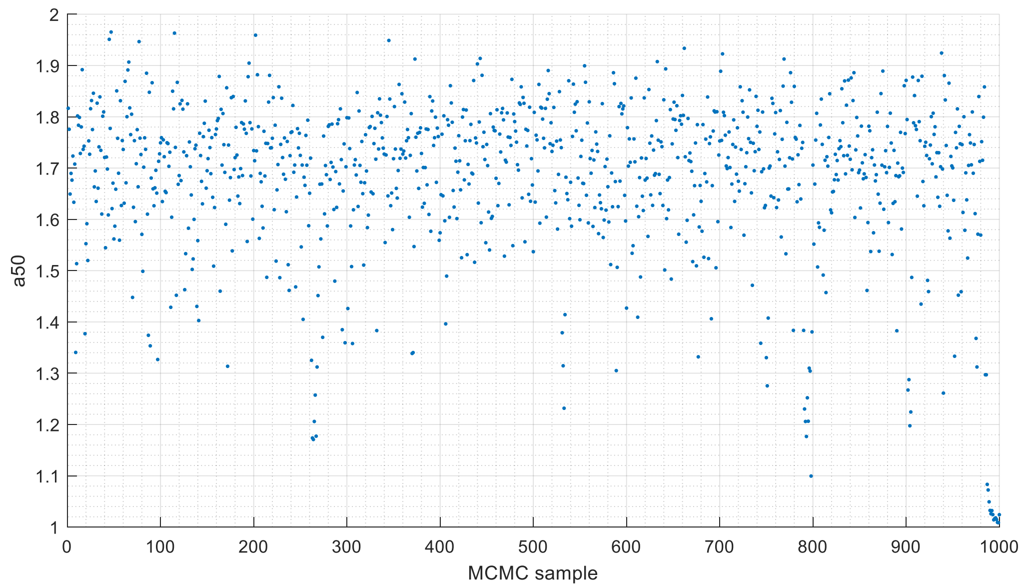


Figure 24. Example stock analysis prediction of fish ages (analysis 5). The predicted model fits were similar for other analyses.


-40
-45
-50
-55
-60
-65
-70
-75
-LL
0
100
200
300
400
500
600
700
800
900
1000
MCMC sample


20
18
16
14
12
10
8
6
4
2
r max
0
100
200
300
400
500
600
700
800
900
1000
MCMC sample


Log R0
MCMC sample
-2
-2.1
-2.2
-2.3
-2.4
-2.5
-2.6
0
100
200
300
400
500
600
700
800
900
1000


a50
MCMC sample
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
100
200
300
400
500
600
700
800
900
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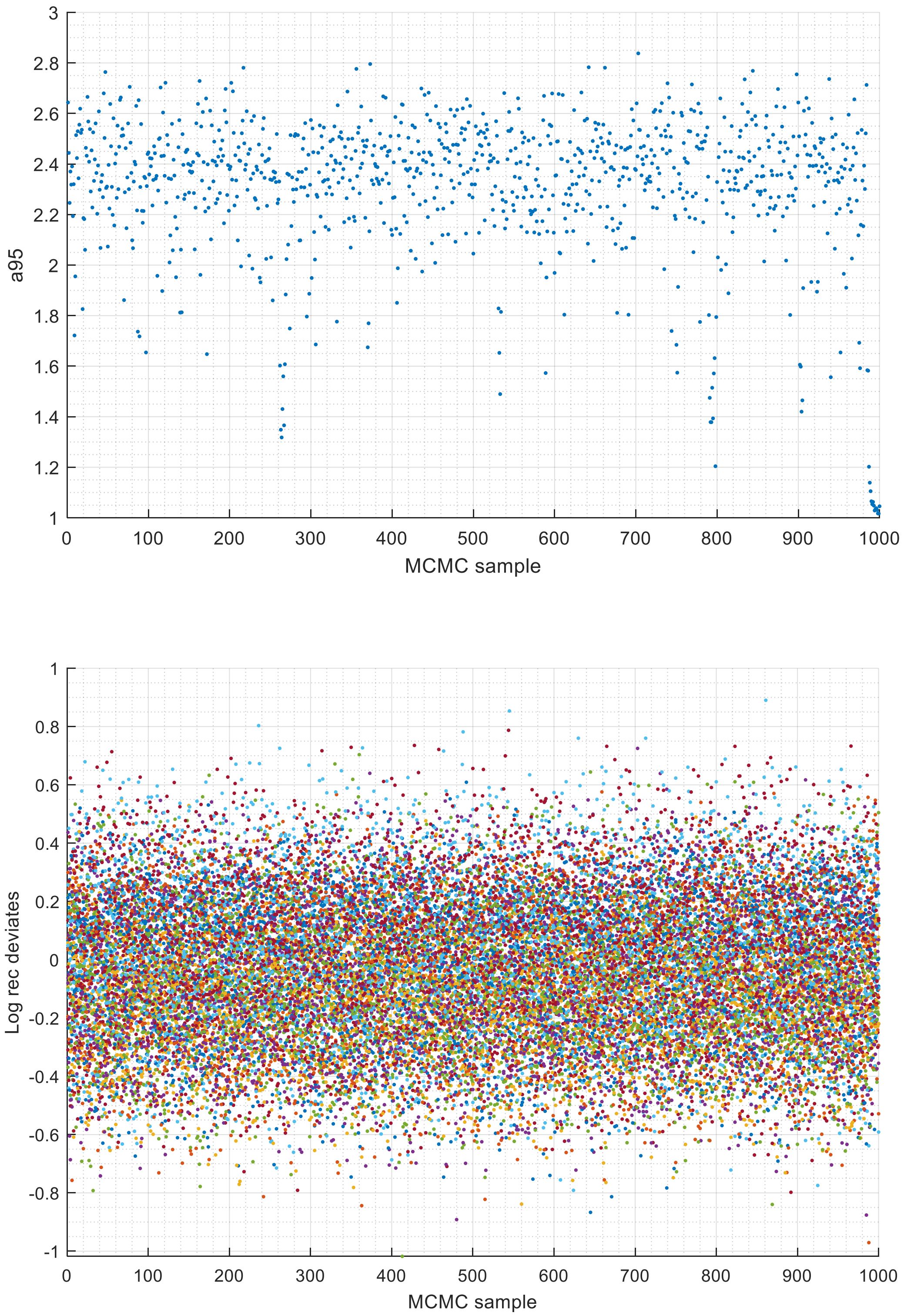

Figure 25. Typical example MCMC traces analysis 2 M=0.3.

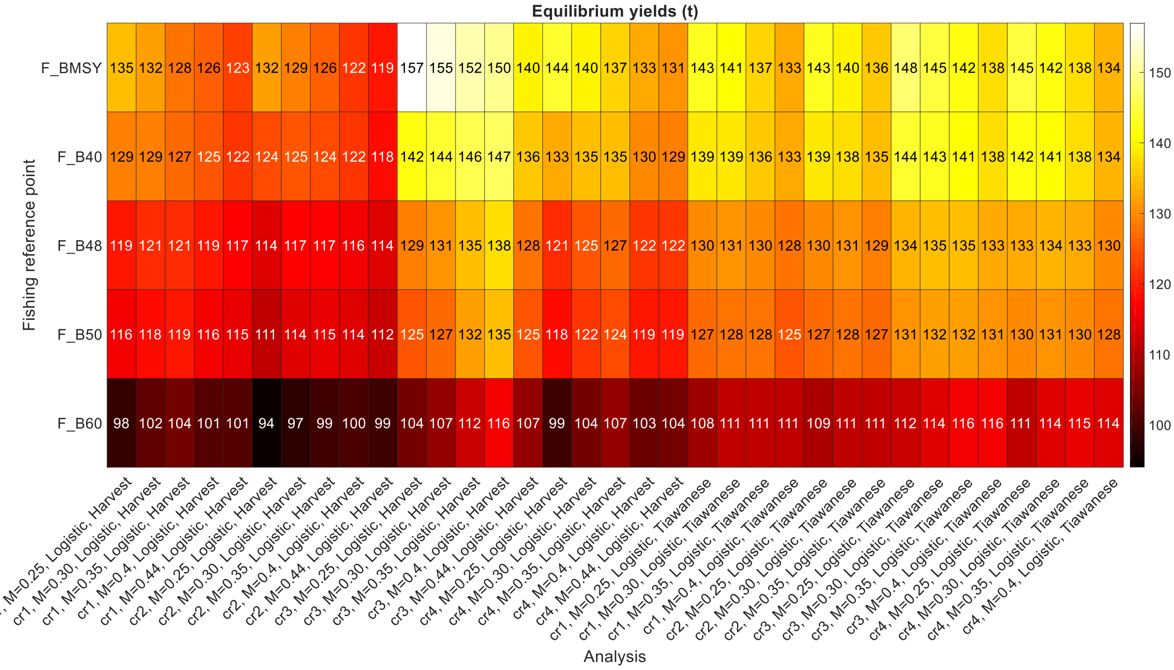

Figure 26. Equilibrium (potential average) yields for each analysis when at their reference point.

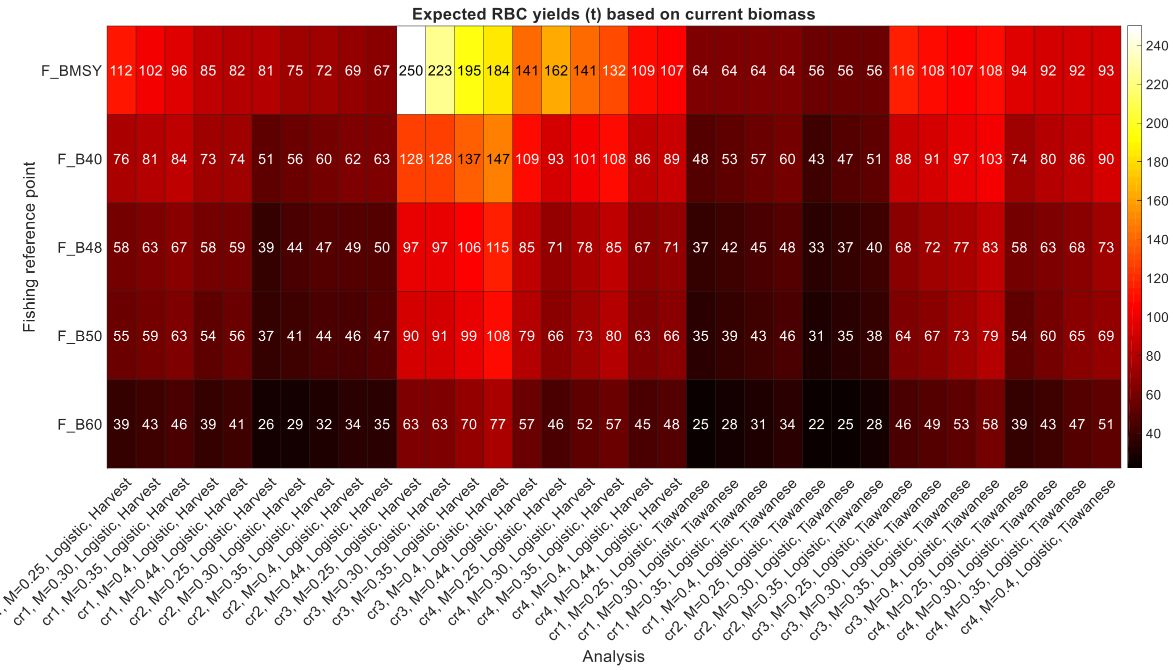

Figure 27. Expected yields for each analysis and reference point at current 2017 biomass.

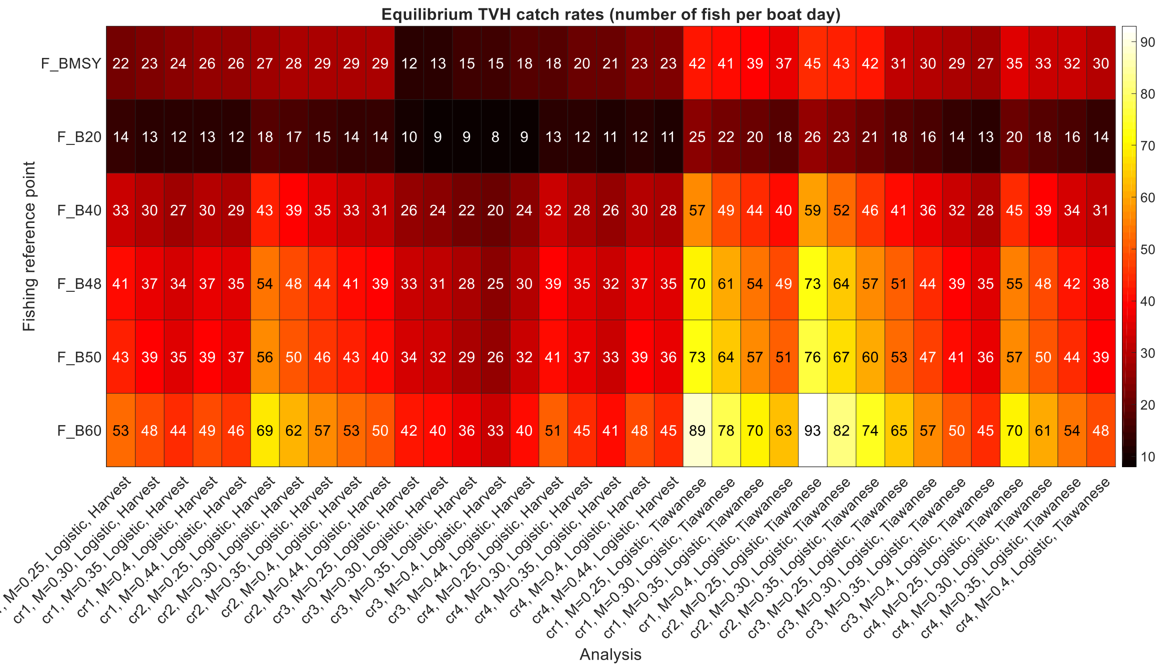

Figure 28. Equilibrium (potential average) TVH catch rate for each analysis when at their reference point

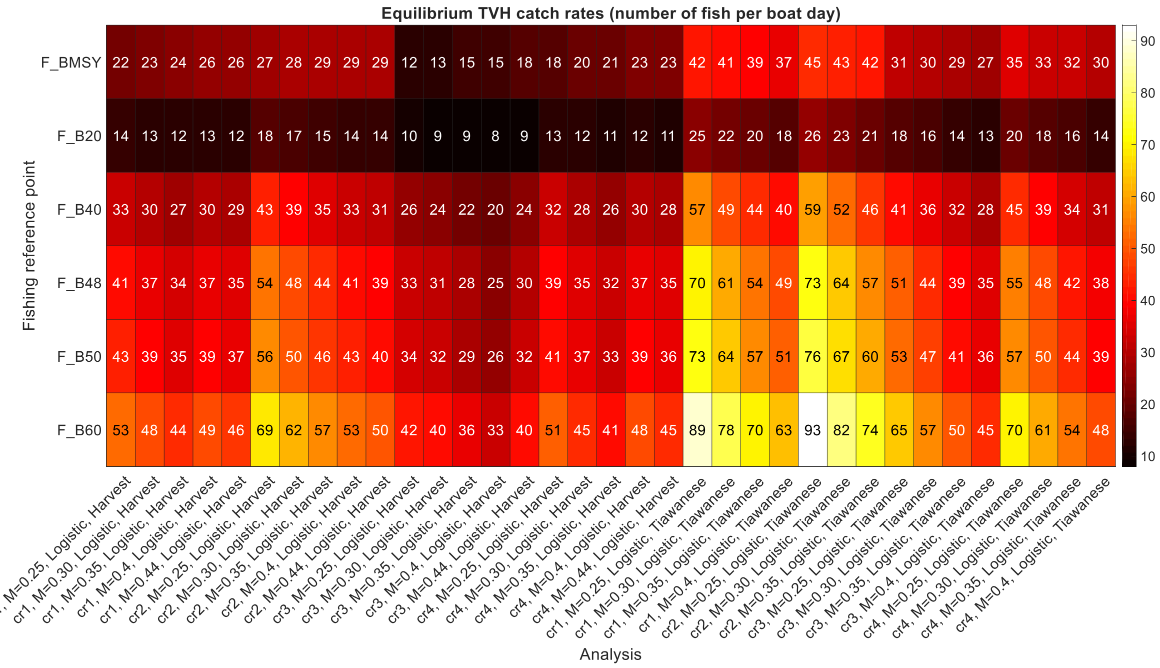

Figure 29. Expected TVH catch rates for each analysis and reference point at current 2017 biomass.

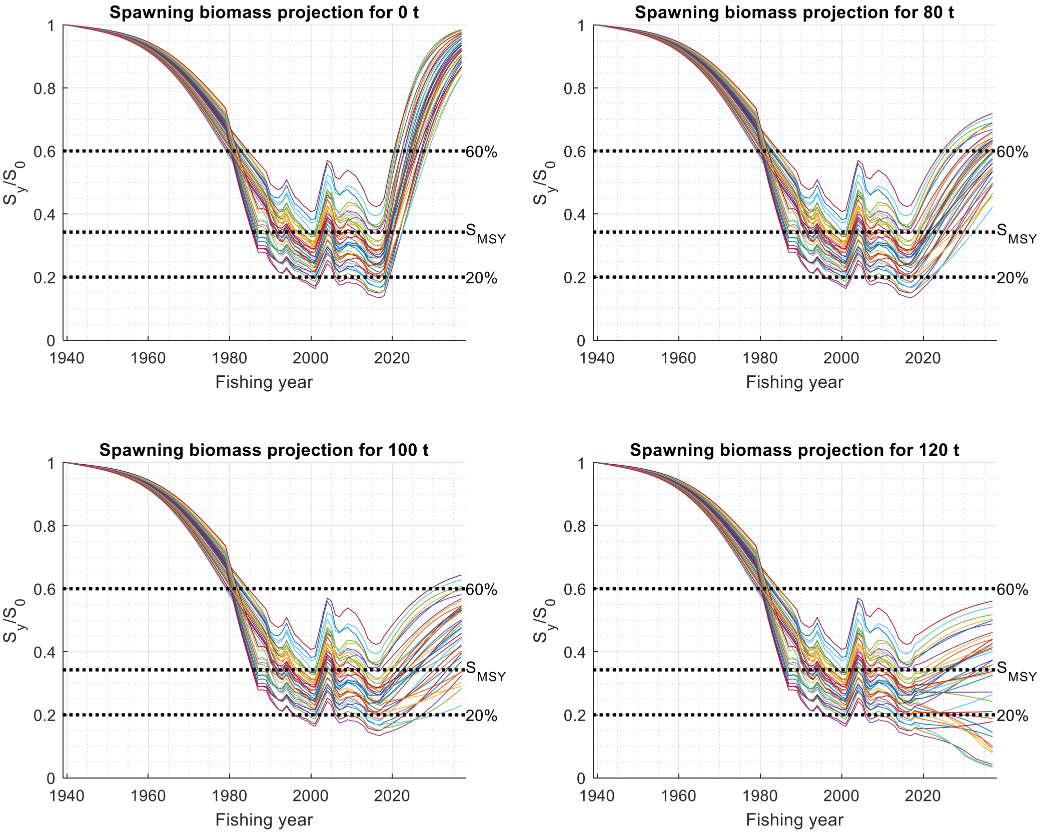

Figure 30. Biomass projections for four different RBCs.

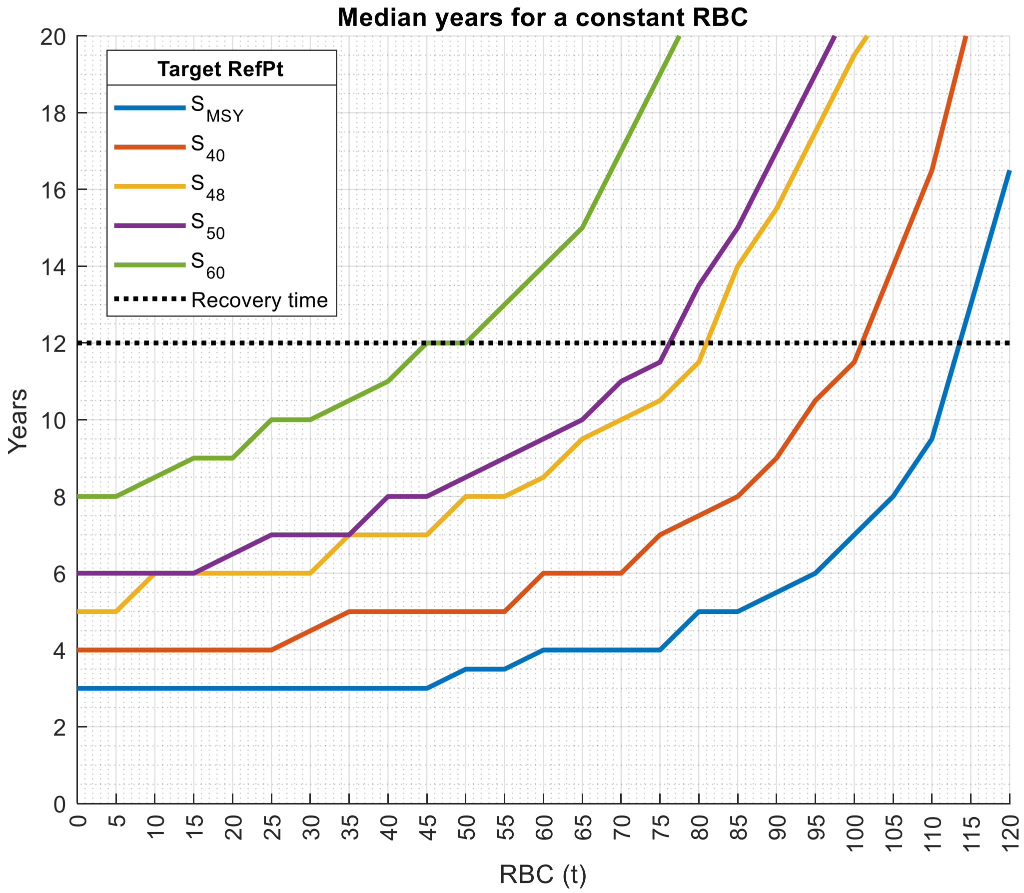

Figure 31. How many years to recover to target biomass? Spanish mackerel age full maturity = 4 years; mean generation time 5 years.

Appendix C

Torres Strait Spanish mackerel Harvest Strategy: one-page table

Table 1. Harvest Strategy for Torres Strait Spanish mackerel stock: one-page summary

Component	Metrics	Detailed values and sources
Indicators	Catch CPUE *Current Biomass/B_0 (date estimated)* Fishing Mortality (*F*)(*date estimated*) Fishery independent survey indices	**1989-2017** (in model 1940-1988 assumed) **2003-2017** (TVH only)(standardised) **0.318** (up to fishing year - 2016)(if 2017 = **0.28**)* **0.6** () Not conducted
Reference Points	Interim TRP - Biomass defined LRP - Biomass defined	**B_{48}** (chosen as B_{60} – is aspirational, i.e. stock << B_{40}) **B_{20}** (as published by ABARES)
Performance Metrics (PMs) *Specified as specific probabilities of meeting level, e.g. >95% by an agreed time period*	<u>Status related</u> Current Biomass/B_0 versus TRP Current Biomass/B_0 versus LRP <u>Utilization related</u> Future catch (year undecided) *versus* a catch target Future CPUE (year to decide) *versus* a CPUE target Average annual variation in catch	 Assessment indicates Current Biomass/B_0 is approx. 0.28* (estimate from midpoint of range obtained from 35 scenarios, taking into account uncertainty) No catch target for SM at this stage TIB (dory level) indicative target CPUE tabled (<u>*x*</u> fish per dory per day) No AAV catch target for SM at this stage
Decision rules Harvest Control Rules *Status related supersedes utilization related*	Setting of RBC: <u>Status related:</u> If Current Biomass/B_0 > TRP If Current Biomass/B_0 < TRP > LRP If Current Biomass/B_0 < LRP <u>Utilization related:</u> Future catch *versus* target Future CPUE *versus* a CPUE target AAV catch versus AAV catch target <u>Rule for TAC</u> TAC=RBC–Traditional-Recreational	**94 tonnes** - based on assessment model (estimated: harvest rate to achieve MSY, median estimate of 35 scenarios, taking into account uncertainty) Could be set based on rate of recovery to TRP (optimal: 12yrs). Current RBC achieves B_{msy} in ~6years, B_{40} in 10 years Increase RBC RBC set to allow stock to achieves B_{msy} in ~6years RBC = 0 Not set Indicative number provided for TIB dory (see FFRAG) Not set **82 tonnes** = 94 tonnes – 10 tonnes – 2 tonnes
Assessment cycle	Every year (i.e. annually) <u>Rule:</u> every year until -	Interim agreement. 1) stock reaches B_{40} at which stage this will be re-evaluated
Monitoring	Catch Effort Other data	Catch (TIB and TVH)(spatial) Effort (TIB and TVH)(not all spatial to lowest unit) WIND, Lunar Fish length-at-age (previous 2000-2002)
Assessment	Age-structured model (fitted to standardised CPUE)	Completed in early 2019 (data till June 2018), labelled as 2017 – fishing year

Appendix D

Torres Strait Fishery for Coral Trout

Harvest Strategy

June 2019

Australian Government
Australian Fisheries Management Authority

Torres Strait Finfish Fishery Coral Trout Harvest Strategy

Harvest Strategy

Working Document - draft

June 2019

Box 7051, Canberra Business Centre, ACT 2610 / Ph (02) 6225 5555 / Fax (02) 6225 5500 / AFMA Direct 1300 723 621 afma.gov.au

CONTENTS

GLOSSARY

Types of reference points:

Reference points	Description
Metarule	A rule that describes how the RBCs obtained from an assessment should be adjusted in calculating a recommended TAC
Target	The desired state of the stock or fishery (for example, MEY or B_{TARG})[1]
Limit	The level of an indicator (such as biomass or fishing mortality) beyond which the risk to the stock is regarded as unacceptably high[1]
MEY	Maximum Economic Yield - the sustainable catch or effort level for a commercial fishery that allows net economic returns to be maximised. In this context, maximised equates to the largest positive difference between total revenue and total cost of fishing[1]
MSY	Maximum Sustainable Yield - the maximum average annual catch that can be removed from a stock over an indefinite period under prevailing environmental conditions[1]

Abundance indicators:

Symbols	Description
B	Spawning biomass - the total weight of all adult (reproductively mature) fish in a population[1] (sometimes designated with a S)
B_0	The unfished spawning biomass (determined from an appropriate reference time point)
F or U	Fishing harvest rate, also called fishing mortality.
B_{LIM}	Biomass limit reference point - the point beyond which the risk to the stock is regarded as unacceptably high[1]
B_{TARG}	Biomass target reference point - the desired biomass of the stock[1]
$B_{CURRENT}$	The estimated biomass in the last year of the most recent assessment.

Other terms:

Acronym	Description
CPUE	Catch Per Unit Effort rate, e.g. number of fish caught per day. Often standardised, meaning a level of catch is calculated for an agreed unit of fishing effort which allows comparison between fishing operations.
HCR	Harvest Control Rule - pre-determined rules that control fishing activity according to the biological and economic conditions of the fishery (as defined by monitoring or assessment). Also called ‘decision rules’. HCR are a key element of a harvest strategy[1]

[1] Definition sourced from the *Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018)

HSP	*Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018)
HS	Harvest Strategy
PZJA	Protected Zone Joint Authority – government body responsible for decision making in Torres Strait Fisheries.
RBC	Recommended Biological Catch, also referred to as 'total kill' which is the maximum harvest that should be taken from a fishery by all users e.g. commercial fishers, recreational fishers, traditional fishing.
FFRAG	Protected Zone Joint Authority Finfish Fishery Resource Assessment Group, advisory group to the PZJA.
FFWG	Protected Zone Joint Authority Finfish Fishery Working Group, advisory group to the PZJA.
TAC	Total Allowable Catch- the annual catch limit set for a stock, species or species group. May be referred to as Total Allowable Commercial Catch (TACC). Used to control commercial harvests and fishing pressure[1]
Tiered approach	A framework that uses different control rules to cater for different levels of uncertainty about a stock
TIB, TIB Sector	Traditional Inhabitant Boat Licence holders – Torres Strait Islander commercial fishers operating in the Torres Strait Protected Zone
Sunset Licence Holders	Also referred to as Sunset Sector. These fishers lease access to the fishery from Traditional Inhabitants under a yearly 'Sunset' licence

OVERVIEW

The Torres Strait Finfish Fishery Coral Trout Harvest Strategy (HS) sets out the management actions needed to achieve the agreed Fishery objectives. The Fishery HS describes the performance indicators used for monitoring the condition of the stock, the stock assessment procedures and the rules applied to determine the recommended biological catch (RBC) and the total allowable catch (TAC) each fishing season.

The HS uses a stock assessment (age-structured model) that is very dependent on a single abundance index at this stage (standardised Catch Per Unit Effort – CPUE) from the TVH (Sunset) fleet daily fishing logbooks. The RBC is the best available scientific advice on what the total fishing mortality should be for the stock.

The HS meets the requirements of the *Commonwealth Fisheries Harvest Strategy Policy: Framework for applying an evidence-based approach to setting harvest levels in Commonwealth fisheries* (June 2018) (HSP) by applying a precautionary approach to the reference points and measures to be implemented in accordance with the reference points. This is reflected in the use of proxy reference points that are more precautionary than those specified in the HSP in line with stakeholder advice in the formation of this HS. The Harvest Control Rule (HCR) is designed to decrease exploitation rate as the stock size decreases below the target reference point. The HS uses a biomass target reference point (set in the short-term) that takes account of the fact that the resource is important for the traditional way of life and livelihood of traditional inhabitants and must be biologically and economically acceptable. The target reference point also takes account of the fact that the coral trout stock is underutilised at present by the TIB commercial sector and is mainly leased to TVH (sunset sector) fishers. The HS proxies are B_{LIM} is 20% of B_0, B_{TARG} is 60% of B_0.

Given the present available data FFRAG has recommended that a stock assessment should be conducted during the 2021-22 season, once further data is available, ahead of setting catch limits for the 2022-23 season. Postponing the stock assessment for three years would allow enough time for additional data to be included. A recommendation was tabled to trigger a stock assessment based on two empirical rules (each examined annually (see Section 2.8)). Further work for the HS will likely include the proposal to collect more data. This approach would likely suit the needs of the fishery with increased participation of TIB commercial fishers or increased leasing of access to non-traditional inhabitant fishers (TVH sunset fishers).

1 BACKGROUND

This Torres Strait Finfish Fishery Coral Trout (CT) Harvest Strategy (HS) has been developed in accordance with the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines* (HSP, 2018) and consistent with objectives of the *Torres Strait Fisheries Act 1984* (the Act).

Importantly the HS has been designed to have regard for traditional knowledge and the ability of communities to manage fishery resources locally, through acknowledging and incorporating customary and traditional laws, recognising; Malo Ra Gelar, Gudumalulgal Sabe Maluailgal Sabe Kulkalgal Sabe.

The strategy takes into account key fishery specific attributes including:

a) Commercial fishing by traditional inhabitants is important for local employment, economic development and for the passing down of traditional knowledge and cultural lore. Enough fish needs to be left in the water for fishers to make money and to protect the traditional way of life and livelihoods and cultural values;

b) The most recent stock assessment is preliminary and the last time an assessment was undertaken was part of a management strategy evaluation project (Williams *et al.* 2007);

c) Since the 2007 industry buyback there has been limited effort in the fishery and the available total allowable catch has been under-caught;

d) Coral Trout is a resource fished by many different users and is important for subsistence, traditional, and commercial sectors alike;

e) there is still risk of local depletion of any of the four species in the Coral trout 'species group' as the existing assessment model assumes all four species are one stock (as did Williams *et al.* 2007).

1.1 COMMONWEALTH FISHERIES HARVEST STRATEGY POLICY

The objective of the HSP is the ecologically sustainable and profitable use of Australia's Commonwealth commercial fisheries resources (where ecological sustainability takes priority) - through implementation of harvest strategies.

To pursue this objective the Australian Government will implement harvest strategies that:

a) ensure exploitation of fisheries resources and related activities are conducted in a manner consistent with the principles of ecologically sustainable development, including the exercise of the precautionary principle

b) maximise net economic returns to the Australian community from management of Australian fisheries - always in the context of maintaining commercial fish stocks at sustainable levels

c) maintain key commercial fish stocks, on average, at the required target biomass to produce maximum economic yield from the fishery

d) maintain all commercial fish stocks, including byproduct, above a biomass limit where the risk to the stock is regarded as unacceptable (B_{LIM}), at least 90 per cent of the time

e) ensure fishing is conducted in a manner that does not lead to overfishing - where overfishing of a stock is identified, action will be taken immediately to cease overfishing

f) minimise discarding of commercial species as much as possible

g) are consistent with the *Environment Protection and Biodiversity Conservation Act 1999* and the *Guidelines for the Ecologically Sustainable Management of Fisheries*.

For fisheries that are managed jointly by an international organisation or arrangement, the HSP does not prescribe management arrangements. This includes management arrangements for commercial and traditional fishing in the Torres Strait Protected Zone, which are governed by provisions of the Torres Strait Treaty and the *Torres Strait Fisheries Act 1984*. However, it does articulate the government's preferred approach.

The HSP provides for the use of proxy settings for reference points to cater for different levels of information available and unique fishery circumstances. This balance between prescription and flexibility encourages the development of innovative and cost effective strategies to meet key policy objectives. Proxies, including those that exceed the minimum standards, must be demonstrated to be compliant with the HSP objective.

With a harvest strategy in place, fishery managers and stakeholders are able to operate with pre-defined rules, management decisions are more transparent, and there are likely fewer unanticipated outcomes necessitating hasty management responses. However, due to the inherently natural variability of fish abundance there may be a need for significant changes in recommended catch on an annual basis.

1.2 DEVELOPMENT OF THE HARVEST STRATEGY FOR CORAL TROUT

The HS has been developed in consultation with the FFRAG the FFWG through a number of meetings from 2017 to 2019[2].

Further updates to this report were made on the basis of recommendations from two dedicated industry Harvest Strategy meetings (Torres Strait Finfish Harvest Strategy

[2] (meeting no. 1 on 9-10 November 2017; meeting no. 2 on 22-23 March 2018; meeting no. 3 on the 19-20 of November 2018; and meeting no. 4 on 13 and 14 March 2019) and FFWG (meeting no. 1 on 16-17 March 2017 and meeting no 2 - 22-23 March 2018).

Meeting, 11-12th June 2019 and Torres Strait Finfish Harvest Strategy Meeting: Combined Resource Assessment Group and Working Group Meeting, 27th -28th June 2019).

2 FINFISH FISHERY FOR CORAL TROUT HARVEST STRATEGY

2.1 SCOPE

This HS applies to the Torres Strait Finfish Coral Trout Fishery (see Patterson et al. 2019) and it takes into account different users of the fishery including TIB fishers, Sunset fishers and those fishing for traditional purposes.

The HS outlines the control rules used to develop advice on the recommended biological catch (RBC) and to recommend total allowable catches (TACs) (an enforced limit on total catches). The HS sets the criteria that pre-agreed management decisions will be based on in order to achieve the HS objectives meaning that a consistent approach to management will be applied over time.

2.2 OBJECTIVES

The operational objectives of the Coral Trout Harvest Strategy are to:

a) maintain the stock at current levels given the assessment is preliminary (the rationale also being Industry were supportive of a conservative B_{TARG} for the stock and in general managing the fishery at a level which leaves more fish in the water than a straight MSY target rate)[3].

b) maintain stocks above the limit biomass level (B_{LIM}), or an appropriate proxy, at least 90 per cent of the time;

c) reduce fishing levels if a stock is below B_{TARG} but above B_{LIM}; and

d) implement rebuilding strategies, if the stock moves below B_{LIM}.

Broader fishery level objectives are outlined in the Finfish Management Plan (Australian Government 2013).

2.3 RECOMMENDING TACs FROM RBCs

The RBC is the recommended total catch (or total kill) of coral trout that can be taken by all users of the Fishery. The HSP states that when setting the TAC for the next fishing season the HS should take into account all sources of fishing mortality.

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[3] Stakeholders were supportive of a target that can take into account the patchiness of the stock (small areas with good trout catch rates separated by large areas of desert), the preliminary nature of the stock assessment, the risk of localised depletion, the basket of four species and that a proportion of the stock is not available.

The HS includes catches taken by non-commercial fishing sectors, for example traditional Islander harvest and commercial TIB harvest.

The HS may be updated in the future to account for changing circumstances in the Fishery, the review provisions are described in Section 2.12.

2.4 MONITORING

There is no ongoing monitoring strategy in place to collect biological or economic information.

Fishery independent surveys

No current fishery independent surveys are funded for Coral trout though FFRAG has given preliminary consideration to the data needs for the fishery including the merits of an underwater visual survey for the Torres Strait.

Catch and effort information

Fishers in the Sunset Sector are required to record catch and effort information in the Torres Strait Daily Fishing Log[4]. The following data is recorded for each TVH fishing operation: the port and date of departure and return, fishing area, fishing method, hours fished and the weight of retained fish. All commercial catch taken by fishers in the Traditional Inhabitant Boat (TIB) sector must be unloaded to a licensed Torres Strait Fish Receiver and weighed and reported at the point of unload through the Torres Strait Catch Disposal Record. Effort reporting through this Fish Receiver System remains voluntary and TIB catch rate data is not used in the present assessment.

Sunset licence holders data from Daily Fishing Logs are used in the stock assessment to compute the annual mean catch rates of fish abundance. Generalised linear models standardised the catch rates of over the period of 1992-2017 to account for factors such as boat effects.

2.5 STOCK ASSESSMENT MODEL

The stock assessment model was first developed in 2018 (it is preliminary) and is an age-structured model based on similar application to the Queensland East Coast stock (see Leigh *et al*. 2014). It is a widely used approach for providing RBC advice and the associated uncertainties.

The model integrates all available information into a single framework to assess resource status and provide a RBC. The model is fitted to TVH catch per unit effort (CPUE) data which has been standardised. A stock-recruitment relationship is used, allowing for annual fluctuation about the average value predicted by the recruitment curve. The model is fitted to the available abundance indices by maximising the likelihood function. Quasi-Newton

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[4] Copies of Torres Strait reporting forms are available here: https://www.afma.gov.au/fisheries-services/logbooks-and-catch-disposal

minimisation is used to minimise the total negative log-likelihood function (using the package AD Model Builder™) (Fournier *et al*. 2012).

2.6 HARVEST CONTROL RULE

There is no current agreed harvest control rule. The FFRAG recommended that the current constant RBC of 134.9 tonnes be adopted as the interim RBC until the stock assessment is updated. The current preliminary assessment indicates the stock is greater than 80% of B_0. In the future the harvest control rule (HCR) would recommend a harvest level (as a recommended biological catch -RBC) on the basis of evaluating the resource status.

2.7 REFERENCE POINTS

The HS reference points are:

a) The unfished biomass B_0 is the model-estimate of spawning stock biomass in 1950 (start of the Fishery). $B_0 = B_{1950}$.

a) The target biomass B_{TARG} is the spawning biomass level equal to 60% of B_0 to take account of the fact that the resource is important for the traditional way of life and livelihood of traditional inhabitants, is leased to sunset licence holders and the target biomass level must be biologically and economically acceptable.

b) The current agreed B_{TARG} is based on the assumption that B_{MSY} is 50% of B_0 for this species and B_{TARG} should be set at 1.2 B_{MSY}.

c) The limit biomass B_{LIM} is the spawning biomass level below which the risk to the stock is unacceptably high and the stock is defined as ‘overfished’. B_{LIM} is agreed to be half of B_{TARG}, B_{LIM} = 0.20 B_0. In this case –it is set to the agreed proxy accepted in other fisheries where there is uncertainty.

   - The agreed B_{LIM} is set to the default proxy HSP B_{LIM}.

d) If the limit reference point (B_{LIM}) is triggered then the Fishery will be closed.

Decision rules have yet not been established for utilization related performance metrics such as future ‘target’ catches or ‘target’ catch rates per primary vessel or per TIB dory day.

Rational for reference points

The HSP recognises that each stock/species/fishery will require an approach tailored to the fishery circumstances, including species characteristics. The HSP identifies that the selection of reference points within harvest strategies need to be realistic with respect to the scale or nature of the fishery and the resources available to manage it. Reference points should be set at levels appropriate to the biology of the species and the proper functioning of the broader marine ecosystem. Further, stocks that fall below B_{LIM} will be subject to the recovery measures stipulated in the HSP. A number of adaptive management approaches may be used to deal with this.

The Fishery is characterised by low effort and a catch that is below the set Total Allowable Catches. A B_{60} target reference point was recommended on the basis of the following rationale:

- Techinical advice that there is a case for using B50 as a proxy for BMSY, rather than B40, based on trout being a longer-lived species, managed as a basket of four species.
- Therefore 1.2 times the B50 BMSY proxy equals a B60 target reference point.

The unfished biomass (B_0) is calculated within the stock assessment model, the value of unfished biomass and target biomass have therefore varied over time in response to annual data updates and model parameter settings and estimates. Estimates of unfished biomass and target biomass are particularly sensitive to changes to parameter *h*, which determines the steepness of the stock-recruit relationship. The biomass limit reference point (B_{LIM}) is 20 per cent of unfished biomass. This is set as the HSP proxy of 20 per cent of unfished biomass.

2.8 HCR AND ASSESSMENT CYCLE

Given the present available data FFRAG has recommended that a stock assessment should be conducted during the 2021-22 season, once further data is available, ahead of setting catch limits for the 2022-23 season. Postponing the stock assessment for three years would allow enough time for additional data to be included. The additional data priorities are:

a) the 1994-95 CSIRO fish survey data which may form a valuable baseline datum;
b) improved catch and effort data from TIB fishers; and
c) fishery independent data such as an underwater survey or biological sampling.

The use of empirical trigger reference points was recommended for the years between stock assessments. The agreed trigger reference points will use standardised CPUE data as a proxy for biomass and the yearly fishery catch data to ensure the maximum yield of the fishery zones are not being exceeded.

The specific trigger points for when an assessment would be undertaken the next season are:

a) In line with the recommended target reference point (B TARG = B60) and taking into account the conservative approach preferred by industry, if the biomass of coral trout is less than B_{60} (B TARG) then an integrated stock assessment will be conducted. To determine the biomass level, this trigger will use CPUE data as a proxy for biomass. It was agreed that the average CPUE from 2012 until 2017 (inclusive) would be used as an indicative reference point of the CPUE at B_{80} (average = 120.8 kg per vessel per day) from which the CPUE at B_{60} can be calculated and used as the trigger reference point. Given the ratio of 80:60 is equal to 0.75 then the trigger reference point which would activate the rule that an assessment must be undertaken is: *if the standardised CPUE falls below 90.6 kg per (primary) vessel per day* (computed as 0.75*120.8 = 90.6).

b) If the combined yearly total catch of the four coral trout species from both commercial sectors is greater than 90 tonnes. Ninety tonnes was agreed because this 2/3 of the current constant RBC of 134.9 tonnes.

If either (a) or (b) above occurs, the stock assessment must be repeated the following year in order to monitor the condition of the stock.

2.9 DATA SUMMARY

The annual data summary reviews the catch per unit effort (CPUE) from the TVH sector, as well as total catch from all sectors. The data summary is used as an indicator to identify if catches correspond to the TAC, and to monitor CPUE.

2.10 DECISION RULES

The decision rules for the HS are:

Biomass target reference point triggered

- The HCR takes the current status of the resource (based on the most recent assessment outcomes) into account and on the basis of this determines the exploitation rate; however the current stock is above the target. The assessment is also to preliminary in order to evoke this rule at this stage.

Biomass limit reference point triggered

- If the HCR limit reference point is triggered the fishery is closed and subject to rebuilding strategy.
    - The nature of the rebuilding strategy will be determined on the basis of the stock assessment (to be applied immediately) and the rate of recovery (i.e. number of years to achieve a Biomass that is greater than B_{LIM}) in line with the HSP.
- If the HCR limit reference point is triggered two years (or more) in a row, a stock assessment must be conducted annually.

Fishery closure rules

- If the stock assessment determines the stock to be below the biomass limit reference point, the Fishery will be closed to fishing.

Re-opening the Fishery

- Following closure of the Fishery, the Fishery can only be re-opened when a stock assessment determines the Fishery to be above the biomass limit reference point.

Based on the decision rules, there are a number of alternative possible scenarios that may occur under the application of the HCR which at this stage are still being evaluated. These will be determined when the next assessment is undertaken.

2.11 GOVERNANCE

The status of the Coral Trout Fishery and how it is tracking against the Harvest Strategy Framework (HSF) is reported to the FFRAG, FFWG and the PZJA as part of the yearly RBC (and TAC) setting process.

2.12 REVIEW

Under certain circumstances, it may be necessary to amend the harvest strategy. For example if:

a) there is new information that substantially changes the status of a fishery, leading to improved estimates of indicators relative to reference points; or

b) drivers external to management of the fishery increase the risk to fish stock/s; or

c) it is clear the strategy is not working effectively and the intent of the HSP is not being met; or

d) alternative techniques are developed (or a more expensive but potentially more cost-effective harvest strategy that includes surveys and annual assessments is agreed) for assessing the fishery, the HS may be amended to incorporate decision rules appropriate for those assessments.

2.13 REFERENCES

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Appendix E

Torres Strait Coral trout Assessment

June 2019

Preliminary Stock Assessment for Coral Trout in Torres Strait

Matthew H. Holden and George M. Leigh

Coral trout data collation

We used six different data sources to perform the stock assessment: (1) commercial logbook data from AFMA, (2) commercial logbook data from Queensland, (3) Traditional Inhabitant Fishing Boat (TIB) freezer data from Murray Island, (4) TIB freezer data from JCU, (5) a general TIB freezer data set, and (6) docket book TIB data. The logbook data sets provide standardized estimates of catch per unit effort (CPUE), whereas the freezer data are not of sufficient quality for this part of the analysis. However, all datasets were included in the total catch estimates input into the stock assessment model. We note that the freezer and docket book TIB data sets probably include duplicate records with no way to tease apart duplication. We discuss how we accounted for this in the section "Modelling TIB catch".

For total catch estimates we used the latest data (described above) from 1992 forward. From 1965 to 1991 we used the estimates from Figure 6 in the Evaluation of the Eastern Torres Strait Reef Line Fishery by Williams *et al.* (2007).

Coral trout CPUE analysis methods

We used a generalized linear model to estimate the CPUE accounting for vessel, spatial, and seasonal effects.

Currently, AFMA and Qld datasets do not consistently report the number of dories used in each record. The AFMA dataset does not record the number of dories or the number of trips taken by these dories. The Qld data, on the other hand, does report the number of dories. Additionally, the number of crew is reported only in the Qld data set. Inconsistencies and systematic differences in the logbook could bias the CPUE estimates. Therefore we performed the CPUE analysis without explicitly including the numbers of dories and crew, and we absorbed these factors into the vessel ID factor. This analysis embodies the assumption that there is no consistent trend for individual vessels to use greater or lesser numbers of dories and crew over time.

We measured catch in *kg* whole weight rather than numbers of fish, as this was the most consistently reported quantity. In the relatively small number of cases where numbers were reported instead of weight, we performed a conversion using the average weight of coral trout in the AFMA database records that include both weight and the number of fish.

Potential duplicate data entries are a concern in these data sets. There are many complete duplicate rows and also many records with most entries the same (e.g., *boat ID*, *date*, *location, catch*) but different "*weight.factor*" entries. It is difficult to decide whether these are duplicates or instances where fishers split their reported catch evenly between different types of weight factors (e.g., *fillet or whole fish*). We decided to include these entries because we believe that the latter is the more likely hypothesis, and therefore including these data reflects a more accurate estimate of harvest. Therefore, for the Queensland dataset we decided to treat each row of the dataset as a duplicate only if all of the following entries were the same, that is: *date, retained weight, species code, species grade, license number, and weight factor*.

Similarly, for the AFMA data, duplicates were considered rows with the same vessel name, date, estimated *kg* kept, species code, and weight conversion code. Duplicates were removed from the CPUE analysis.

Logbook data from charter fishers and commercial fishers targeting other species were excluded from the CPUE standardization because they do not provide consistent measures of effort. However, their total catches are input into the stock assessment model. To do this we excluded all entries that did not use “line” fishing.

In addition, we also excluded records from any fisher who only fished for one year or caught less than one tonne of fish over all logbook records in the data set.

QLD logbooks recorded data up to 2006 and AFMA logbooks ran from 2000 to 2017. There is a period from 2000 to 2006 where logbooks from both agencies were used. We retrieved a table mapping vessel names to fishing license numbers under the QLD management tenure. From this data we were able to identify a portion of the QLD boats by vessel name. Some of these vessel names matched vessel names in the AFMA data set. Therefore, it was possible to determine the effect of the management agency on reported CPUE. This turns out to be very important as the management agency factor did end up explaining a large portion of the variance in CPUE across the data. This result is an important contribution to better understanding the underlying nuances in the data and potentially how to account for them.

We used two different modelling approaches to take account of the regions. The first uses a model that includes all of the Torres Strait data, across all regions. It factors in region type as an independent variable which scales CPUE up or down based on the CPUE observed in that region, while controlling for other variables. This means that the effect of region on CPUE is assumed to be the same every year. In the second approach, to get a more accurate estimate for CPUE in the two regions making up 95 percent of the total catch (region: TS3 and TS5, as described in the mapping section) we ran models that consider CPUE in these two regions separately. This is preferred for getting a region-specific CPUE estimate because it can account for potential variations in CPUE in the different regions in a more flexible way; for example, CPUE trends over the years can vary between regions. The disadvantage of this method is that each region only contains a subset of the data. The implications are also profound. If productivity is estimated to be different in the regions and fishing pressure varies by region, then the management options would have to be spatially disaggregated.

We also made use of two different statistical models for CPUE:

- The quasi-Poisson model (*model 1*) which weights the data according to the conventional definition of CPUE as total catch divided by total effort in a year–region combination; and
- The lognormal model *(model 2*) which assumes that all data records are subject to the same percentage error; this model gives proportionately more weight to the smaller catch records.

Mapping data and coral trout habitat area

The Queensland coral trout assessment relies heavily on mapping data provided by the Great Barrier Reef Marine Park Authority (GBRMPA) to quantify the habitat available to coral trout. The assessment specifies three types of habitat: reef slope, reef patches and submerged reef. The GBRMPA mapping data come in two sets: “wet reef”, the outlines of which are very roughly 10 m deep, and “dry reef” or more correctly “reef flat” which is much closer to sea level (Hopley *et al*. 2007, p. 140).

One recent mapping data set is available for the Torres Strait, as a result of the extensive research project by Lawrey and Stewart (2016). This data set was intended to provide wet reef outlines but occasionally these were too deep or the water was too turbid for them to be distinguished in satellite images (Eric Lawrey, AIMS, personal communication). The result is a data set that usually provides the equivalent of wet reef but for some reefs is more similar to dry reef.

We use the mapping data (from the study referenced above) to quantify habitat in Torres Strait and also use abundance data from the Great Barrier Reef (GBR) (e.g., underwater visual surveys) to infer the absolute abundance of coral trout in Torres Strait (measured as the number of adult fish per hectare). The absolute abundance data come from the extensive series of underwater visual surveys conducted on behalf of GBRMPA in the mid-1980s (Ayling and Ayling 1986).

From satellite photographs we divided the Torres Strait region into seven zones of different perceived reef types, as shown in Figure 1 below. Our classification of habitat types based on satellite photographs agrees closely with results of Haywood *et al*. (2007) that was based on surveys of biota, especially coral types. There may be scope to refine our classification in future, based on their data; however for now the demarcation should be reasonably robust to all the co-variates. Not all of the zones we defined are open to fishing for finfish.

We initially envisaged that most of the fishing for coral trout would have taken place in Region 5, which has large amounts of suitable coral trout habitat in reef patches and submerged reef. Region 3 appears to consist largely of planar reefs that have been infilled by coral debris, while Region 6 contains barrier reefs which serve to shelter the mid-shelf reefs in Regions 5 and 3 from large waves. While the results from the catch analysis below did confirm our hypothesis that Region 5 would provide significant coral trout habitat and therefore catch, Region 3 also generated high catch. This may be due to access and/or choice of fishers in terms of fishing ground preference. Preliminary analysis (see below) indicates that this Region 3 has the highest catch per unit effort (despite lower total harvest size than Region 5). The habitat area in each of the major Torres Strait fishery regions was inferred from:

- the corresponding total reef area in the region, as given by the mapping data, and
- the ratio of habitat area to total reef area in a northern GBR region that has similar reef morphology to the Torres Strait region.

As in the Queensland coral trout stock assessment (Leigh *et al.* 2014), we express habitat area as equivalent reef slope area. The Queensland assessment found that reef slope was the most productive habitat, followed by reef patches and submerged reef. An assumption in our methodology is that the proportions of reef slope, reef patches and submerged reef in a Torres Strait region were the same as in a northern GBR region with similar reef morphology. The southern GBR has high tidal ranges (see Leigh *et al.* 2014, Figure 5, page 13) so we regarded it as a less suitable comparison to Torres Strait.

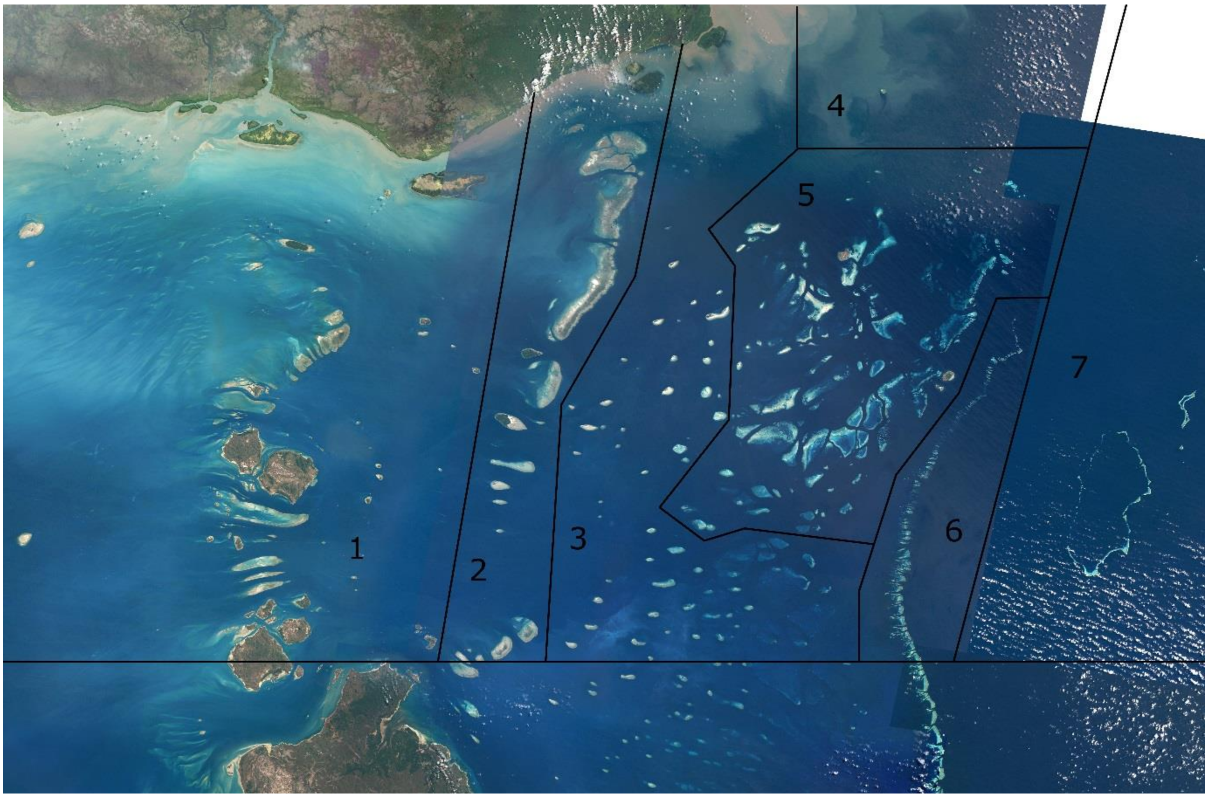

Figure 1: Landsat satellite image of Torres Strait, with numbered Regions shown. Source: eAtlas, www.eatlas.org.au, *originally from LandSat,* http://landsat.usgs.gov, *Creative Commons by Attribution licence.*

Total harvest size results

In this section we discuss the total harvest size and further describe the catch data for the Torres Strait broken down by region and data source.

Total catch was considerably higher prior to 2005 than it was after 2005 (Figure 2). Consistently, across all years, region TS5 provided the majority of harvest according to the logbook data, making up roughly 72% of the total harvest size in the fishery. Region TS3 makes up an additional 24%. All other regions, combined, make up less than 5% (Figures 3 and 4). This trend is consistent even across management agencies (compare the green dotted crosses and dashed diamonds to all other curves in Figures 3 and 4 to see this).

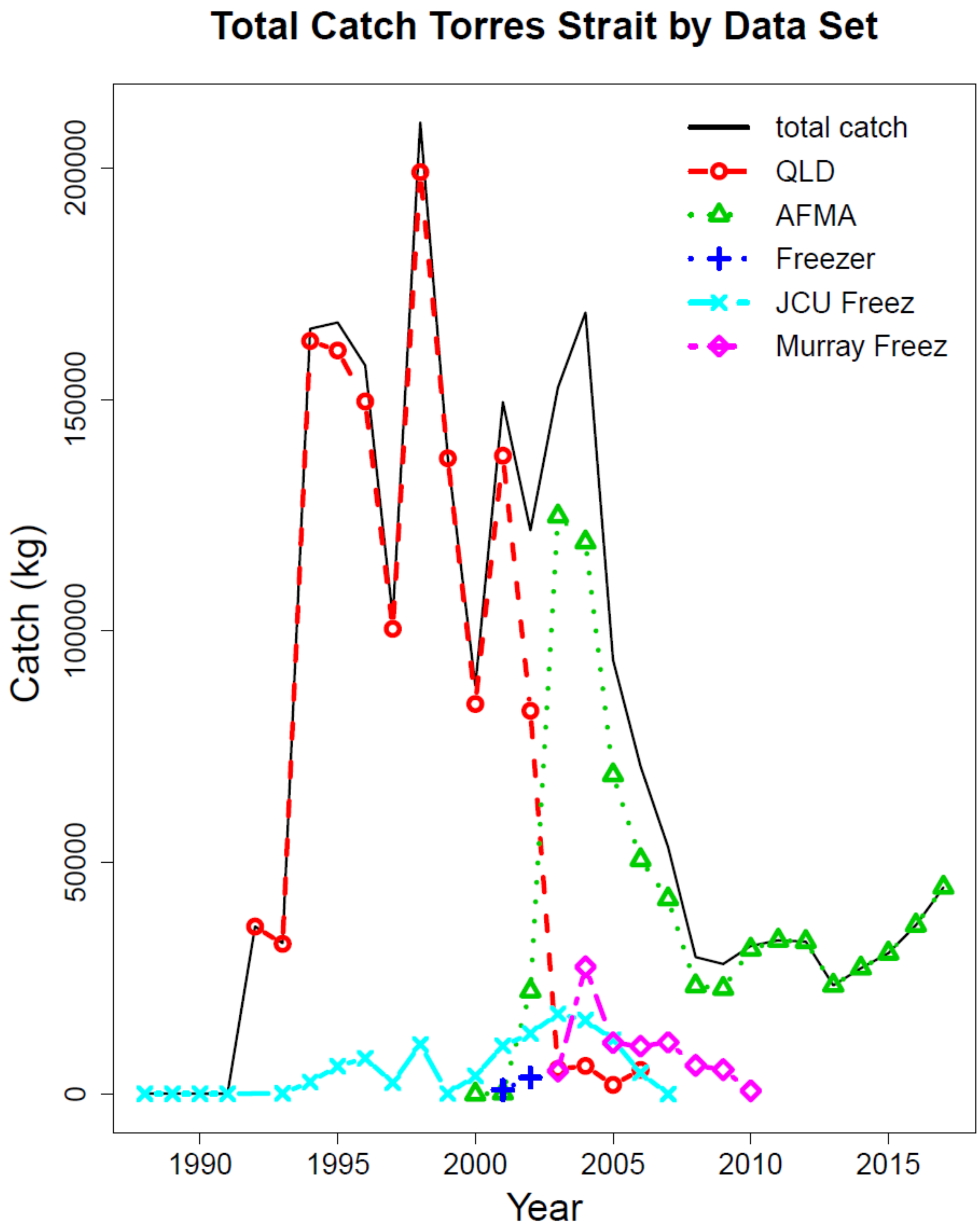

Figure 2: Total harvest size for different data sources summed over all regions in Torres Strait

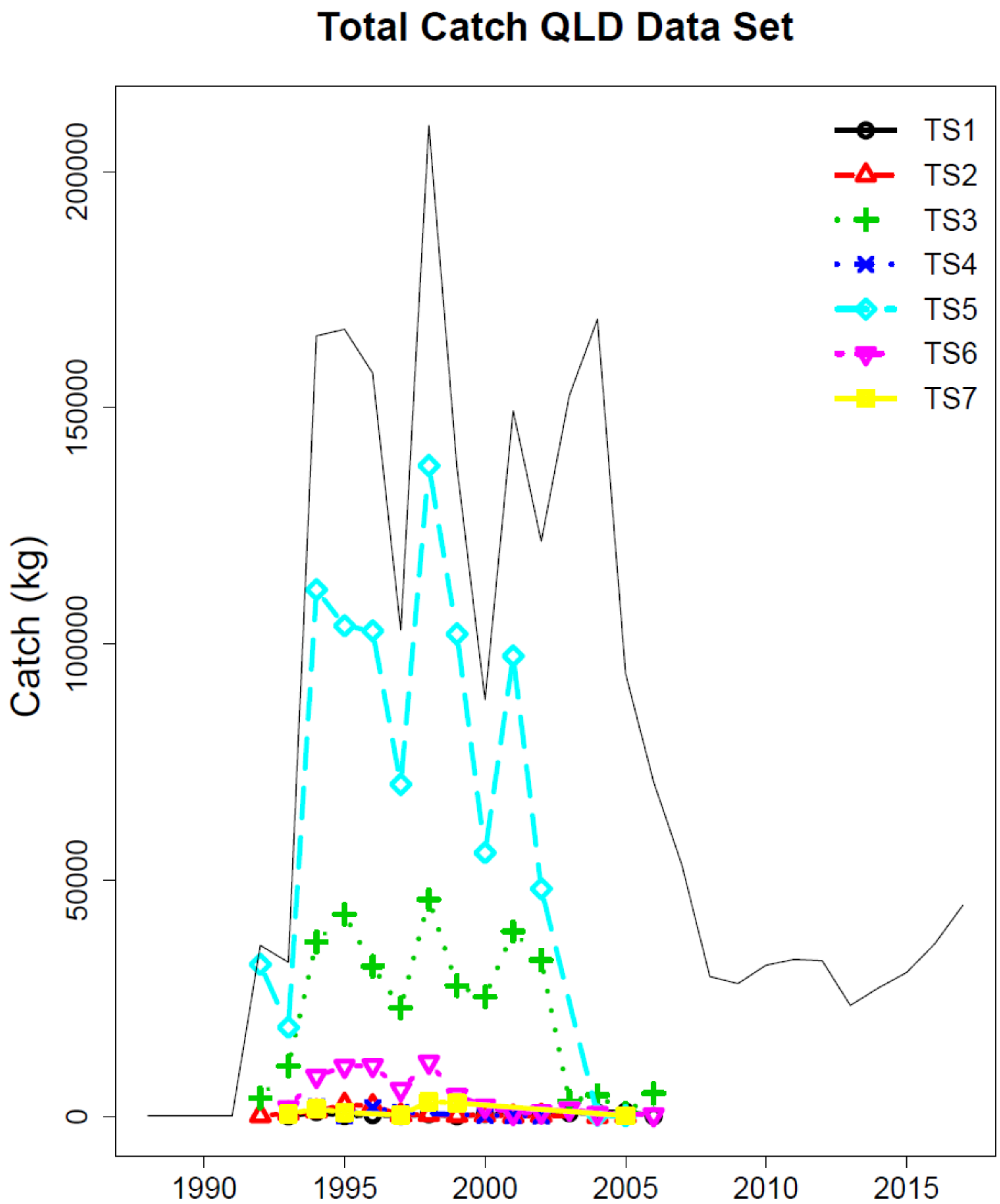

Figure 3: Total catch size for the QLD dataset for different regions. Note that TS5 and TS3 make up the vast majority of the harvest.

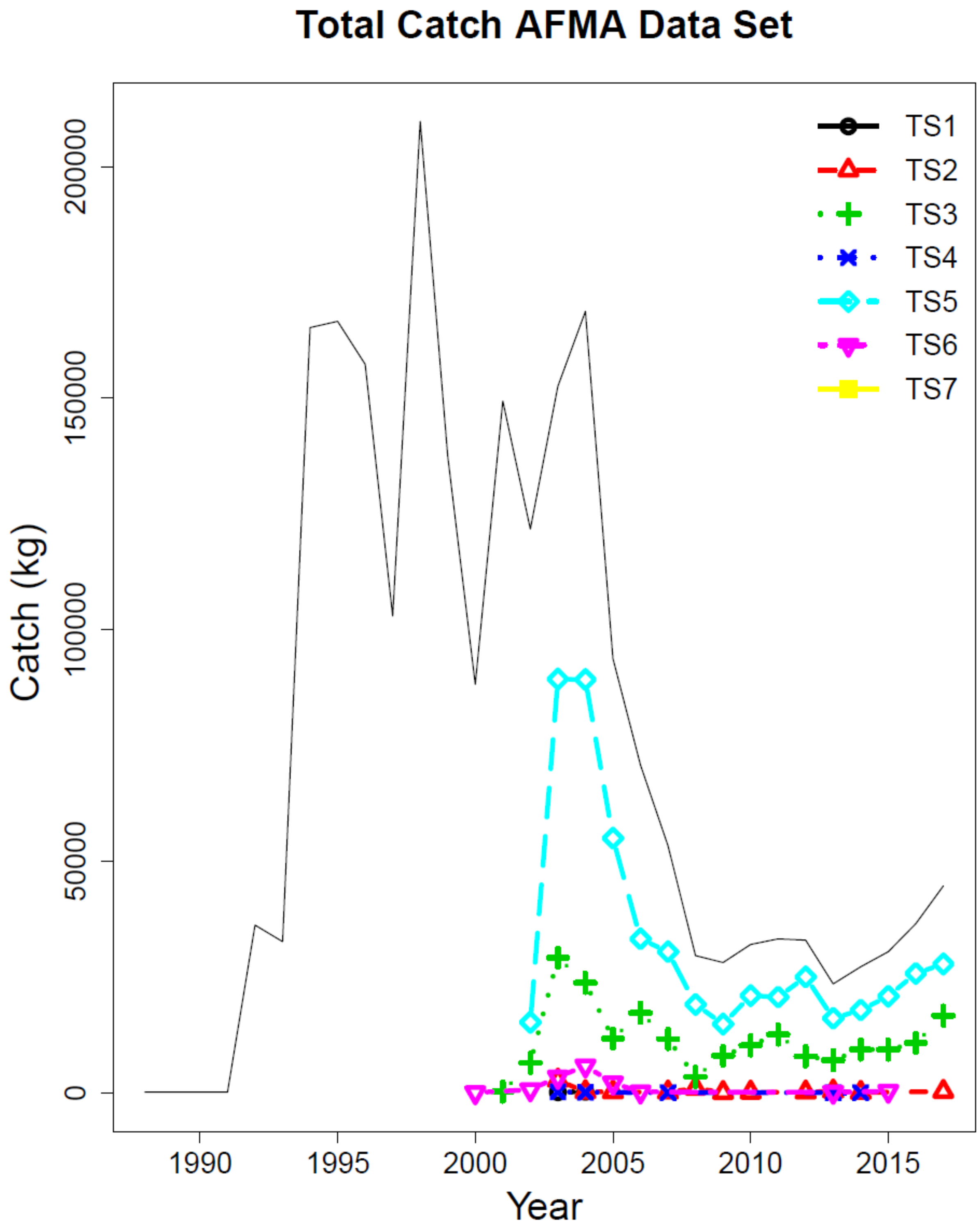

Figure 4: Total harvest size for the AFMA dataset for different regions. Note that TS5 and TS3 make up the vast majority of the harvest (as with the QLD dataset shown in Figure 3).

Modelling TIB catch

We also had docket book data for TIB fishers (Figure 5). But because the freezer data sets and docket book data sets likely contain duplicates it is inappropriate to sum these data sets to get total catch from TIB fishers. We therefore chose to model TIB catch. We considered two hypotheses that TIB fishers removed a fixed amount of fish each year or that TIB fishers removed a proportion of the sunset fisher catch each year. We tested these hypotheses using a linear model and found much greater support for the proportional catch model. Additionally, assuming the freezer data is complete during the years where the freezers were running, then the models suggest that the docket book data is 4.2 times lower than the actual catch. Therefore, when accounting for TIB data, when freezer data was unavailable for certain years we used 4.2 times the docket book catch for that entry.

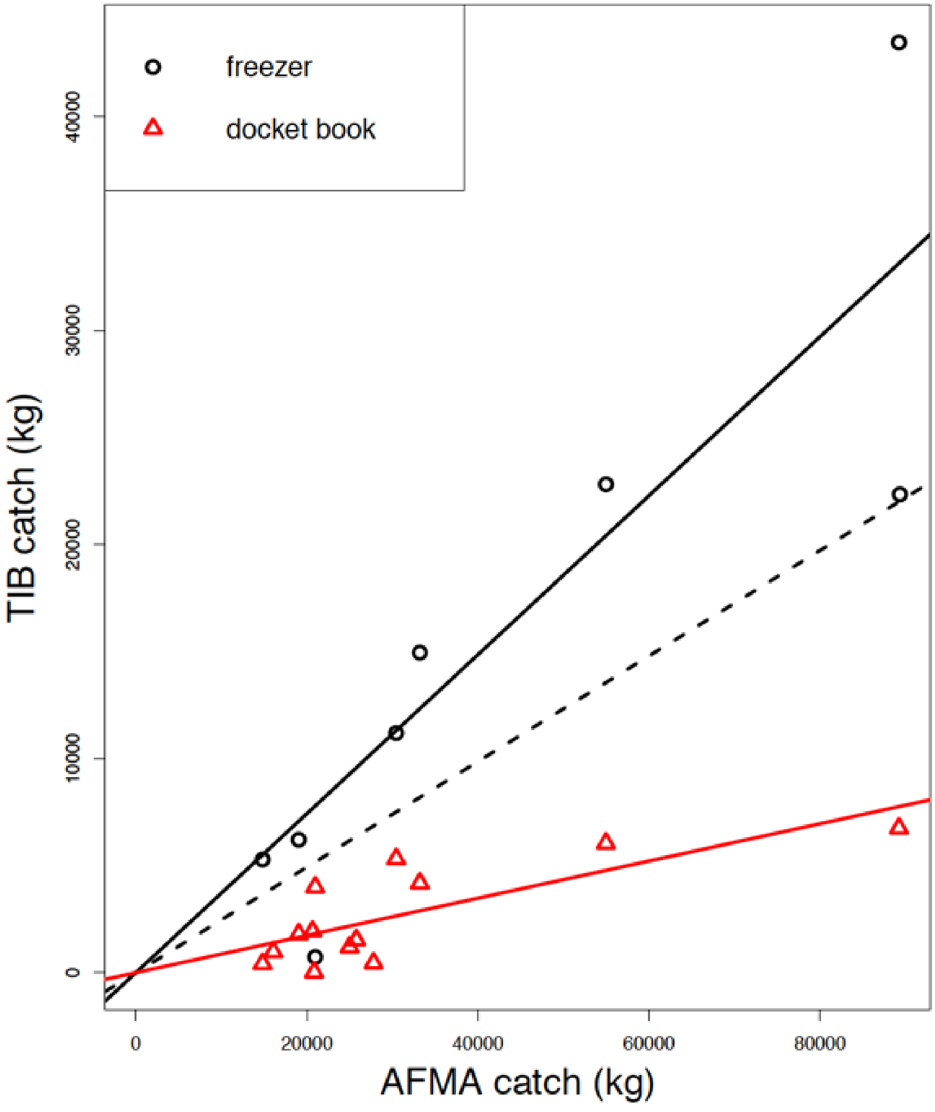

Figure 5: TIB catch from the freezer data set (circles) and docket book data set (triangles) vs sunset fisher catch in the AFMA data set. The lines are the best fitting linear models of TIB catch as a function of AFMA catch. Note that the slope of the line from the model using only the freezer data (black) is 4.2 times higher than the slope from the model using only the docket book data (red).

CPUE (catch per unit of effort) results

In this section we present standardised CPUE for coral trout in the Torres Strait using the two different regional approaches and the two different statistical models described above.

Due to the smaller catch sizes reported in the other Torres Strait regions, it was only statistically sensible to fit the region-specific models to TS3 and TS5. In the plots below, we only plot CPUE for a given year if there are at least 50 records that year.

Overall, the CPUE peaked in 2000–2001, fell sharply to lower values in 2004–2005, rose again to a lower peak in 2009 and showed less variation after that (see Figure 6).

It is possible that the rise after 2005 was a response to much lower fishing pressure (see plots of harvest size in Figures 2, 3 and 4 above). It is difficult to explain the magnitudes of the changes in CPUE prior to 2005, although we must consider this data assumes all the catch is from one species of coral trout when in fact the catch is a suite of species. Thus, many hypotheses could explain the deviance in historical CPUE but without good data we are unable to refute any hypothesis. Local depletion on some key areas could also provide an explanation.

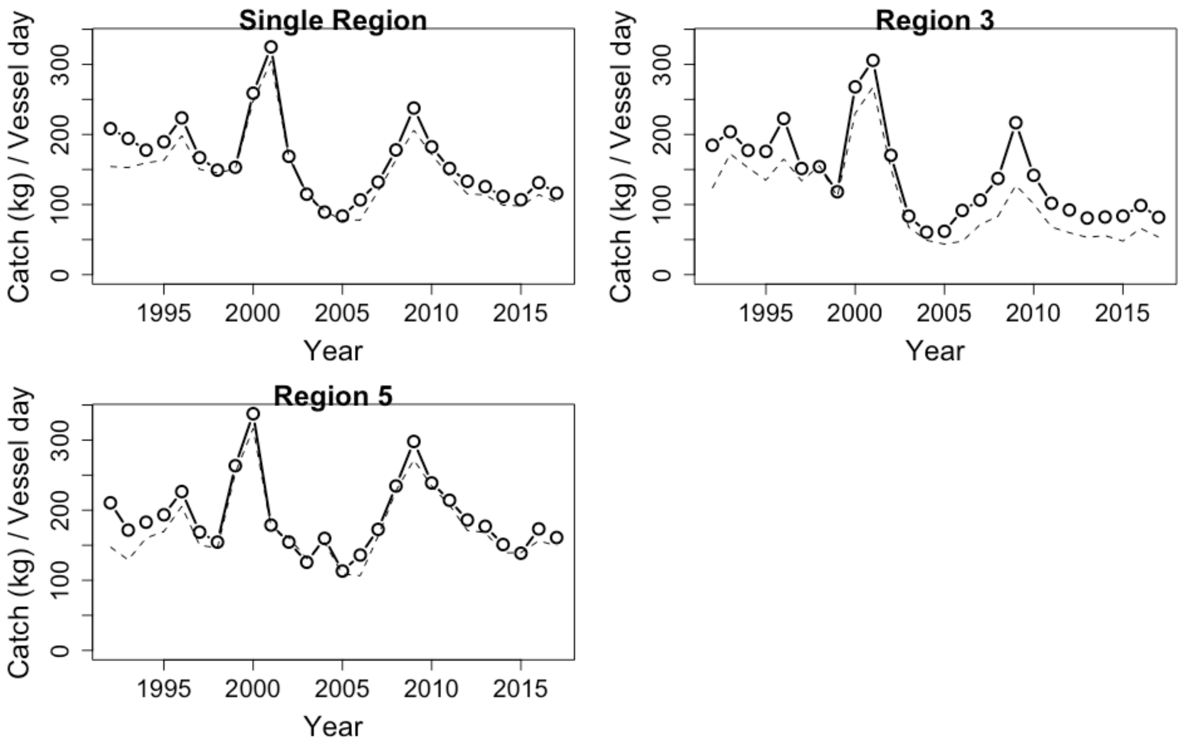

Figure 6: Standardised CPUE across all of Torres Strait and in the two regions that make up 95% of fishing. The solid line represents the results from the quasi-Poisson model (*model 1*) and the dashed line represents the results from the linear model with response log of catch (which assumes lognormal error) (*model 2*).

Habitat area results

On the basis of coral reef morphology, we judged the major Torres Strait fishing regions TS3 and TS5 to be similar to the northern parts of the following Great Barrier Reef Bioregions (see Figure 1 above and Figure 7 below):

- TS3 was judged similar to Bioregion RC2 (mid-shelf reefs between Cape York and 12.5 degrees south) (see Leigh *et al.* 2014 – for reef codes, maps and definitions, and Figure 7 and noted reference in figure caption)
- TS5 was judged similar to either RG2 (mid-shelf reefs off Cairns and Townsville) or RG1 (mid-shelf reefs off Cooktown).

On the basis of these judgements and the mapping data from GBRMPA and from Lawrey and Stewart (2016), the habitat areas were estimated as follows (equivalent reef slope area, cf. Table 23 of Leigh *et al.* 2014, p. 82):

- TS3: 19,721 hectares
- TS5: 35,574 hectares (using Bioregion RG2) or 30,735 hectares (using Bioregion RG1).

We note that there is no fine-scale network of marine protected areas ("green zones") in the Torres Strait fishery as there is in the GBR, so all of these areas were open to fishing. As remarked above, some whole regions of Torres Strait are currently not open to fishing for finfish, but this does not affect our analysis of regions TS3 and TS5.

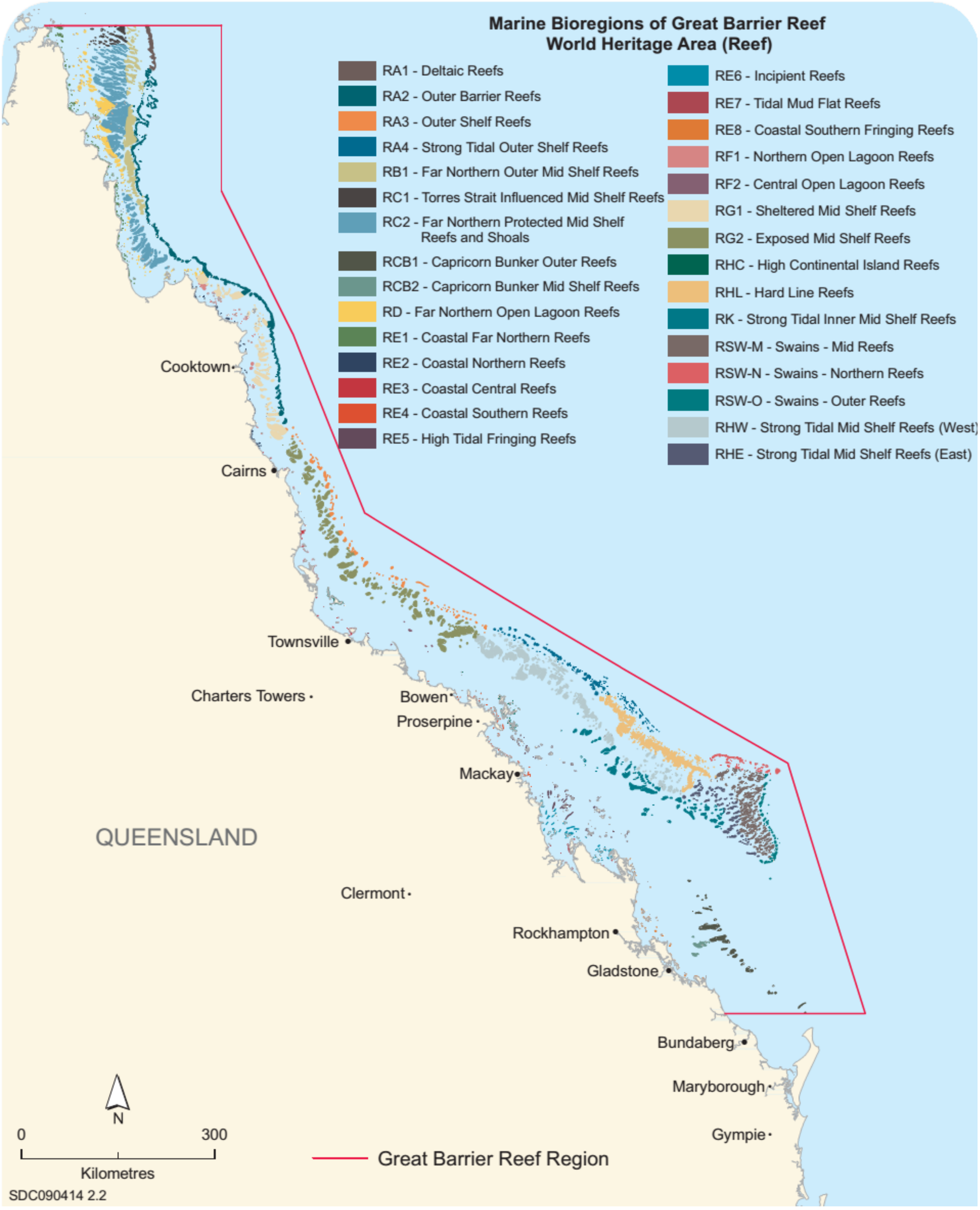

Figure 7: Reef Bioregions defined by GBRMPA expert taskforces as part of the preparation for the Representative Areas Program implemented in 2004. *Source: GBRMPA (2009).*

Stock assessment model summary

The preliminary stock assessment model for Coral Trout in the Torres Strait is taken from the model from the Great Barrier Reef (GBR). We substituted the two major Torres Strait regions (TS3 and TS5) for two of the GBR "Sub-bioregions" which had similar coral reef morphology. This was undertaken for efficacy in terms of model coding and does not impact on the model estimates. The harvest sizes, standardised CPUE time series and reef-habitat areas from the GBR model are replaced by corresponding values from the Torres Strait, as provided in the previous sections of this report. The model then generates estimates of key parameters including biomass estimates for the fishery.

For the modelling reported here region TS3 was substituted for GBR Sub-bioregion RB2 North and TS5 was substituted for GBR Sub-bioregion RG2 North. As documented above, an alternative for TS5 is Sub-bioregion RG1, and we plan to run the model with this region prior to reporting the final results of the assessment (after presenting at the Finfish RAG, and receiving peer review and feedback).

Data from the GBR were included as inputs to the model. The model produced estimates for the whole GBR (except the Sub-bioregions that were substituted for Torres Strait regions) in addition to the Torres Strait. In this way, we were able to take into account the wealth of data that were available for coral trout on the GBR. In particular, some of the absolute abundance data from the GBR underwater visual surveys were transferred to the corresponding Torres Strait regions.

The population model is a regional, age-structured, forward-prediction model. It was written in the software AD Model Builder (ADMB) (Fournier *et al*., 2012). It calculates the number of fish of each age and sex in each year, and applies harvest rates (calculated from the recorded catch sizes) and the natural mortality rate to progress forward from one year to the next. It includes calculations of length-at-age and weight-at-age. Fishing is assumed to take place as a short pulse in the middle of each calendar year. This does not exactly match the coral trout fishery, in which fishing takes place all year round, but because the coral trout are relatively long-lived we did not believe that such errors would be significant. The model specified numerical equations that are not presented here, as they are standard and are reported in detail in Leigh *et al.* (2014). Reproducing all the equations would only lengthen this report without adding any information that is not already published and easily available.

Model projections can be matched against abundance indices, age-frequency data and length-frequency data. The only abundance indices specific to the Torres Strait were the CPUE time series (see above). GBR data comprising absolute abundance indices, age-frequency data and length-frequency data were also input to the model. This, at this stage, is the "best" we can do and is reputable given the lack of data for the Torres Strait. This is also defensible scientifically, given there is not a vast geographic distance between the Torres Strait region and the northern GBR, and because we have no additional information that infers the growth rate of coral trout stocks are very different over this geographic scale.

The software ADMB, firstly estimates the model parameters by maximum likelihood (numerical approaches), which is a long-standing and widely used statistical technique. It can then run simulations using Markov Chain Monte Carlo (MCMC) to provide a random sample of potential parameter values. Confidence limits for the parameters can be constructed from the simulations.

The following special capabilities were incorporated into the model. Many of these are specific to the GBR and would not be needed if the Torres Strait were to be analysed completely independently from the GBR, but in that case a large amount of very informative data would not be used:

- Regional structure, taking into account qualitatively different Regions, Subregions, Bioregions and Sub-bioregions of the GBR, and green zones.
- Green-zone fishing parameter: This parameter was the ratio of the fishing intensity in a green zone to that in blue zones in the same Subregion. This was impossible to estimate from the available data, and, based on advice from industry and government, was set to 0.2. We expect the value of this parameter to decrease to almost zero when compulsory vessel monitoring of individual dories is introduced in Queensland over 2019–2020.
- Absolute abundance measures from underwater visual surveys (UVS): Generally, abundance measures in stock assessment are only *relative* abundance indices, which compare one year against another and do not provide information on the actual numbers of fish present. An *absolute* abundance measure specifies the actual density of fish in a population, in this case as a number of fish per hectare.
- Habitat area: The area of habitat (in hectares) of each regional population of fish provided a way to scale up the fish density (number of fish per hectare) into an estimate of population size (an absolute number of fish in a Population).
- Changes in zoning: The appropriate numbers of fish were transferred between green and blue zones in years when the zoning changed, according to the area of the rezoned habitat.
- Size limits: A reduced fishing mortality rate (the post-release mortality rate) was assumed to operate on fish that were below the minimum legal size (MLS). The model assumed that fishers released all undersized fish, but a proportion of them still died shortly after release, due to the stress of being captured, or predation upon release; this proportion was set to 25% based on previous consultations with GBR fishery stakeholders. The model made use of two different versions of the vulnerability to fishing (or selectivity of fishing): a "K" version which included only kept fish, above MLS; and a "D" version which included the mortality fraction of discards of fish under MLS. The K version was used for matching to reported harvest sizes, and the D version for all of the population dynamics.

Population dynamics: detailed model description

Overview

The description of the population dynamic model is taken from the GBR stock assessment report (Leigh *et al.*, 2014). Some details that are not important to the assessment of coral trout in the Torres Strait have been omitted. The model has a detailed regional structure involving Regions based on the GBRMPA Bioregions (see Figure 7), Subregions which split the Regions based on fishing intensity, and Sub-bioregions which split the Bioregions based on fishing intensity. Figure 8 below shows the regions and subregions used in the GBR stock assessment.

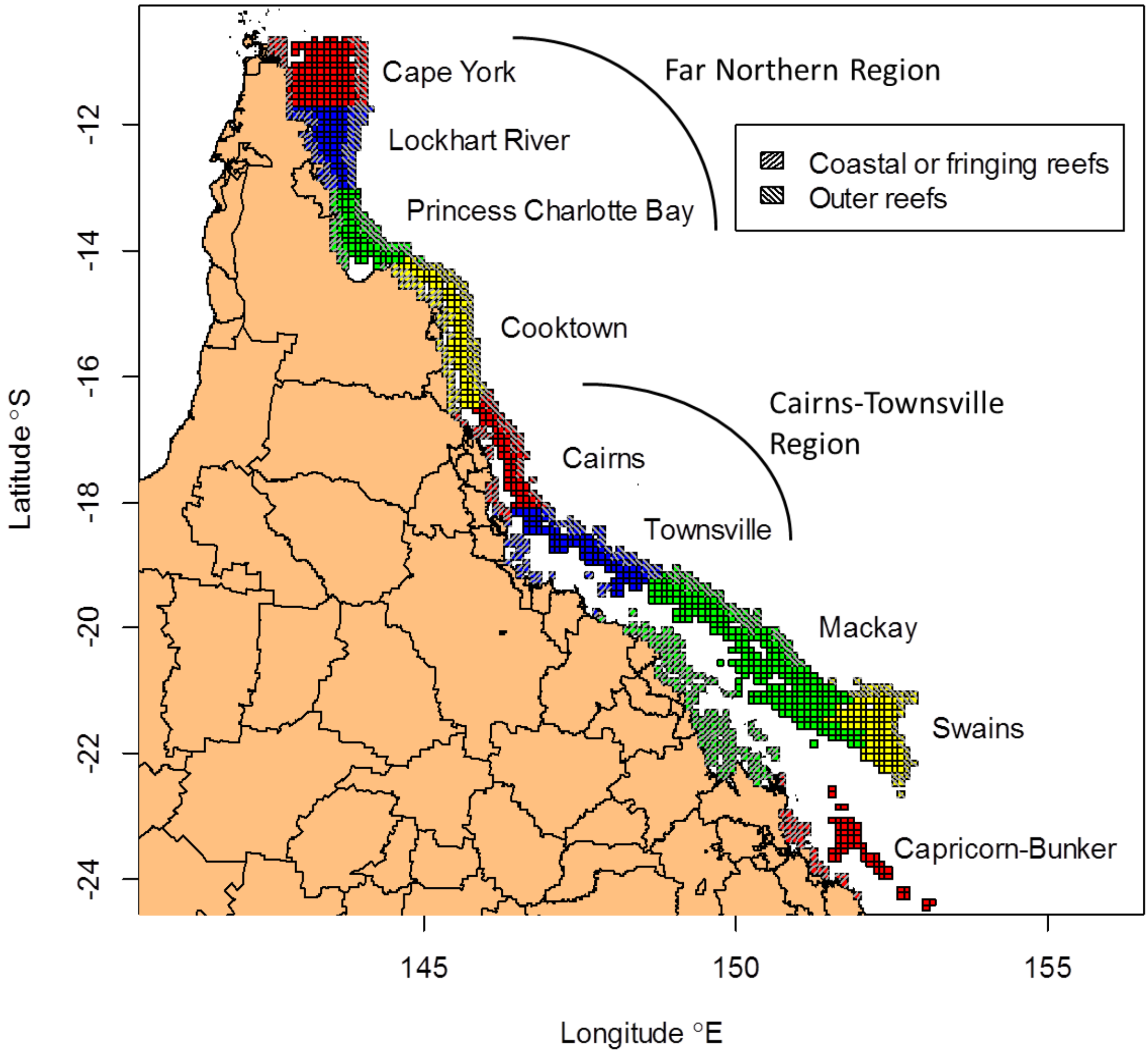

Figure 8. Regions and Subregions used in the GBR stock assessment. The Far Northern Region is divided into three Subregions, and the Cairns–Townsville Region into two Subregions. The small squares are six-nautical-mile fishery logbook grid squares. Colours are chosen only to distinguish the Regions and Subregions, and have no other meaning. The Capricorn–Bunker Region was excluded from the GBR stock assessment because fishers there did not strongly target coral trout, and underwater visual surveys showed dramatically different trends in coral trout abundance from the rest of the GBR.

The population model operated on calendar years. We believed that this structure suited the biology of coral trout whereby recruitment of new individuals to reef populations occurs in the first few months of the year (Doherty 1991; Doherty et al. 1994), and annual rings on otoliths, which are used for ageing, are laid down late in the year between July and November (Ferreira and Russ 1994). Numbers of fish N present in the model at the beginning of a year were indexed by Population (k), year (t) and age (a). Sexes were not distinguished, as coral trout change sex and the sex ratios were assumed to be socially controlled; i.e., a female fish has a greater chance of changing to male if there is a scarcity of males in the locality. Each Sub-bioregion contained two Populations, one zoned blue (open to fishing) and the other zoned green (closed to fishing). The number of fish of age zero was set as equal to the recruitment $R_{k\,t}$ to Population k in year t:

$$N_{k\,t\,0} = R_{k\,t}\,. \tag{1}$$

For ages year-one and upwards, population numbers are derived from those for the same year-class in the previous year (year $t - 1$ and age $a - 1$): for $1 \le a < a_{\max}$,

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\,e^{-M}\,(1 - V_{a-1}\,U_{k\;t-1})\,, \tag{2}$$

where $a_{\max}$ is the age of the oldest age-class in the model, M is the instantaneous natural mortality rate, V_a is the vulnerability to fishing at age a, and $U_{k\,t}$ is the harvest rate of population k in year t. The quantities $a_{\max}$, V_a and $U_{k\,t}$ are discussed in the following paragraphs.

The oldest age-class $a_{\max}$ was a "plus group", holding all fish of age $a_{\max}$ or older. The formula for it was slightly different to (2): for $a = a_{\max}$,

$$N_{k\,t\,a} = N_{k\,t-1\,a-1}\,e^{-M}\,(1 - V_{a-1}\,U_{k\;t-1}) + N_{k\,t-1\,a}\,e^{-M}\,(1 - V_a\,U_{k\;t-1})\,. \tag{3}$$

The value of $a_{\max}$ was chosen as 20 years.

The fishery was assumed to start from the virgin (never fished) state in year 1, which was calendar year 1957, five years before the Queensland Fish Board recorded any harvest of coral trout. The level of fishing before then was assumed to be negligible. The population structure in year 1 was given by, for $1 \le a < a_{\max}$,

$$N_{k\,1\,a} = R_{k\,0}\,e^{-aM}\,,$$

where $R_{k\,0}$ is the deterministic number of recruits to population k in the virgin state. For the plus group the formula took account of older fish: for $a = a_{\max}$,

$$N_{k\,1\,a} = R_{k\,0}\,e^{-aM} \big/ (1 - e^{-M})\,.$$

The vulnerability V_a is estimated in the model and represents the relative chance that a fish of age a that is present in the population will be caught by fishing.

The model used a logistic function for vulnerability as a function of length. This function gradually increases from very low vulnerability for small fish, to approach 1 for large fish:

$$V_L^* = 1\big/\left[1 + \exp\left\{-(\log 19)\,(L - L_{50}) / (L_{95} - L_{50})\right\}\right], \tag{4}$$

where L_{50} is the fork length at 50% vulnerability and L_{95} is the fork length at 95% vulnerability (see Haddon, 2001, p. 353); both L_{50} and the parameter $L_{95\,\text{diff}} = L_{95} - L_{50}$ were estimated in the model. The asterisk distinguishes length-dependent vulnerability V_L^* from age-dependent vulnerability V_a . The conversion factor of 0.9409 was used to convert total length to fork length.

Length-dependent vulnerability was converted to age-dependent vulnerability using the distribution of length at age in the middle of the year. This distribution was assumed to be normal, with mean given by the growth curve and standard deviation by the estimated coefficient of variation: at a given age a, it produced the proportion of fish $p(L\,|\,a)$ in each length-class L, such that $\sum_L p(L\,|\,a)=1$. Then the age-dependent vulnerability was given by

$$V_a=\sum_L p(L\,|\,a)\,V_L^*. \qquad (5)$$

The model used 1 cm length categories with midpoints ranging from 1 cm to 70 cm, and calculated the vulnerability in the middle of the year, at exact age $a+\frac{1}{2}$.

The harvest rate $U_{k\,t}$ is the proportion of vulnerable fish in Population k that are caught in year t. In fact, catch sizes were specified only to Subregion level, so it depended only on the Subregion g that contained Population k:

$$U_{k\,t}=U_{g\,t}^*,$$

and the Subregion harvest rate $U_{g\,t}^*$ was calculated as the ratio of catch weight from Subregion g in year t, to the mid-year vulnerable biomass in Subregion g just before the start of fishing in year t:

$$U_{g\,t}^*=C_{g\,t}\Big/\sum_{k\in K(g)}\sum_{a=0}^{a_{\max}}N_{k\,t\,a}\,e^{-M/2}\,W_a\,V_a, \qquad (6)$$

where W_a is the average mid-year weight of a fish of age a, and $K(g)$ is the set of Populations that make up Subregion g.

Recruitment

Spawning and recruitment were assumed to take place simultaneously at the beginning of each calendar year. The model allowed no time lag between spawning and subsequent recruitment. This formulation matched that used by the software Cabezon (Cope and Punt, 2005) and ELFSim (Little *et al*., 2007), but differed from the standard theory used in stock assessments of other Queensland fisheries (described in, e.g., Haddon, 2001) which assumes spawning in the middle of the year, and subsequent recruitment at the beginning of the following year. In the Cabezon–ELFSim formulation, one year has to be added to the age of the fish, and the fecundity is taken at the beginning of the year, not the middle of the year. Either approach is adequate for long-lived fish.

There is debate over the distance that coral trout larvae migrate from the location where they were spawned, but current evidence favours short distances that are still sufficient for green zones (marine protected areas) to seed recruits into blue zones (see Leigh *et al*., 2014, section 1.5.1). Therefore, the model summed egg production over Bioregions, rather than larger-scale elements such as Regions, or very small-scale regions such as would apply to Populations.

In a Population k that is contained in a Bioregion b, the recruitment $R_{k\,t}$ in year t followed a Beverton-Holt stock-recruitment relationship (Beverton and Holt, 1957) with random, annual lognormal deviations:

$$R_{k\,t}\big/R_{k\,0}=e^{d_t}\,\frac{r\,S_{b\,t}\big/S_{b\,0}}{1+(r-1)\,S_{b\,t}\big/S_{b\,0}},$$

where $S_{b\,t}$ is the egg production in year t in Bioregion b (blue zones and green zones combined), $R_{k\,0}$ and $S_{b\,0}$ are the deterministic values of $R_{k\,t}$ and $S_{b\,t}$ in a virgin (never fished) population, $r > 1$ is the recruitment compensation ratio, and d_t is the log-recruitment deviation.

The egg production in Bioregion b, which comprises a set of Populations $K_B(b)$, is

$$S_{bt} = \sum_{k \in K_B(b)} \sum_{a=1}^{a_{\max}} x_a \, N_{k\,t\,a} \, ,$$

where x_a is the product of the maturity proportion and the fecundity at age a.

The recruitment compensation ratio r was estimated in the model and was common to all Regions.

Within each Sub-bioregion, the parameters $R_{k\,0}$ were made proportional to the habitat areas H_k of the Populations. A value of the recruitment density R_{k0} / H_k, being the number of recruits per hectare, was estimated within the model for each Sub-bioregion; the same density value R_{k0} / H_k was used for both blue zones and green zones.

The log-recruitment deviations d_t were estimated within the model and followed a normal distribution with a mean of zero. A lower bound of 0.1 was applied to the standard deviation to prevent the likelihood from becoming infinite.

There was only one recruitment deviation per year, covering all Regions, because Region-specific deviations could not be estimated reliably from the available data.

Vulnerable biomass

The vulnerable biomass in Subregion g at the beginning of year t is equal to the denominator in equation (6). To use vulnerable biomass as an abundance index to compare to catch rates, we adjusted it to the middle of the fishing pulse:

$$B_{g\,t} = \sqrt{1 - U^{*}_{g\,t}} \sum_{k \in K(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a} \, e^{-M/2} \, W_a V_a \, . \qquad (7)$$

This is different to, and slightly more accurate than, the equation used in Cabezon, which uses $1 - \frac{1}{2} U^{*}_{g\,t}$ in place of the square-root factor.

The actual model contained adjustments for fishing in green zones and changes in zoning which are not discussed here (see Leigh et al., 2014, sections 6.5–6.6).

Size limits and discard mortality

Minimum legal sizes (MLS), which could change over time, were handled by adjusting the vulnerability function in equation (5), and specifying a post-release mortality rate u. Let the MLS be L_{MLS}. Then (5) is altered to

$$V_a = u \sum_{L < L_{\mathrm{MLS}}} p(L \mid a) \, V^{*}_{L} + \sum_{L \geq L_{\mathrm{MLS}}} p(L \mid a) \, V^{*}_{L} \, ,$$

which is used in the population dynamic equations (2) and (3).

For the harvest-rates and abundance indices defined by equations (6) and (7), the catch and catch-rate are assumed to comprise only legal-sized fish. Therefore, we defined a separate vulnerability function for fish that the fishers keep,

$$V_{a\,\text{keep}} = \sum_{L \geq L_{\text{MLS}}} p(L \mid a)\, V_L^*,$$

and (6) became

$$U_{g\,t}^* = C_{g\,t} \Big/ \sum_{k \in K(g)} \sum_{a=0}^{a_{\max}} N_{k\,t\,a}\, e^{-M/2}\, W_a\, V_{a\,\text{keep}}\,.$$

Likelihood for relative abundance measures

Fishery-dependent abundance measures could only be defined for Subregions, as the spatial resolution of logbook data did not allow any finer resolution. A relative abundance index $Y_{g\,t}$ for Subregion g in year t follows a lognormal distribution. In the model, the abundance from standardised catch rates is assumed to be proportional to the ratio $\hat{Y}_{g\,t}$ of vulnerable biomass $B_{g\,t}$ from equation (7) to the corresponding habitat area. The constant of proportionality is captured in the parameter μ below.

When the mean μ and standard deviation $\sigma_{g\,t}$ of $\log Y_{gt} - \log \hat{Y}_{gt}$ are specified, the likelihood is

$$\prod_g \prod_t \left(\left\{ 1 \Big/ \left(\sqrt{2\pi}\sigma_{gt} \right) \right\} \exp\left[-\tfrac{1}{2} \left\{ \log Y_{gt} - \log \hat{Y}_{gt} - \mu \right\}^2 \Big/ \sigma_{gt}{}^2 \right] \right).,$$

It is convenient to use the negative log-likelihood (NLL), which, omitting the constant factors of $\sqrt{2\pi}$ above, is

$$\ell = \sum_g \sum_t \left[\log \sigma_{gt} + \tfrac{1}{2} \left\{ \log Y_{gt} - \log \hat{Y}_{gt} - \mu \right\}^2 \Big/ \sigma_{gt}{}^2 \right].$$

The standard deviation $\sigma_{g\,t}$ is set to the standard error from catch-rate or encounter-rate analysis, multiplied by a scale factor $\sigma \geq 1$ which is intended to account for process error whereby the model would still not fit perfectly even if the amount of data were extremely large. Then the NLL, omitting constant terms, is

$$\ell = \sum_g \sum_t \left[\log \sigma - \tfrac{1}{2} \log w_{gt} + \tfrac{1}{2} w_{gt} \left\{ \log Y_{gt} - \log \hat{Y}_{gt} - \mu \right\}^2 \Big/ \sigma^2 \right], \qquad (8)$$

where $w_{gt} = 1 \big/ \text{CVY}_{gt}^2$.

Standard estimators of μ and σ^2 are:

$$\hat{\mu}_Y = \sum_g \sum_t w_{gt} \left\{ \log Y_{gt} - \log \hat{Y}_{gt} \right\} \Big/ \sum_g \sum_t w_{gt}$$

and

$$\hat{\sigma}_Y^2 = \sum_g \sum_t \left[w_{gt} \left\{ \log Y_{gt} - \log \hat{Y}_{gt} - \hat{\mu}_Y \right\}^2 \right] \Big/ (n_Y - 1) , \tag{9}$$

where n_Y is the total number of Subregion–year combinations in the index series. Substituting these expressions into (8) yields

$$\ell = (n_Y - 1) \log \tilde{\sigma}_Y + \tfrac{1}{2} (n_Y - 1) \hat{\sigma}_Y^2 \big/ \tilde{\sigma}_Y^2 , \tag{10}$$

where $\tilde{\sigma}_Y$ is the estimate of σ taking account of its lower bound $\sigma_{Y\,\min} = 1$:

$$\tilde{\sigma}_Y = \max(\hat{\sigma}_Y , \sigma_{Y\,\min}). \tag{11}$$

Formula (10) is similar to the negative log-likelihood derived by Haddon (2001, p. 89) but includes the adjustment term for the lower bound on σ.

The "max" function is not suitable for ADMB because its derivative is discontinuous. In fact, it is better not to calculate $\hat{\sigma}_Y$ either, but to use $\hat{\sigma}_Y^2$ directly from (9), because $\hat{\sigma}_Y$ involves a square root which causes trouble if $\hat{\sigma}_Y^2 = 0$. Therefore, we used the following expression for $\tilde{\sigma}_Y$:

$$\tilde{\sigma}_Y = \sqrt{\tfrac{1}{2} (\hat{\sigma}_Y^2 + \sigma_{Y\,\min}^2) + \sqrt{\tfrac{1}{4} (\hat{\sigma}_Y^2 - \sigma_{Y\,\min}^2)^2 + 4 \delta^2 \sigma_{Y\,\min}^4 }} , \tag{12}$$

where $\delta > 0$ is a smoothness parameter that took the value 0.1. The value $\delta = 0$ makes (12) the same as (11), which is the formula that has to be avoided. The smoothing has the side effect of shifting the value of $\tilde{\sigma}_Y$ at $\hat{\sigma}_Y = \sigma_{Y\,\min}$ up to approximately $(1 + \delta)\, \sigma_{Y\,\min}$ instead of the desired value of $\sigma_{Y\,\min}$. The value $\delta = 0.1$ shifted it up 10%, which we believed to be a reasonable compromise.

For underwater visual survey data, the relative abundance index Y_{kt}^{UVS} uses numbers instead of biomass. Also UVS data are defined on Populations instead of Bioregions, because the reefs on which the UVS data were collected are known.

Likelihood for absolute abundance measures

The likelihoods for absolute abundance measures A_{kt} do not contain the mean-offset parameter μ in (8), as it is set equal to zero. Then (8) becomes

$$\ell = \sum_k \sum_t \left[\log \sigma - \tfrac{1}{2} \log w_{kt} + \tfrac{1}{2} w_{kt} \left\{ \log A_{kt} - \log \hat{A}_{kt} \right\}^2 \Big/ \sigma^2 \right] ,$$

where k denotes a Sub-bioregion, t a year and $\hat{A}_{kt}$ is the model's prediction of A_{kt}. The standard deviation parameter σ and weighting factors w_{kt} are different to those in (8). The final negative log-likelihood (10) becomes

$$\ell = n_A \log \tilde{\sigma}_A + \tfrac{1}{2} n_A \hat{\sigma}_A^2 / \tilde{\sigma}_A^2 , \qquad (13)$$

where n_A is the total number of Sub-bioregion–year combinations in the index series,

$$\hat{\sigma}_A^2 = \sum_k \sum_t \left[w_{kt} \left\{ \log A_{kt} - \log \hat{A}_{kt} \right\}^2 \right] \Big/ n_A ,$$

$$\tilde{\sigma}_A = \max(\hat{\sigma}_A , \sigma_{A\,\min}) \qquad (14)$$

and $\sigma_{A\,\min} = 1$. The number of degrees of freedom is n_A, not $n_A - 1$, because the mean μ is no longer estimated. The max function in (14) was also made into a smooth function in the same way as in equation (12).

Likelihood for age frequencies and length frequencies

An age frequency consists of a number of fish y_a measured in each age class $a = 0, \ldots, a_{\max}$. When each fish is considered to be independent of all other fish, the likelihood of a single age frequency is multinomial:

$$\binom{y_{\text{tot}}}{y_0 , \ldots, y_{a_{\max}}} \prod_{a=0}^{a_{\max}} p_a^{\;y_a} , \qquad (15)$$

where y_{tot} is the total number of fish whose ages are measured (sum of the y_a), p_a is the model's predicted proportion of fish in age-class a, the multinomial coefficient is defined as

$$\binom{y_{\text{tot}}}{y_0 , \ldots, y_{a_{\max}}} = y_{\text{tot}}! \Big/ \prod_{a=0}^{a_{\max}} y_a! ,$$

and the factorial function is defined as

$$y! = \prod_{i=1}^{y} i .$$

In practice, sampled fish are not independent, and instead of the total number y_{tot} the sample has an "effective sample size" that is usually much less than y_{tot} (Pennington and Vølstad, 1994; McAllister and Ianelli, 1997; Francis, 2011).

We deal with the problem of effective sample size by adjusting the multinomial likelihood. The approach estimates the effective sample size from the "raggedness" of the age-frequency distribution: a smooth distribution gives a high effective sample size, and a very ragged one gives a low effective sample size. It does not use the actual sample size y_{tot}.

The estimate of the effective sample size T is

$$\hat{T} = \tfrac{1}{2}(q-1) \Big/ \sum_{a \in Q} \hat{p}_a \log\left(\hat{p}_a / p_a\right) \tag{16}$$

and the final negative log-likelihood for the age-frequency sample is

$$\ell = -\tfrac{1}{2}(q-1)\log \hat{T}\,. \tag{17}$$

The details of the derivation of these expressions are contained in Leigh *et al.* (2014, section 6.10.4).

For every available age-frequency sample, the negative log-likelihood given by (17) and (16) is added into the overall negative log-likelihood for the model.

We note that, in the fishery-independent sampling programs that provided age-frequency data for this assessment, nearly all fish sampled were aged. Therefore we did not need to deal with the additional complexity of age-length keys to combine length frequencies with ageing data on some of the fish to produce overall age-frequencies.

Length-frequency samples were handled in exactly the same way as age-frequency samples. Each age-frequency or length-frequency produced a term of the form (17) that was added into overall negative log-likelihood for the model.

Likelihood for recruitment deviations

The recruitment deviations d_t were assumed to follow a lognormal distribution and were treated identically to the relative abundance indices described above. This produced a single term to add into the overall negative log-likelihood.

Stock assessment model results

Virgin exploitable biomass in regions TS3 and TS5, as preliminarily estimated by the model, are 1,522 and 1,442 tonnes respectively, corresponding to a total virgin exploitable biomass of 2,964 tonnes, when allowing for nonzero recruitment deviations. Maximum sustainable yield, combined in regions three and five of the Torres strait, is 258 tonnes. This number is also approximately the yield at B40, which is consistent with stock assessment models for many species. Note that when we force zero recruitment deviations (see below for justification), these estimates go up. For example, B60 for the fishery goes up from 218 tonnes to 296 tonnes when we force the recruitment deviations to be zero. For a full list of the estimated reference points see Tables 1 and 2.

Vulnerable biomass, relative to virgin biomass, is estimated to be lower in region 5 where coral trout is more heavily fished. When recruitment deviations are set to zero, this reaches a minimum of 75% of virgin, and with positive recruitment deviations it declined to a minimum of 69% of virgin. In both scenarios the stock is projected to have rebounded to 79% and 85% of virgin biomass respectively. Region 3 in both scenarios is always well above 80% of virgin biomass. Figure 9 shows a time series of vulnerable biomass with no recruitment deviations (estimated corresponding harvest rates are in figure 10), while Figure

11 shows the estimated time series of vulnerable biomass and harvest rates when allowing for recruitment deviations.

The reason why we modelled a scenario where recruitment deviations were set to zero is because when we allow for non-zero recruitment deviations, the model estimates the biomass increasing above virgin levels in the years leading up to logbook data being recorded. Figure 11 shows vulnerable biomass as a function of time. Biomass increasing above virgin for such an extended period of time seems unlikely.

Parameters in the model combining GBR data and Torres Strait data mostly agree. For example, natural mortality using only the GBR data is estimated to be 0.45, while it is estimated to be 0.46 when the Torres Strait data are also included. For a full list of estimated parameter values in the GBR and GBR + Torres Strait models, see Table 3.

Given the reference points estimated in the model we also provide a table of rationale behind potential biological catch implications. One important aspect of the Torres Strait Coral Trout fishery is the high spatial heterogeneity in fishing effort. With 72% of total effort occurring in Torres Strait region 5, if a total biological catch was set to B60 or MSY summed over the fished regions then region 5 would likely be overexploited, because more fishers target this region. Therefore, one possible way to better protect region 5 from overfishing and more equitably set the total allowable catch, is to investigate the scenario where: if the long-run historical spatial catch proportion occurs in region 5, what would the total allowable catch have to be set at so that region 5 reaches the local reference point specific to that region. This would help protect that region from local overfishing, even if the fishery was relatively healthy in other Torres Strait regions.

Table 1: Reference points derived from parameter estimates in the model, allowing for non-zero recruitment deviations (rounded to the nearest tonne)

Quantity Estimated From Model	Region 3	Region 5	Total Regions 3 & 5
Virgin Exploitable Biomass (t)	1,522	1,442	2,964
Yield (tonnes) [at B20]	109	103	213
Yield (tonnes) [at B40]	132	125	258
Yield (tonnes) [at B50]	126	120	246
Yield (tonnes) [at B60]	112	106	218
Yield (tonnes) [at B80]	103	97	200
Yield (tonnes) [at MSY]	133	126	258

Table 2: Reference points derived from parameter estimates in the model, without recruitment deviations (rounded to the nearest tonne)

Quantity Estimated From Model	Region 3	Region 5	Total Regions 3 & 5
Virgin Exploitable Biomass (t)	1,725	1,570	3,295
Yield (tonnes) [at B20]	174	159	333
Yield (tonnes) [at B40]	193	176	369
Yield (tonnes) [at B50]	179	163	342
Yield (tonnes) [at B60]	155	141	296
Yield (tonnes) [at B80]	125	114	239
Yield (tonnes) [at MSY]	196	178	374

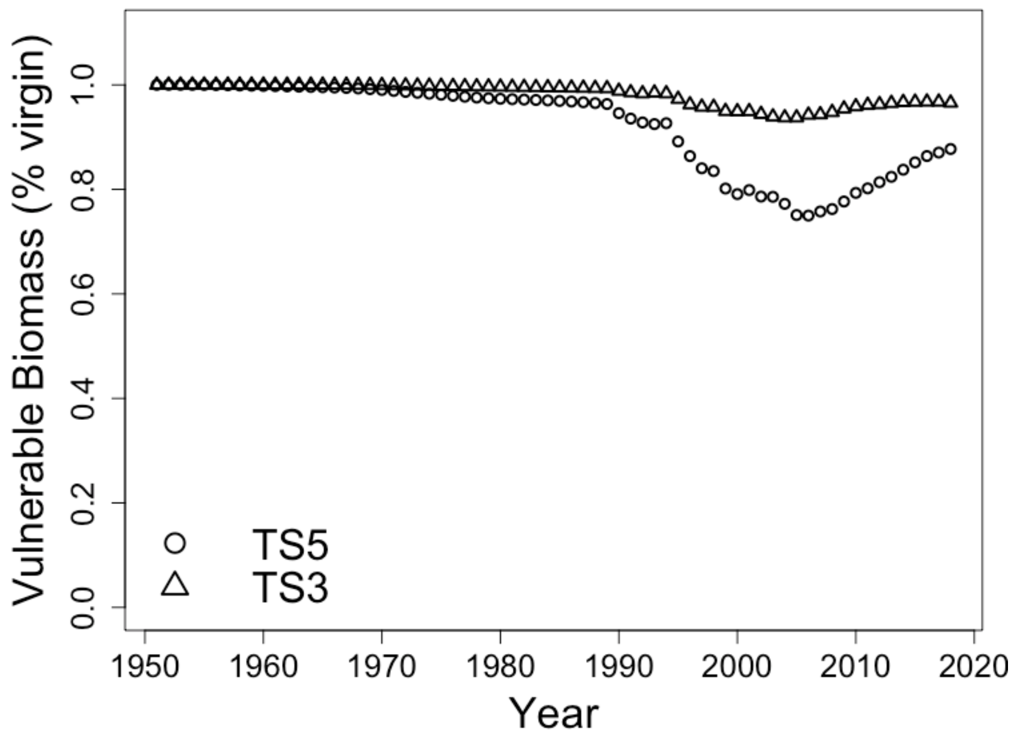

Figure 9: Estimated vulnerable biomass in Torres Strait Regions five and three respectively. Biomass in region 5, the most heavily fished region, always remains above 75% of vulnerable virgin biomass, and region 3 is always above 90% of virgin biomass.

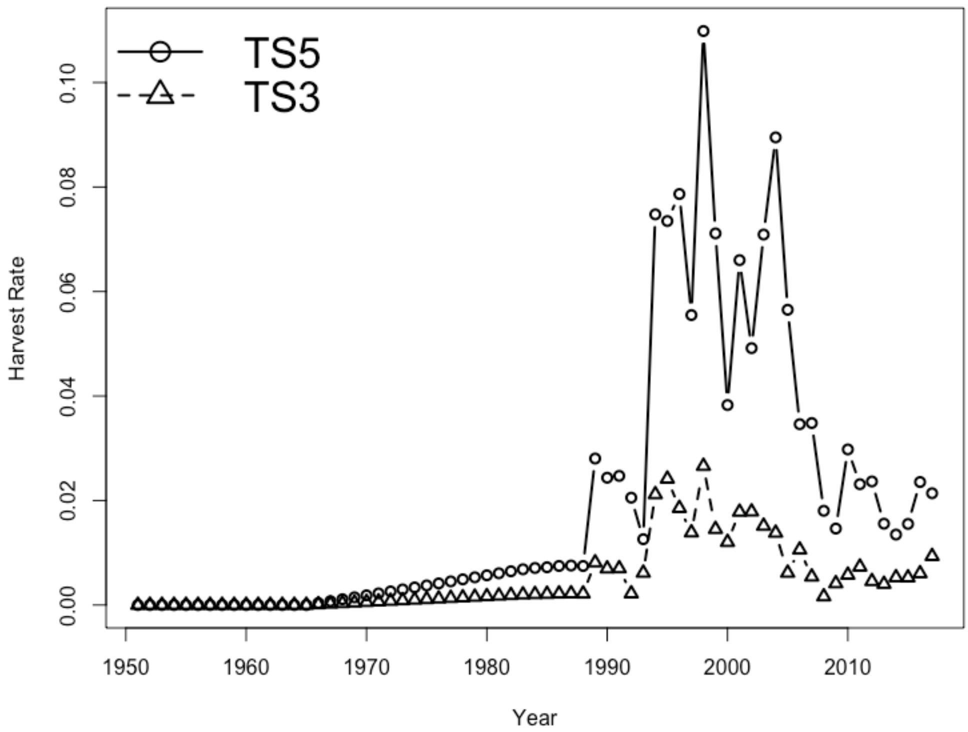

Figure 10: Plot of corresponding estimated fishing mortality in the two regions, with recruitment deviations turned off.

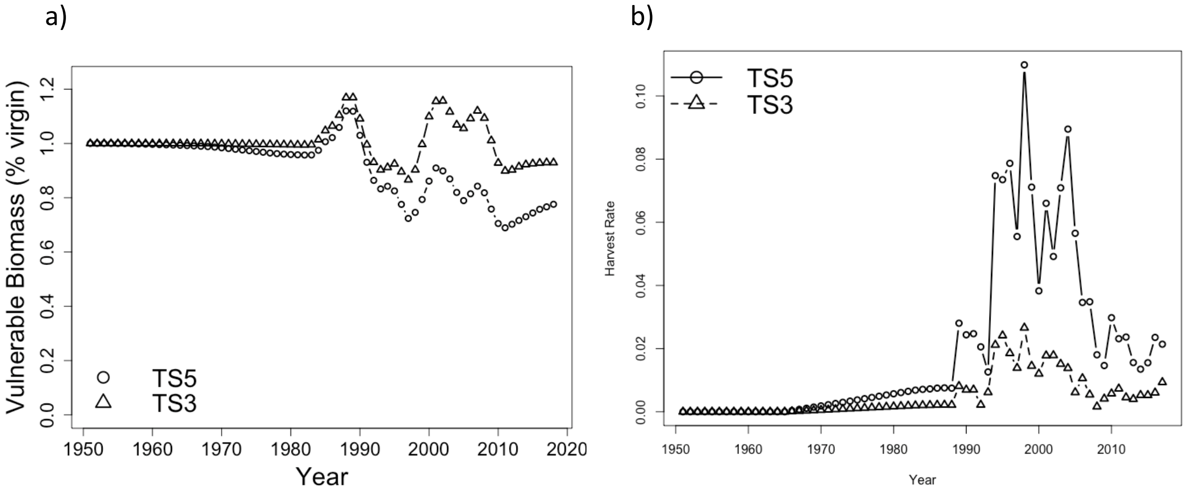

Figure 11: Corresponding Vulnerable Biomass and fishing mortality if recruitment deviations are turned on. Even in this scenario in region 5 vulnerable biomass does not drop below 69% and is currently at 79%. However, it should be noted that allowing for non-zero recruitment deviations allows the model to estimate vulnerable biomass above virgin during the early years.

Table 3: Parameter estimates in the model, with and without recruitment deviations, and the analogous values in the GBR only modelled as a check for model robustness.

Parameter	TS + GBR estimate without recruitment deviations	TS + GBR estimate with recruitment deviations	GBR only estimate with recruitment deviations
M (natural mortality, yr^{-1})	0.46	0.48	0.45
rcomp	4.34	2.74	3.99
Fishing in green zones	0.35	0.21	0.23
SelexPar[1] (length at 50% vulnerability to line fishing)	30.89	31.49	31.95
SelexPar[2] (difference between lengths at 50% and 95% vulnerability to line fishing)	14.27	14.25	14.75

Table 4: Possible options for biological catch limits and their corresponding rationale, and subjective levels of risk. Note that these are purely based on the preliminary model outputs. The table uses the reference point estimates allowing for non-zero recruitment deviations as this methodology yields the smaller estimates for biomass and therefore would generate more conservative biological catch recommendations given. This is important due to the high degree of uncertainty in this system.

Biological Catch	Risk	Rationale
106 tonnes	Very conservative	YB60 solely in TS5
126 tonnes	Conservative	MSY solely in TS5
134.9 tonnes	Conservative	No change
147 tonnes	Conservative / Moderate	If 72% of future catch occurs in TS5, this catch, for the whole fishery, would yield B60 in TS5
174 tonnes	Moderate	If 72% of future catch occurs in TS5, this catch would yield MSY in TS5
218 tonnes	High	Yield that achieves B60 if everyone fishes the regions in optimal proportion
258 tonnes	Very high	MSY if everyone fishes the regions at an optimal proportion

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Appendix F

Torres Strait Coral trout Harvest Strategy: one-page table

Table 1. Harvest Strategy for Torres Strait Coral trout stocks: one-page summary.

Component	Metrics	Detailed values and sources
Indicators	Catch CPUE *Current Biomass/B_0* (*date estimated*) Fishing Mortality (*F*)(*date estimated*) Fishery independent survey indices	**1965-2017** (in model: 1965-1991 - assumed) **1992-2017** (standardised) **>0.8** (2017)(estimated for two regions separately) **0.02** (2007) Not conducted
Reference Points	TRP – Biomass defined LRP – Biomass defined	$\mathbf{B_{60}}$ $\mathbf{B_{20}}$ (as published by ABARES)
Performance Metrics (PMs) *Specified as specific probabilities of meeting level, e.g. >95% by an agreed time period*	Status related Current Biomass/B_0 versus TRP Current Biomass/B_0 versus LRP Utilization related Future catch (year undecided) *versus* a catch target Future CPUE (year undecided) *versus* a CPUE target Average annual variation in catch	 Preliminary assessment > 0.8, i.e. B_{80} (thus >> B_{60}) No catch target for CT at this stage No catch rate target for CT at this stage No AAV catch target for CT at this stage
Decision rules Harvest Control Rules *Status related supersedes utilization related*	Setting of RBC: Status related: If Current Biomass/B_0 > TRP If Current Biomass/B_0 < TRP > LRP If Current Biomass/B_0 < LRP Utilization related: Future catch *versus* target Future CPUE *versus* a CPUE target AAV catch versus AAV catch target Rule for TAC TAC=RBC–Traditional-Recreational	**Constant = 139.9 tonnes.** Based on average catches: 2001-05 (Assessment completed but preliminary) Increase RBC (not applied as RBC is a constant) Decrease RBC (not applied as RBC is a constant) RBC = 0 Not set Indicative number provided for TIB dory Not set **134.9 tonnes = 134.9 tonnes – 0 – 0**
Assessment cycle	Every 3 years Rule: Not undertaken unless two Triggers are undertaken -	Interim agreement – more data from TIB to be obtained 1) If Current Biomass<B60 (proxy for this level is ¾ of standardised CPUE from 2012-2017; 90.6kg per vessel [TVH primary] day)(3/4 based on 60/80 as in that time period stock was at B80) or 2) If yearly catch > 90 tonnes (2/3 of current RBC)
Monitoring	Catch Effort Other data	Catch (TIB and TVH)(spatial)(requires species split) Effort (TIB and TVH)(not all spatial to lowest unit) Mapping data
Assessment	Age-structured model (fitted to CPUE) *For Coral trout 'group' of species:*	Preliminary completed in 2019 (data till 2017) *Increases uncertainty*

CONTACT US

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

FOR FURTHER INFORMATION

CSIRO Oceans & Atmosphere
Dr Trevor Hutton
Principal Research Scientist
t +61 7 3833 5931
e Trevor.Hutton@csiro.au
w www.csiro.au