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## Science to support Australia's Southern Ocean Fisheries 2018-2020

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

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# Executive Summary

**What the report is about**

This collaborative project between the Australian Antarctic Division (AAD) and the Institute for Marine and Antarctic Studies (IMAS) addressed key research needs between 2018 and 2020 for Patagonian Toothfish (*Dissostichus eleginoides*), Antarctic Toothfish (*Dissostichus mawsoni*) and Mackerel Icefish (*Champsocephalus gunnari*) which are targeted by Australian fishing vessels at Heard Island and McDonald Islands (HIMI), Macquarie Island (MI) and in exploratory fisheries managed by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) in the Australian Antarctic Territory (AAT) and the Ross and Amundsen Seas. The project substantially advanced our understanding of the population dynamics of Toothfish and Icefish, in particular it provided robust estimates of key population parameters, and updated and improved the stock assessments for these species at HIMI. Significant work was also conducted to evaluate seabird interactions in the HIMI Toothfish longline fishery, assess skate bycatch at HIMI, and advance research towards the development of an integrated stock assessment for Toothfish in the AAT.

**Background**

Patagonian and Antarctic Toothfish are large benthopelagic fish species with circumpolar distributions. Both species are characterised by high longevity (> 40 years) and broad depth distribution between 10-2500 m. A large fishery for Patagonian Toothfish is located in the Australian Exclusive Economic Zone (EEZ) around HIMI, while Antarctic Toothfish is targeted by Australian fishing vessels in the AAT and in the Ross and Amundsen Seas. Mackerel Icefish is a smaller benthopelagic fish species with a maximum weight of around 2 kg, short longevity (up to around 6 years at HIMI) and strong fluctuations in abundance. At HIMI, Icefish is targeted by bottom trawl and catch limits can vary substantially from year to year. Ongoing research is required for the Toothfish and Icefish fisheries at HIMI and the AAT to collect reliable and representative data and estimate precautionary catch limits of target and bycatch species, to ensure that these fisheries are managed sustainably by the Australian Fisheries Management Authority (AFMA) and CCAMLR.

**Objectives**

The objectives of this project were to:

1. Support and improve the collection of biological, ecological and population dynamics data for key target and bycatch species in the Toothfish and Icefish fisheries at Heard Island and McDonald Islands (HIMI), in the Australian Antarctic Territory (AAT), and in the Ross & Amundsen Seas.
2. Provide robust estimates of key population parameters (growth, reproduction, recruitment, mortality, and movement) and their uncertainty for Toothfish, Mackerel Icefish, and key bycatch species at HIMI and in the AAT.
3. Develop, implement, and improve stock assessment methods that account for species population dynamics and ecosystem linkages, and uncertainty in key parameters and processes at HIMI and in East Antarctica.
4. Evaluate environmental impacts on the HIMI fishery and develop adaptation strategies to climate change on the Kerguelen Plateau
5. Monitor, evaluate, and mitigate fish and skate/ray bycatch, seabird bycatch and cetacean depredation in the HIMI longline fleet.

**Methodology**

To ensure that the fisheries and biological data collected are of a high standard and suitable to inform the management of Australia's Southern Ocean fisheries, this project supported the data collection program by fishery observers on fishing vessels through with logistics, database software and IT support. The observer data collection program was also improved through a review of otolith data collection needs. Toothfish from HIMI, MI and the AAT were aged following a standard ageing program and associated quality control.

Annual random stratified trawl surveys at HIMI were planned and analysed, and number of important parameters for the Toothfish stock assessment were estimated or updated. Stock assessments for Icefish and Toothfish at HIMI were conducted using the Generalised Yield Model (GYM) and the CASAL framework, respectively. Seabird interactions during season extension trials in the longline fishery at HIMI were estimated, and a preliminary assessment of skates at HIMI using the GYM was conducted.

In the AAT, a program to collect crucial information for the effective management of the Antarctic Toothfish fishery and a preliminary stock assessment using CASAL were developed.

**Key results**

Key findings against each objective are as follows:

1. Support and improve the collection of biological, ecological and population dynamics data
    - The data collection programs on Australian vessels at HIMI, MI and in CCAMLR's exploratory fisheries were supported and improved.
    - The sampling protocol to collect fish otoliths in the Toothfish fishery at HIMI was reviewed.
2. Provide robust estimates of key population parameters
    - The annual random stratified trawl surveys (RSTS) in 2018, 2019 and 2020 provided robust estimates of fish abundance for Icefish, Toothfish, and bycatch species.
    - Toothfish from HIMI, MI and the AAT were aged in large numbers.
    - Estimates of biological parameters were updated as part of the Icefish and Toothfish stock assessments. Fishing-induced mortality from longline gear loss at HIMI, and vessel tagging performance at HIMI and in the AAT were estimated for the first time.
    - A research plan to collect crucial information for the effective management of the Toothfish fishery in the AAT was developed, resulting in improved understanding of Toothfish and bycatch and in the development of a preliminary stock assessment.
3. Develop, implement, and improve stock assessment methods
    - Mackerel Icefish at HIMI was assessed using the GYM in 2018 - 2020 to provide advice on sustainable catch limits following the CCAMLR decision rules for Icefish.
    - Patagonian Toothfish at HIMI was assessed by an integrated stock assessment using CASAL to provide advice on sustainable catch limits following the CCAMLR decision rules for Toothfish.
    - Antarctic Toothfish in the AAT was assessed by an integrated stock assessment using CASAL which indicated that the Toothfish stock was unlikely to be depleted, and that the catch limits estimated by CCAMLR's proxy method were likely to be precautionary.
4. Evaluate environmental impacts
    - Annual trends in the Toothfish fishery were monitored, and options explored for an appropriate sampling program to collect data on sea lice.
5. Monitor, evaluate, and mitigate bycatch
    - The risk of seabird mortality during longline season trial extensions was analysed and found to be comparable to that during the existing pre-season extension.

- A preliminary GYM assessment provided first estimates of long-term annual yield for individual skate species at HIMI and a framework for setting and allocating bycatch limits for data-poor species.

**Implications for relevant stakeholders**

The fishing industry, fisheries management, the Australian Government, CCAMLR and the wider public can continue to have trust that:

- Scientific and management advice for Australia's Southern Ocean fisheries is based on reliable data and best-available science.
- The Icefish and Toothfish harvest strategies provide sound advice on stock status and sustainable catch limits at HIMI.
- There is sound advice for the effective fisheries bycatch management at HIMI.
- The Antarctic Toothfish fishery in the AAT is sustainable and a program to collect crucial information for the effective management of the fishery is in place.

**Recommendations**

- Continue the support of the fisheries and observer data collection programs at HIMI, MI and in CCAMLR's exploratory fisheries at a high standard, and evaluate new approaches to data collection including electronic monitoring.
- Review the purpose and required periodicity of the random stratified trawl surveys (RSTS).
- Continue representative Toothfish ageing as important sources of data for estimates of biological parameters and age-length keys.
- Develop a structured fishing program such as a Random Stratified Longline Survey (RSLS) at HIMI for a fishery-independent tag-recapture time series.
- Evaluate appropriate approaches to adequately represent tag-recapture data in an integrated tag-based stock assessment model through e.g. spatially-explicit stock assessment approaches, and estimate and account for tag-release mortality and vessel-specific tagging performance.
- Evaluate the CCAMLR harvest strategy to investigate issues such as the behaviour of the decision rules and approaches to account for potential effects of climate change.
- Continue and ensure adequate monitoring of odontocete whale sightings and interactions with the Toothfish longline fishery at HIMI.
- Continue to monitor seabird interactions with the Toothfish fishery at HIMI and if necessary improve mitigation measures.
- Continue stock assessment and evaluation of appropriate mitigation measures for skates.
- Review effectiveness of current measures for other bycatch species.
- Develop a survey program to investigate sea lice species occurrence and diversity at HIMI, and assess the potential impacts of sea lice occurrence on the HIMI Toothfish fishery.
- Continue participation in Toothfish research fishing in the AAT to collect suitable data for the development of a representative stock assessment which can provide advice on sustainable catch limits for CCAMLR Divisions 58.4.1 and 58.4.2.

**Keywords**

Patagonian Toothfish (*Dissostichus eleginoides*), Antarctic Toothfish (*Dissostichus mawsoni*), Mackerel Icefish (*Champsocephalus gunnari*), Skates (*Bathyraja* spp.), Stock Assessment, Generalised Yield Model (GYM), CASAL, Heard Island and McDonald Islands (HIMI), Macquarie Island (MI), East Antarctica, Australian Antarctic Territory

# Introduction

Australia is obliged to ensure that fishing activities within the Exclusive Economic Zone (EEZ) around Heard Island and McDonald Islands (HIMI), and the Australian Antarctic Territory (AAT) are ecologically sustainable, as outlined in the Environment Protection and Biodiversity Conservation Act (1999, 2020), the Fisheries Management Act (1991), and the Commonwealth Fisheries Harvest Strategy Policy (2007). These waters also fall within the Convention area of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), and as a signatory to CCAMLR and based on the Antarctic Marine Living Resources Conservation Act (AMLRCA, 1981), Australia is obliged to ensure that fishing in CCAMLR regions considers management advice put forward and developed by CCAMLR.

The Australian Antarctic Division (AAD) is the lead agency for Australia's engagement with CCAMLR and has responsibility for the administration of the AMLRCA, the HIMI Marine Reserve and the associated World Heritage Area. The AAD is in a unique position to perform fisheries research on behalf of the Australian Fisheries Management Agency (AFMA), and to enable AFMA to manage and enforce regulated fishing activities occurring in these waters. The AAD also provides important advice to AFMA through the Sub-Antarctic Resource Assessment Group (SARAG) and the Sub-Antarctic Fishery Management Advisory Committee (SouthMAC).

Australia is proactive in developing sound management advice and scientific methods that CCAMLR routinely uses for its management measures. This project has followed on from previous FRDC projects (e.g. FRDC Project 2013-013) to develop best practice methods to address key uncertainties in the scientific management of Australia's Southern Ocean fisheries, to ensure that management advice meets Australia's domestic and international obligations.

There are currently three main fish species commercially fished by Australian fishing vessels in the Southern Ocean, namely Patagonian Toothfish (*Dissostichus eleginoides*), Antarctic Toothfish (*Dissostichus mawsoni*) and Mackerel Icefish (*Champsocephalus gunnari*). Patagonian Toothfish are targeted in the Australian fisheries at HIMI and Macquarie Island (MI), and Antarctic Toothfish are targeted in the international fisheries in the AAT (CCAMLR Divisions 58.4.1 and 58.4.2), the Ross Sea and the Amundsen Sea. Mackerel Icefish are targeted solely at HIMI.

Since 1997, Australian vessels have fished commercially in the Australian EEZ at HIMI for Patagonian Toothfish and Mackerel Icefish. The Toothfish fishery started as a trawl fishery, but since the introduction of longlining in 2003, the proportion of the catch taken by longline has gradually increased and longline is now the primary fishing method (CCAMLR Fishery Report[1]). Mackerel Icefish are taken exclusively by demersal trawl. The current fleet at HIMI comprises two longline vessels and two dual purpose trawler/longline vessel, while another longline vessel fishes for Toothfish at MI. Longline operations are limited to the winter season, while trawl can be used at any time of the year.

[1] https://fishdocs.ccamlr.org/FishRep_HIMI_TOP_2020.html

Uniquely, demersal stratified random trawl surveys (RSTS) had been conducted prior to the commencement of commercial fishing at HIMI (Williams and de la Mare 1995), and an annual survey has taken place since 1998. Estimates of target species biomass derived from the RSTS are key inputs for the annual Icefish stock assessments using the Generalised Yield Model (GYM) and the biennial integrated Toothfish stock assessments using the CASAL assessment framework (Bull et al. 2012). In the latter, tag-recapture data have provided the main information for the index of abundance since 2014 (Ziegler and Welsford 2019).

Since 2016, Australia has also been a key participant in the CCAMLR-managed exploratory fishery for Antarctic Toothfish in the AAT and has regularly fished in the Toothfish fisheries in the Ross Sea and Amundsen Sea. Antarctic Toothfish are exclusively targeted by longline albeit with different gear configurations. Vessels of some CCAMLR members including Australia use Autoline, while others use trotline or Spanish longline.

This project addressed some key research needs for the HIMI Toothfish and Icefish fisheries, and this report covers the following:

- Review of the otolith sampling program to optimise data collection by fishery observers;
- Results from the annual RSTS to provide biomass estimates for the Icefish and Toothfish stock assessments;
- Annual Icefish stock assessments from 2018 to 2020 to inform the setting of catch limits;
- Estimation of Toothfish fishing mortality related to longline gear-loss;
- Estimation of Toothfish tagging performance by fishing vessels;
- Toothfish stock assessment in 2019 to inform the setting of catch limits;
- Update of the Toothfish fishery in 2020 to inform on fishery trends;
- Seabird bycatch analysis to evaluate the effects of season extensions;
- Skate bycatch analysis to inform their bycatch management.

The participation in the exploratory fishery in the AAT required the development of a research plan as specified in CCAMLR Conservation Measure CM 21-02. This research plan, jointly developed by the co-proponents Australia, France, Japan, Republic of Korea and Spain in 2018 and revised annually thereafter, had several objectives, including (1) an assessment of the status and productivity of Toothfish stocks in Divisions 58.4.1 and 58.4.2, (2) the identification of the spatial distributions of Toothfish, important habitats and vulnerable marine ecosystems (VME), (3) the evaluation of the spatial and depth distributions of bycatch species to inform bycatch mitigation measures, and (4) an examination of trophic relationships and ecosystem function.

In this report, we summarise key results for the Antarctic Toothfish fishery in the AAT which were conducted for this project:

- Evaluation of catch rate standardisation to inform the CCAMLR discussion on the use of multiple gear types in the AAT;
- Season report of fishing in the AAT in 2020;
- Toothfish stock assessment in 2020.

# Objectives

| No. | Details |
|---|---|
| 1 | Support and improve the collection of biological, ecological and population dynamics data for key target and bycatch species in the Toothfish and Icefish fisheries at Heard Island and McDonald Islands (HIMI), in the Australian Antarctic Territory (AAT), and in the Ross & Amundsen Seas. |
| 2 | Provide robust estimates of key population parameters (growth, reproduction, recruitment, mortality, and movement) and their uncertainty for Toothfish, Mackerel Icefish, and key bycatch species at HIMI and in the AAT. |
| 3 | Develop, implement, and improve stock assessment methods that account for species population dynamics and ecosystem linkages, and uncertainty in key parameters and processes at HIMI and in East Antarctica. |
| 4 | Evaluate environmental impacts on the HIMI fishery and develop adaptation strategies to climate change on the Kerguelen Plateau |
| 5 | Monitor, evaluate, and mitigate fish and skate/ray bycatch, seabird bycatch and cetacean depredation in the HIMI longline fleet. |

# Chapter 1: Review of the Toothfish otolith sampling program at Heard Island and McDonald Islands (HIMI)

Genevieve Phillips and Philippe Ziegler

## Abstract

The current sampling protocol to collect fish otoliths in the longline fishery for Patagonian Toothfish at Heard Island and McDonald Island (HIMI) results in several thousands of otoliths being collected from commercial fishing operations per fishing season, while only a much smaller subsample of around 500 otoliths are subsequently aged. We evaluate the effects of alternative requirements for collecting fish otoliths per length bin per fishing trip and recommend to reduce the maximum number of fish sampled for otoliths per length bin from 5 to 3.

## 1.1. Background

In the commercial longline fishery for Patagonian Toothfish at Heard Island and McDonald Island (HIMI), observers collect otoliths from a set number of fish per length bin per fishing trip. Length bins are defined as 10 mm intervals that span the entire range of fish lengths observed during a fishing trip. The samples are then pooled from all trips in a year, and a samples of around 500 otoliths from all commercial fishing operations is selected for ageing so that every length bin in a year has an equal number of observations, i.e. otoliths are chosen at random from all otoliths in every length bin. This usually results in approximately 5 otoliths per length bin per year.

Otoliths are also collected during the annual random stratified trawl survey (RSTS) and a random sample 300 otoliths selected using the same approach.

The current sampling protocol results in several thousands of otoliths being collected from commercial fishing operations, while only a much smaller subsample of 500 otoliths are subsequently aged. Here, we evaluate the effects of alternative requirements for collecting fish otoliths per length bin per fishing trip.

The current ageing protocol of reading 500 otoliths, used for age-length keys and other analysis, results in around 5 otoliths per length bin per year being processed. Therefore, in theory sampling 5 otoliths per length bin per year, not per trip, would provide enough samples for ageing across all length bins. The number could be achieved with sampling on a single trip only. However, it is beneficial to collect more otoliths than the number used for ageing, due to a number of reasons:

- Some otoliths may get lost or damaged in transport or during processing;
- There may be future requirements to age more fish for a particular research question;
- There are known differences in growth between the males and females, and there may also be variability in growth between different areas of the fishery, therefore sampling from only a single trip which does usually not cover all fishing grounds, may not provide a representative sample.

## 1.2 Methods and results

For this analysis, we used the commercial data from the longline fishery at HIMI which is currently the dominant fishing method. We focus on the fishing seasons from 2013 to 2018 inclusive when similar sampling protocols were used.

Given the current observer instructions, the numbers of otoliths collected obviously depends on the number of fishing trips. From 2013 - 2018, the number of fishing trips varied between 5 and 13 trips per year (Table 1.1). The numbers of otoliths collected has varied accordingly, with an average number of 429 - 581 otoliths collected per trip and year. Across the six years from 2013-2018, observers collected otoliths from 27,978 individual fish, i.e. annually over 4000 on average.

Of these collected samples, otoliths from 4000 fish have been aged, which is about 14% of the sampled fish. This small proportion suggested that the number of otoliths collected at the first stage of sampling could be substantially reduced.

Ageing of otoliths per length bins has been variable between years (Figure 1.1). Since 2015 around 500 fish have been aged in the laboratory which corresponds closely with around 5 fish per length bin.

**Table 1.1:** Number of fishing trips per year, number of otoliths collected, and average numbers of otoliths collected per fishing trip in the HIMI longline Toothfish fishery from 2013-2018.

| Year | Number of Fishing trips | Number of otoliths collected | Average numbers of otoliths collected per Trip |
|---|---|---|---|
| 2013 | 5 | 2318 | 464 |
| 2014 | 7 | 3001 | 429 |
| 2015 | 13 | 6276 | 483 |
| 2016 | 12 | 5146 | 429 |
| 2017 | 11 | 5431 | 494 |
| 2018 | 10 | 5806 | 581 |

While observers were instructed to collect otoliths from a maximum of 5 fish per length bin, they typically collected more otoliths from fish that are more common in the catch rather than being consistent across length bins (Figure 1.2). Conversely, fish < 500 mm and > 1300 mm length are generally less abundant in the catch so these length bins have been under-sampled. For example, in 2018 when there were 10 fishing trips, we would expect that otoliths of 50 fish per length bin would have been collected. However, over 100 fish have been sampled for length bins around 800 mm, and many less for very small and large fish (Figure 1.3).

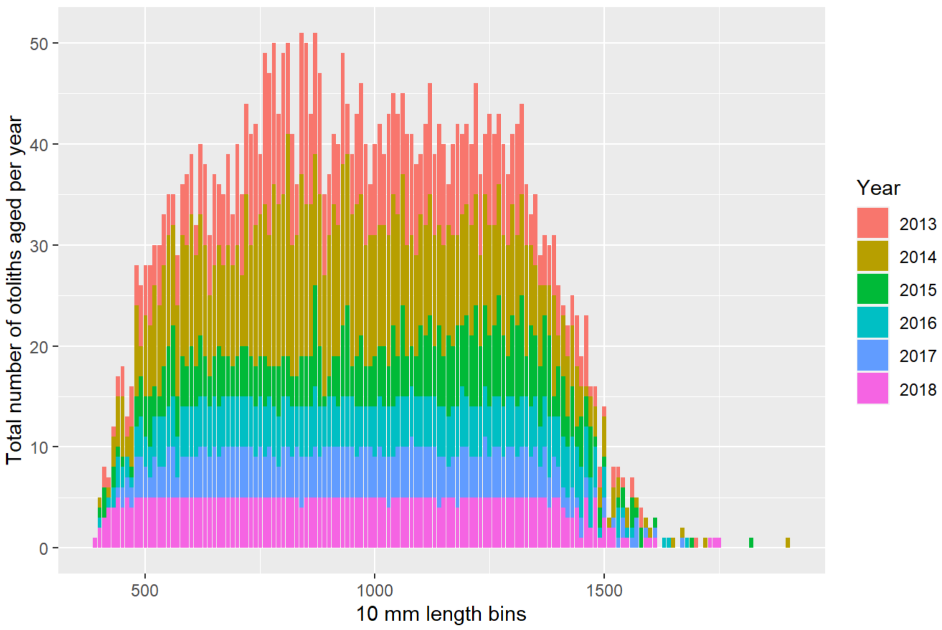



**Figure 1.1:** Cumulative number of otoliths aged by 10 mm length bins for 2013-2018.

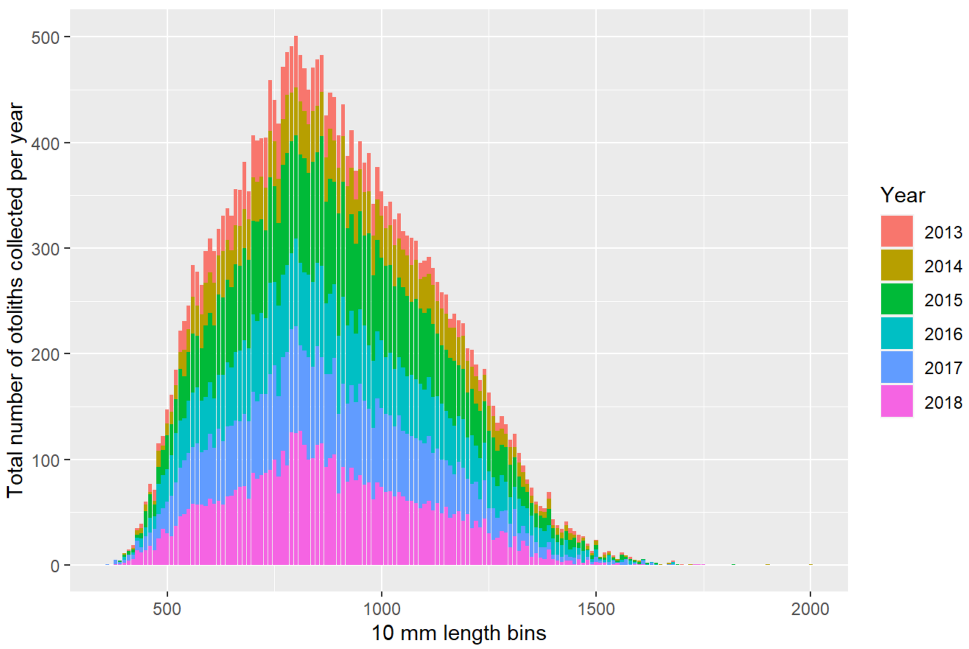



**Figure 1.2:** Cumulative number of otoliths collected by 10 mm length bins for 2013-2018.

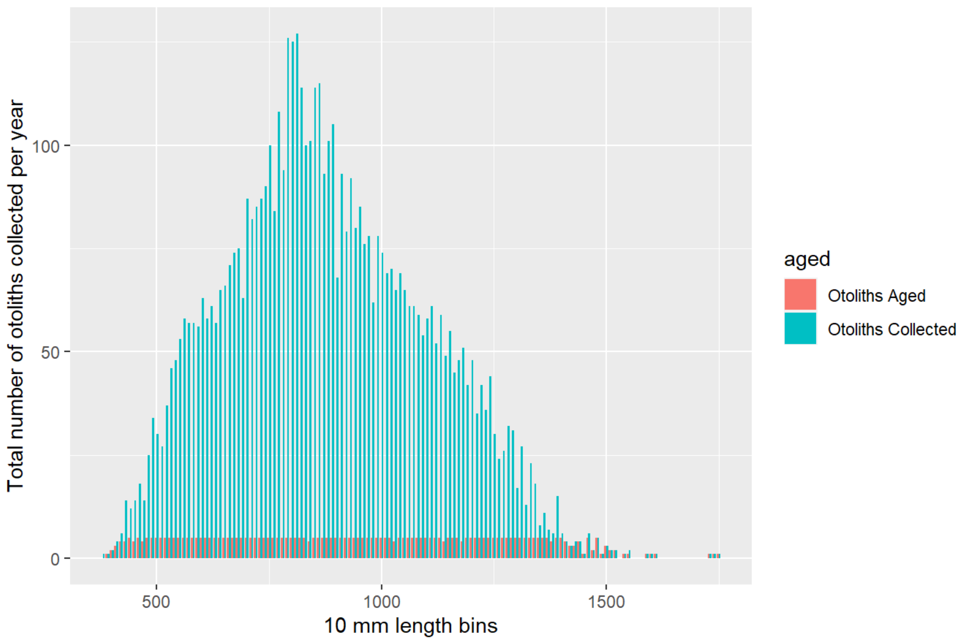



**Figure 1.3:** Total number of otoliths collected (magenta) and aged (red) by 10 mm length bins for 2018.

On average across all fishing trips and years, observers have collected otoliths of up to 8 fish per length bin (Figure 1.4). This indicated that observers did not cap the number of sampled otoliths at 5 as instructed, but over-sampled length bins which occurred more often in the catch and under-sampled rarer length bins. To calculate the expected total number of otoliths collected for a variable number of fishing trips, we used this distribution, capped at alternative maximum sampling rates of 5, 4, 3, 2 and 1 otolith per length bin.

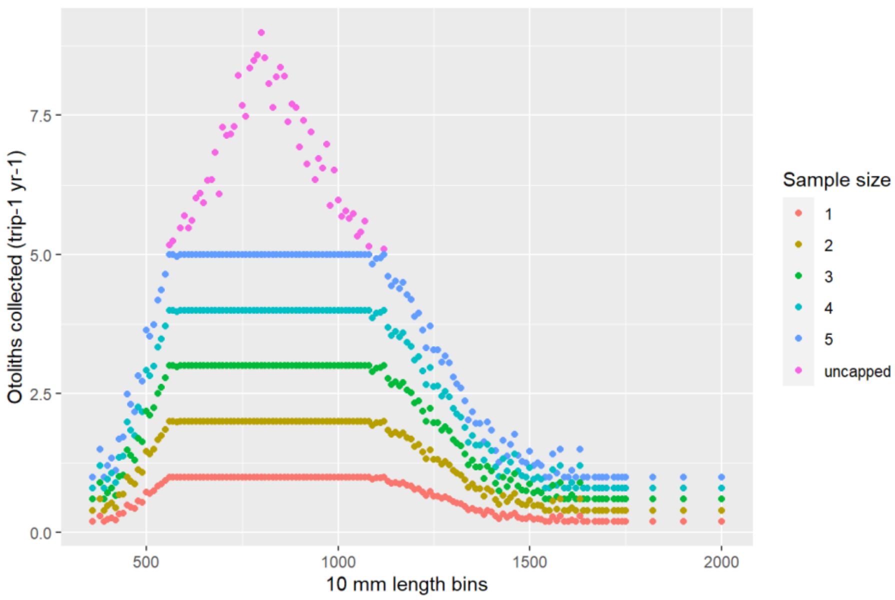



**Figure 1.5:** Total number of otoliths collected by 10 mm length bins per trip and year (pink) and when sample size is capped at 1 to 5 otoliths per length bin (red to blue).

The total number of otoliths which would be collected per year if the maximum number of otoliths per bin was capped at 5, 4, 3, 2 is given in Table 1.2. For the current sampling protocol and 10 fishing trips, the number of sampled fish for otoliths is close to 5000, and would be reduced to around 4000, 3000 or 2000 if sampling was capped at 4, 3 or 2 fish per length bin. Even if the number of fishing trips were substantially smaller as may be the case with a lower catch limit, capping the sampling at 3 fish per length bin would still yield a multiple of the aged 500 fish. For example, around 1800 fish would be sampled with 6 fishing trips.

**Table 1.2:** Total number of otoliths which would be collected depending on the maximum number of otoliths per length bin and the number of trips during a year.

| Number of | Maximum number of otoliths collected per length bin | | | | |
|---|---|---|---|---|---|
| Trips | 5 | 4 | 3 | 2 | 1 |
| 1 | 492 | 394 | 295 | 197 | 98 |
| 2 | 1002 | 801 | 601 | 401 | 200 |
| 3 | 1522 | 1217 | 913 | 609 | 304 |
| 4 | 2018 | 1615 | 1211 | 807 | 404 |
| 5 | 2452 | 1962 | 1471 | 981 | 490 |
| 6 | 2999 | 2399 | 1800 | 1200 | 600 |
| 7 | 3515 | 2812 | 2109 | 1406 | 703 |
| 8 | 4057 | 3246 | 2434 | 1623 | 811 |
| 9 | 4534 | 3627 | 2720 | 1814 | 907 |
| 10 | 4989 | 3991 | 2994 | 1996 | 998 |
| 11 | 5452 | 4361 | 3271 | 2181 | 1090 |
| 12 | 5976 | 4781 | 3586 | 2390 | 1195 |
| 13 | 6494 | 5196 | 3897 | 2598 | 1299 |
| 14 | 7016 | 5613 | 4210 | 2806 | 1403 |
| 15 | 7413 | 5931 | 4448 | 2965 | 1483 |
| 16 | 7989 | 6391 | 4793 | 3196 | 1598 |
| 17 | 8529 | 6824 | 5118 | 3412 | 1706 |
| 18 | 9087 | 7269 | 5452 | 3635 | 1817 |
| 19 | 9549 | 7639 | 5729 | 3819 | 1910 |
| 20 | 10161 | 8129 | 6096 | 4064 | 2032 |

## 1.3 Discussion

The current sampling protocol to collect fish otoliths in the longline fishery for Patagonian Toothfish at Heard Island and McDonald Island (HIMI) results in several thousands of otoliths being collected from commercial fishing operations per fishing season, while only a much smaller subsample of around 500 otoliths are subsequently aged.

Based on this analysis, we recommend that:

- Observers should limit the number of fish sampled within a length bin to the maximum number required. This could be facilitated with a change in Fishlog to indicate how many fish have been already sampled for otoliths in the particular length bin.
- The maximum number of fish sampled for otoliths per length bin can be limited to 3 without loss of representation of the fish caught by the fishery.

# Chapter 2: Results of the random stratified trawl surveys (RSTS) in 2018, 2019 and 2020 at Heard Island and McDonald Islands (HIMI)

Gabrielle Nowara, Tim Lamb, Philippe Ziegler and Genevieve Phillips

**This Chapter is based on:**

Nowara G., Lamb T. and Ziegler P. (2018) Estimates of abundance of *Dissostichus eleginoides* and *Champsocephalus gunnari* from the random stratified trawl survey in the waters surrounding Heard Island in Division 58.5.2 for 2018. Document WG-FSA-18/55, CCAMLR, Hobart, Australia

Nowara G.B., Lamb T.D. and Ziegler P. (2019) Estimates of abundance of *Dissostichus eleginoides* and *Champsocephalus gunnari* from the random stratified trawl survey in the waters surrounding Heard Island in Division 58.5.2 for 2019. Document WG-FSA-2019/03, CCAMLR, Hobart, Australia

Delegation of Australia (2020a) Estimates of abundance of *Dissostichus eleginoides* and *Champsocephalus gunnari* from the random stratified trawl survey in the waters surrounding Heard Island in Division 58.5.2 for 2020. Document SC-CAMLR-2019/BG/35, CCAMLR, Hobart, Australia

# Abstract

During March to April 2018, 2019 and 2020, annual random stratified trawl surveys (RSTS) were conducted in CCAMLR Division 58.5.2 around Heard Island and McDonald Islands (HIMI), with the completion of 163, 150 and 151 stations respectively. All three surveys were conducted on the *FV Atlas Cove*. Sampling protocols such as the design and the duration of the hauls were similar to recent surveys, but with a new set of randomly selected station points. While in 2018 all random haul locations could be sampled, in 2019 only 5 of 18 stations were sampled in Gunnari Ridge since the catch limit for *Champsocephalus gunnari* (Mackerel Icefish) in Division 58.5.2 was reached prior to the completion of the survey. In 2020 only 18 of the 30 stations allocated in Plateau Deep East could be sampled due to damage to the trawl warps which prevented fishing on deeper stations.

The catch of Patagonian Toothfish *(Dissostichus eleginoides)* varied between 30.5 t in 2019 and 86.3 t in 2020 which was the highest catch since the RSTS began and more than three times the average since 2015. The catch of Mackerel Icefish *(Champsocephalus gunnari*) was highest in 2019 with 11.7 t even though less than a third of the stations were completed in Gunnari Ridge in that year.

The estimated biomass of the target species *D. eleginoides* and *C. gunnari* in the 2020 survey were the highest for the past 10 years. Biomass estimates for the managed bycatch species Unicorn Icefish (*Champsocephalus rhinoceratus*) and *Macrourus* spp. were also at their highest levels of the past 10 years and the estimate for Grey Rockcod (*Lepidonotothen squamifrons*) showed the first substantial increase since 2014. Amongst the three species of skate, biomass estimates show an upward trend over the last few years with of *Bathyraja murrayi* also being at the highest levels for the past 10 years.

Length and weight measurements were taken for more than 15,000 fish each year and for more than half of those, other biological measurements were also recorded. Otoliths were collected from a total of 1702 *D. eleginoides* and a number of other species, and 1720 Toothfish were tagged and released over the three surveys.

## 2.1 Introduction

The fishery for Patagonian Toothfish (*Dissostichus eleginoides*) and Mackerel Icefish (*Champsocephalus gunnari*) has been operating since 1997 in the Australian Fishing Zone around the Australian territory of Heard Island and McDonald Islands (HIMI) in Division 58.5.2. The fishery started as a trawl fishery, but moved to both trawl and longline gears in 2003. Changes in the fishery have seen an increase in the number of longline vessels and from 2015 a phasing out of trawling for *D. eleginoides*.

In each year since 1997, a random stratified trawl survey (RSTS) has been conducted to assess the abundance and biology of fish and invertebrate species. The survey provides information for input into the stock assessments for the two target species, *D. eleginoides* and *C. gunnari*. Surveys have been conducted as consistently as possible each year and ensure a continuous time series of data from the fishery.

The random stratified trawl surveys have two long-term aims:

- To assess the abundance of juvenile and adult *D. eleginoides* on the shallow and deep parts of the Heard Island Plateau (300 to 1000m); and
- To assess the abundance of *C. gunnari* on the Heard Island Plateau.

For the annual survey, the area of the plateau down to 1000 m was divided into ten strata, each covering an area of similar depth and/or fish abundance. Although the number and boundaries of strata have been adjusted over the years, they have been consistent since 2002 (Welsford *et al.* 2006). The first three surveys of this series were focused on sampling Icefish habitat (1997 and 1998) and Toothfish habitat (1999), and are included in the relevant assessments. From 2000, the surveys were designed to sample both Toothfish and Icefish populations in waters to a depth of 1000 m, although in 2000 and 2003 some of the strata in deeper waters were not sampled.

Since a review of the survey design in 2003 (Candy *et al.* 2004), a minimum of 10 stations have been sampled in each of nine strata. The tenth stratum, Shell Bank, is closed to fishing but has been occasionally included in the survey, the two most recent being 2005 and 2014. The sampling regime has been stable, with the same number of hauls in each stratum between 2006 and 2014. From 2015 onwards, an additional 5 hauls were included in the Ground B stratum.

## 2.2 Methods

### Survey design

All nine strata in the survey area were sampled for *D. eleginoides* and three strata were also sampled for *C. gunnari* (Table 2.1). The survey strata boundaries and the number of stations chosen for sampling in eight strata has remained the same since the 2006 survey (Nowara *et al.* 2006). The sampling strategy for the ninth stratum, Ground B, was changed in 2015 to make it more consistent with that of the rest of the survey. Prior to the 2015 survey the ground was divided into 29 squares and a subset of 20 were sampled with one haul in each. From 2015, the ground was stratified into two areas with randomly allocated stations, 15 in the first area and 10 in the second. Thus, there were 5 more stations added to the total hauls in this stratum.

As in previous surveys, unique random starting locations and headings for each trawl station were selected for each survey, with station numbers per strata as shown in Table 2.1.

A set of starting position co-ordinates and headings for each station in each stratum was provided to the fishing vessel conducting the survey, including first choice and reserve positions. If it was not possible to trawl at one of the first-choice locations due to unsuitable bottom conditions, the first suitable station on the reserve list for that stratum was chosen instead. If weather conditions made it difficult to follow the prescribed heading, the tow was made in the reverse direction, terminating approximately at the nominated starting point.

**Table 2.1:** Allocation of stations to strata and time of day for sampling of principal species for each survey.

| Stratum | Name | Number of stations | Principal species | Time of day for sampling |
|---|---|---|---|---|
| 1 | Plateau Southeast | 30 | Toothfish, Icefish | daytime only |
| 2 | Gunnari Ridge | 18 | Toothfish, Icefish | daytime only |
| 3 | Plateau West | 10 | Toothfish, Icefish | daytime only |
| 4 | Plateau North | 15 | Toothfish | any time of day |
| 5 | Plateau Deep Northeast | 15 | Toothfish | any time of day |
| 6 | Plateau Deep East | 30 | Toothfish | any time of day |
| 7 | Plateau Deep Southeast | 10 | Toothfish | any time of day |
| 8 | Plateau Deep West | 10 | Toothfish | any time of day |
| 9 | Ground B | 25 | Toothfish | any time of day |

### Vessel and gear specifications

The annual survey has been conducted aboard the industry vessel *FV Atlas Cove* since 2015. The vessel specifications are included in Table 2.2. The same Champion trawl net was used as in previous years (Table 2.3) which included a small mesh (50 mm) codend liner, designed to retain small organisms.

**Table 2.2:** Vessel specifications for the *FV Atlas Cove*. Source: CCAMLR

| | |
|---|---|
| Year built | 1999 |
| Length | 68.1 m |
| Beam | 12.6 m |
| Engine power | 3407 kW |
| Gross tonnage | 1906 t |
| Carrying capacity | 550 t |
| Fish hold capacity | 800 $m^3$ |

**Table 2.3:** Champion trawl net specifications.

| Net specifications | |
|---|---|
| Headrope length | 38.5 m |
| Groundrope length | 45 m (18.1 m rig) |
| Bobbin diameter | 55 cm |
| Horizontal opening | 23.5 m |
| Vertical opening | 3.8 m |
| Belly mesh size | 152 mm |
| No. meshes in belly | 480 |
| Throat mesh size | 120 mm |
| Codend mesh size | 90 mm (50 mm liner) |
| Codend mesh orientation | diamond |
| Trawl board type | Mobydick |
| Trawl board weight | 3000 kg |
| Trawl board to wing length | 150 m |

### Trawling procedure

Each survey trawl was of approximately 30 minutes duration on the bottom at a towing speed of 3 knots. For strata 1-3, which were sampled to assess *C. gunnari* as well as *D. eleginoides*, tows were conducted only between sunrise and sunset when Icefish are concentrated near the bottom (van Wijk *et al.* 2001). Strata designed to assess the abundance of *D. eleginoides* only (strata 4-9, Table 2.1) were sampled throughout the day.

The survey design required all tows within a particular stratum to be completed within as short a time frame as possible. In two Icefish strata, Gunnari Ridge and Plateau Southeast, sampling was required to take place without large delays in between, in case there was movement of Icefish between these strata.

All shots were conducted as far as possible within the specifications for towing speed and gear configuration. Under the circumstances where a shot had to be aborted, it was counted as valid as long as 15 minutes of fishing time was completed. Otherwise the shot was repeated at the same or a reserve location, depending on the reason for abandoning the shot.

Tow distance was calculated as the shortest distance between start and finish positions of the trawl established by GPS. A standard effective net opening of 19 m was applied to the tow distance to calculate swept area. Estimates of headline height of 7 m and wingspread of 19 m during normal fishing operations were provided by the skipper.

### Catch and biological sampling

The catch was recorded separately for each haul. Start and end time, geographical location and depth at the start and end of each haul were recorded in the database. The catch was first sorted into species/taxon groups, then weighed and sampled for biological measurements. For catches of less than 400 kg of each target fish species (*D. eleginoides* and *C. gunnari*) as well as for Grey Rockcod (*Lepidonotothen squamifrons*) and Unicorn Icefish (*Channichthys rhinoceratus*), the entire catch was weighed. If the catch was greater than 400 kg, the skipper's estimate and the weight from factory production were recorded.

Length measurements were taken from a random sub-sample of fish (numbers dependent on the species and availability) on an electronic measuring board and biological measurements from a smaller sample. For *D. eleginoides*, *C. gunnari* and *L. squamifrons*, up to 200 individuals of each species were measured for each haul. For *C. rhinoceratus* and *Bathyraja* spp., up to 50 individual length measurements were taken. Numbers and weights of any other species of bycatch were recorded and similar measurements were taken for benthos where practical.

For each haul, biological measurements were taken from a random sample of up to 50 of each of the four main species of fish and from skates. Measurements recorded were individual weight, standard length and total length (TL), sex, and gonad stage. Otoliths were collected from most D. eleginoides and some of the fish bycatch species which had biological measurements taken.

**Tagging**

*Dissostichus eleginoides* and *Bathyraja* spp. were tagged with two T-bar tags (Hallprint). As biological sampling was the first priority, fish were tagged only if time permitted.

**Abundance estimates for Icefish**

The abundance per haul for *C. gunnari* was estimated for the three Icefish strata, Gunnari Ridge, Plateau Southeast and Plateau West. Catches were divided by the swept area to calculate fish density (t/km$^2$).

**Length density distributions**

For each of the four major fish species (*D. eleginoides*, *C. gunnari, C. rhinoceratus* and *L. squamifrons*) and the three skate species (*Bathyraja eatonii*, *B. irrasa*, *B. murrayi*), estimated length density distributions from the survey were calculated using the CMIX package in R.

**Biomass estimates**

Total biomass estimates of the targeted and main bycatch fish and skate species in the survey area were calculated by summing each stratum biomass, based on the mean densities calculated from all hauls in a stratum. A stratified non-parametric bootstrap was used to estimate uncertainty (95% confidence intervals) from resampling the haul data.

## 2.3 Results and Discussion

**Survey coverage**

A total of 163 valid stations were completed for the survey between the 28th March and 23rd April 2018, 150 stations were completed between the 27th March and 12rd April 2019, and 151 stations were completed between the 23rd March and 16th April 2020 (Table 2.4). In 2019, only 5 of the 18 stations were completed in Gunnari Ridge because the catch limit for Icefish for the season was reached prior to the completion of the survey. In 2020, a significant length of trawl warp was damaged following a 'hookup' on 3rd April preventing fishing deeper than 800m which prevented fishing at the twelve of deepest stations in the Plateau Deep East stratum. The locations for proposed and actual hauls for the 2020 survey are shown in Figure 2.1.

**Table 2.4:** Number of planned and completed hauls for each stratum in each survey.

| Stratum | Area (km$^2$) | No. hauls allocated | No. hauls completed | | |
|---|---|---|---|---|---|
| | | | **2018** | **2019** | **2020** |
| Ground B | 481 | 25 | 25 | 25 | 25 |
| Gunnari Ridge | 521 | 18 | 18 | 5 | 18 |
| Plateau Deep East | 13,120 | 30 | 30 | 30 | 18 |
| Plateau Deep Northeast | 15,090 | 15 | 15 | 15 | 15 |
| Plateau Deep Southeast | 5,340 | 10 | 10 | 10 | 10 |
| Plateau Deep West | 13,370 | 10 | 10 | 10 | 10 |
| Plateau North | 15,170 | 15 | 15 | 15 | 15 |
| Plateau Southeast | 10,404 | 30 | 30 | 30 | 30 |
| Plateau West | 10,440 | 10 | 10 | 10 | 10 |
| **All Strata** | **83,936** | **163** | **163** | **150** | **151** |

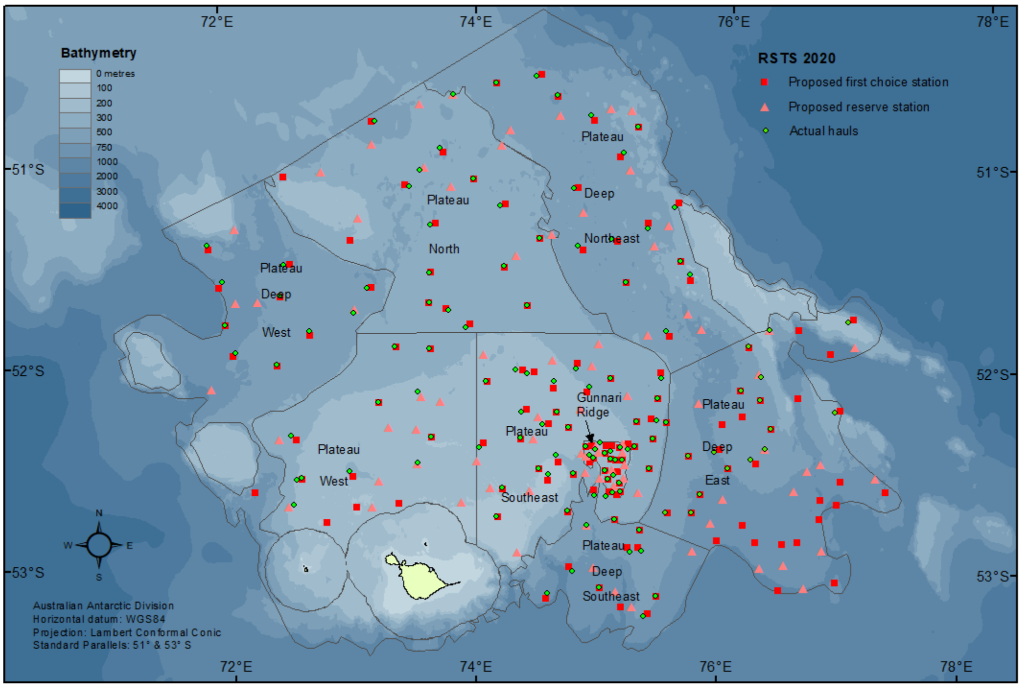



**Figure 2.1:** The distribution of sampling hauls within strata for the 2020 survey. Hauls on the main trawling ground (Ground B) are not shown.

## Catch

The most abundant fish caught during the entire survey was the main target species of the fishery, *D. eleginoides,* with 44.2t, 30.5 t and 86.3 t taken in the three surveys (Table 2.5). Catches of the second target species, *C. gunnari,* were 8.8 t, 11.7 t and 7.3 t, mostly caught on Gunnari Ridge.

The catches of managed bycatch species was dominated by *Channichthys rhinoceratus*, *Lepidonotothen squamifrons* and *Bathyraja eatonii*. *Gobionotothen acuta* and *Muraenolepis sp.* dominated the catch of other fish species. The most abundant invertebrate species in the catch were medusoid jellyfish, but anemones, sponges and seastars were also well represented in the catch.

Overall 65 taxonomic groups were represented in the survey, with the most diversity recorded in the Plateau Deep North stratum.

**Table 2.5:** Catches of main taxa (kg) in the surveys since 2010. Note that since 2015, an additional 5 hauls have been conducted in stratum Ground B.

| | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Taxon group** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019**[1] | **2020**[2] |
| **Target species** | | | | | | | | | | | |
| ***D. eleginoides*** | 8776 | 6597 | 15017 | 8171 | 13699 | 27664 | 14017 | 20818 | 44264 | 30520 | 86251 |
| ***C. gunnari*** | 285 | 465 | 4429 | 17687 | 6902 | 2526 | 12594 | 14266 | 8816 | 11736 | 7290 |
| **Managed bycatch species** | | | | | | | | | | | |
| ***C. rhinoceratus*** | 1417 | 1584 | 2178 | 2889 | 3378 | 4591 | 3288 | 1774 | 3458 | 2551 | 5897 |
| ***L. squamifrons*** | 1603 | 2582 | 7840 | 1699 | 3011 | 1818 | 1084 | 2262 | 4247 | 838 | 3556 |
| ***Macrourus* spp.** | 644 | 1458 | 1744 | 1803 | 1321 | 3333 | 1263 | 1079 | 3892 | 2847 | 1406 |
| ***Bathyraja* spp.** | 673 | 801 | 884 | 928 | 1009 | 1060 | 1617 | 2277 | 2337 | 2292 | 2616 |
| **Other fish** | | | | | | | | | | | |
| **Other bony fish** | 430 | 588 | 470 | 537 | 710 | 768 | 678 | 494 | 862 | 716 | 680 |
| **Other elasmobranchs** | 9 | 25 | 7 | 33 | 8 | 2 | 22 | 1 | 1 | 36 | 25 |
| **Invertebrates** | | | | | | | | | | | |
| **Crustaceans** | 7 | 4 | 6 | 6 | 3 | 3 | 10 | 14 | 7 | 10 | 20 |
| **Molluscs** | 98 | 114 | 63 | 66 | 60 | 36 | 85 | 57 | 170 | 151 | 127 |
| **Jellyfish** | 622 | 668 | 862 | 3044 | 302 | 1580 | 8437 | 586 | 872 | 794 | 5346 |
| **Other invertebrates** | 16793 | 4445 | 3429 | 3070 | 3110 | 3050 | 4188 | 4265 | 6821 | 5112 | 7597 |
| **Total invertebrates** | 17520 | 5231 | 4360 | 6186 | 3475 | 4670 | 12720 | 4922 | 7870 | 5906 | 13089 |
| **No. hauls** | 158 | 156 | 158 | 158 | 158 | 163 | 163 | 163 | 163 | 150 | 151 |

1 Only 5 of 18 stations were completed on Gunnari Ridge in 2019 where most of the *C. gunnari* are caught.

2 Only 15 of 30 stations were completed in Plateau Deep East in 2020.

## Length density distributions

The estimated length density distributions from the 2020 survey for each of the major target and bycatch species are shown in Figures 2.2a and 2.2b. The most abundant length classes of *C. gunnari* were between 250 and 280 mm, *D. eleginoides* showed the highest density from 400 to 700 mm. The peak density for *C. rhinoceratus* was between 250 to 400 mm, and *L. squamifrons* showed two peaks from 200 to 300 mm and from 350 to 420 mm. *B. eatonii*, *B. irrasa* and *B. murrayi* showed a scattered distribution throughout the size ranges without any dominant peaks.

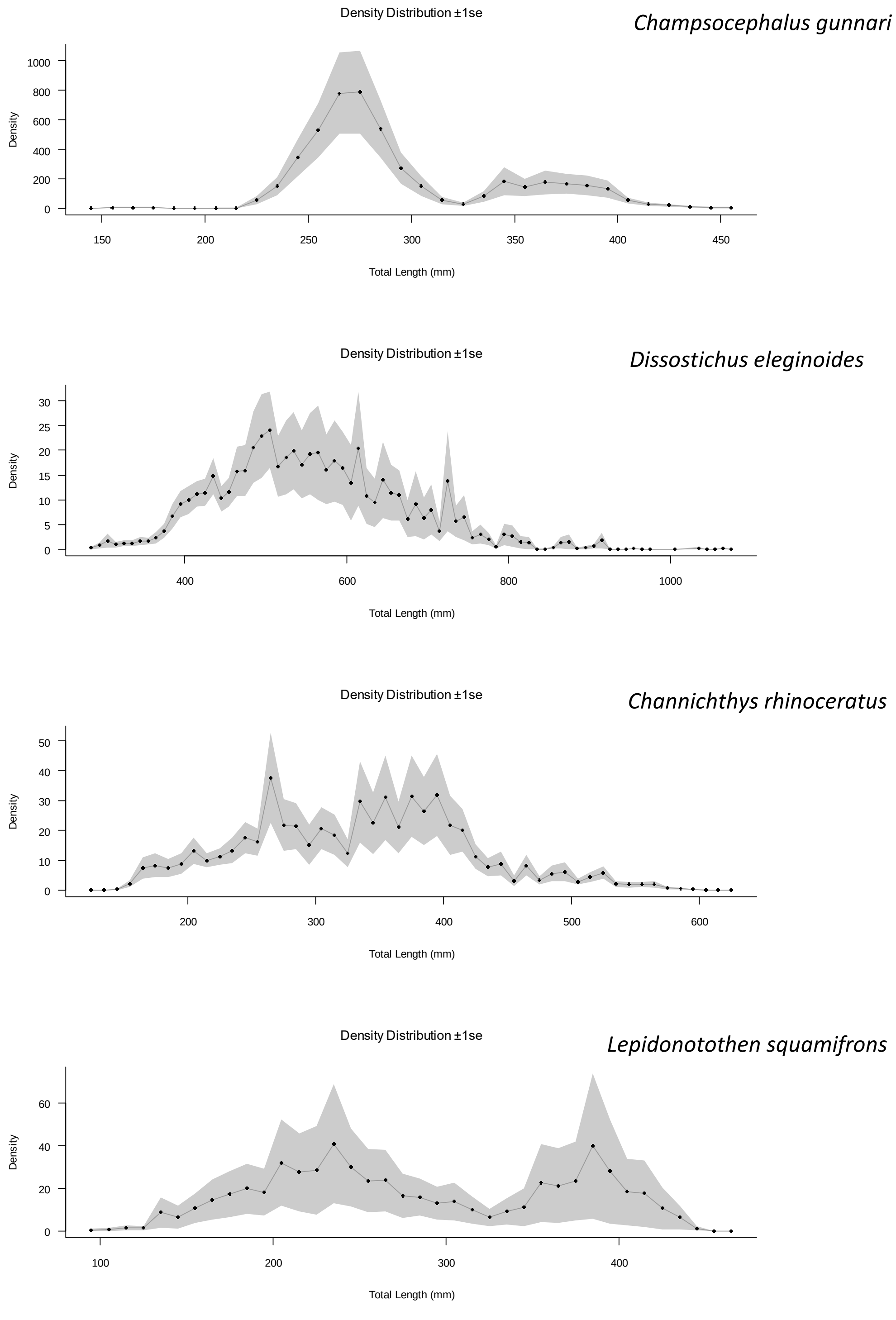



**Figure 2.2a:** Length density distributions (Numbers/km ± 1 standard error) for *C. gunnari*, *D. eleginoides*, *C. rhinoceratus* and *L. squamifrons* in the 2020 survey.

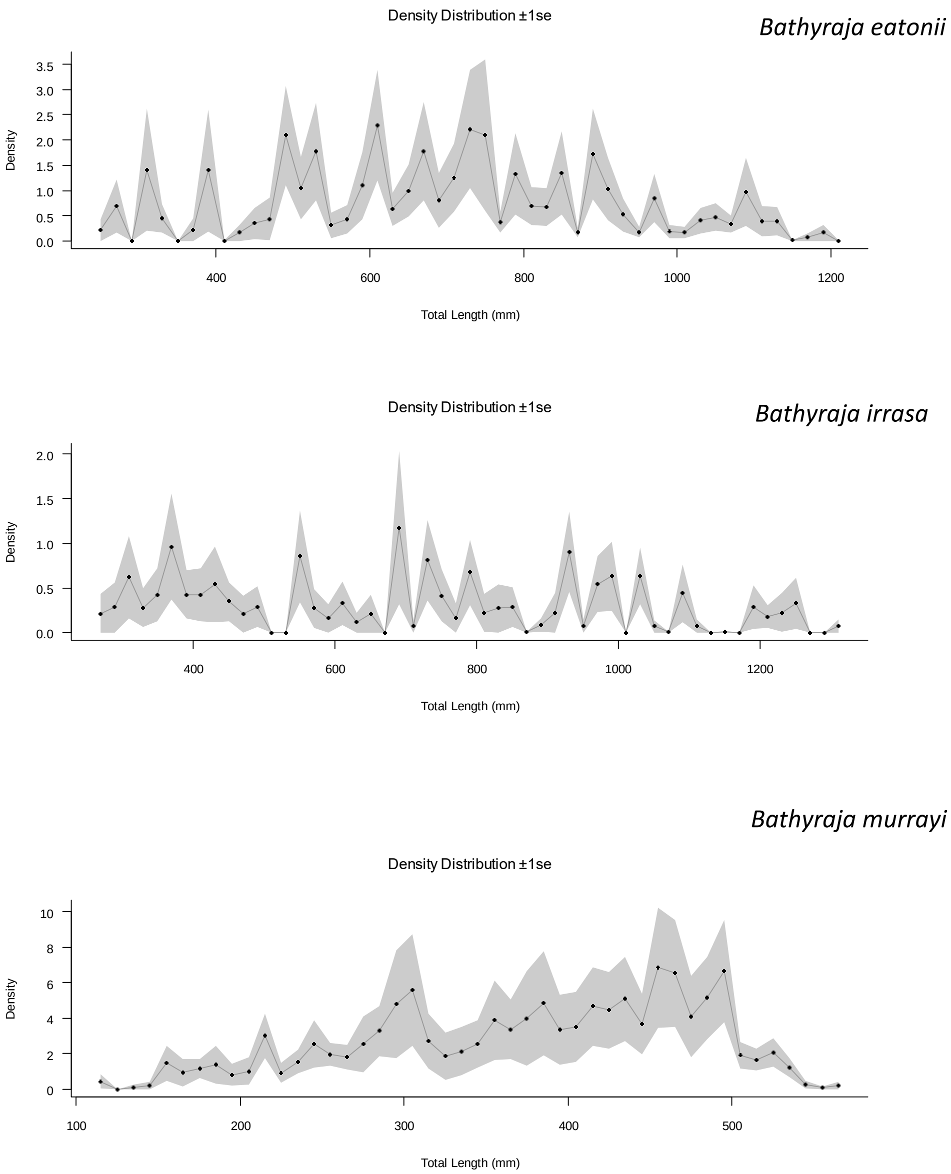



**Figure 2.2b:** Length density distributions (Numbers/km ± 1 standard error) for three species of skates (*B. eatonii, B. irrasa, B. murrayi*) in the 2020 survey.

### Spatial density estimates of Champsocephalus gunnari

Local estimates of *C. gunnari* density were highest on Gunnari Ridge where high densities were recorded for four hauls, ranging from 17-38 t per km$^2$. Overall, Icefish density was greater than 1 t per km$^2$ in a further seven hauls, and less than 1 t per km$^2$ in all other hauls from Gunnari Ridge, Plateau Southeast and Plateau West. Icefish density was low or zero in all other strata (Figure 2.3).

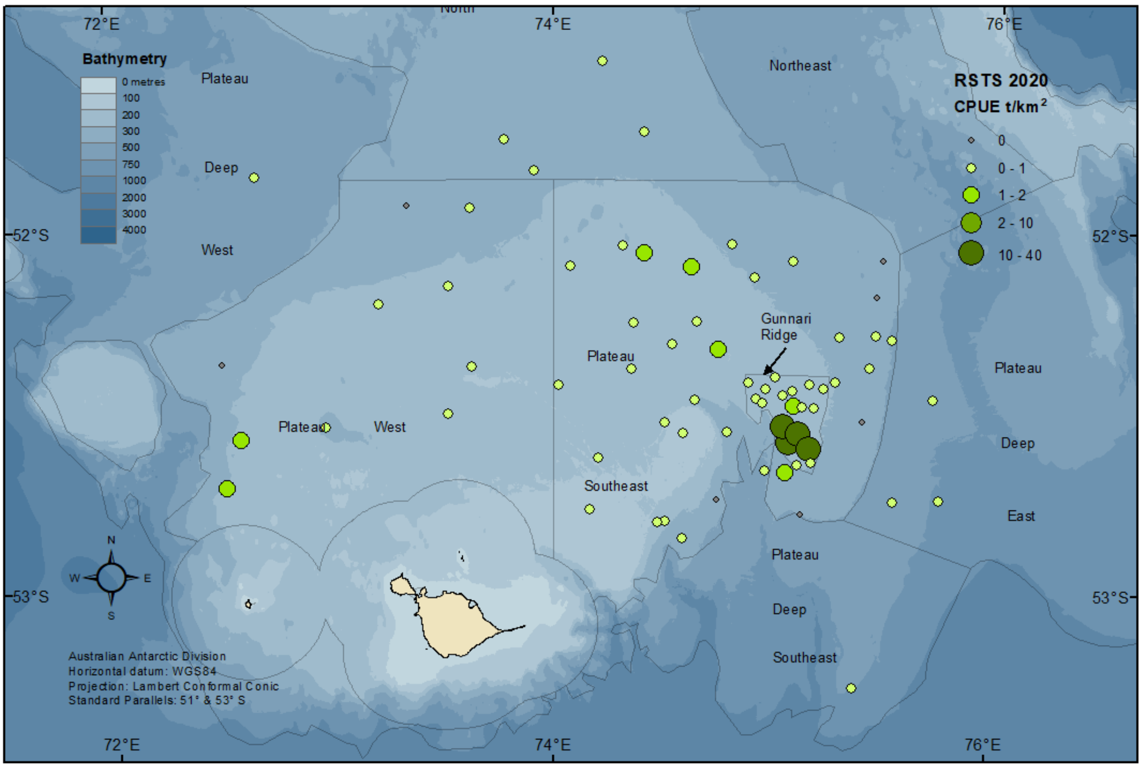



**Figure 2.3:** Estimated density (t/km$^2$) of *C. gunnari* in the 2020 survey in strata Gunnari Ridge, Plateau Southeast and Plateau West.

### Biomass estimates

Biomass estimates from the surveys for the last 10 years for *C. gunnari* have ranged between 1,400 and 12,800 t, with 2020 being the highest estimate to date (Figure 2.4a).

The biomass estimate for *D. eleginoides* in 2020 was also the highest for the last 10 years, and possibly an underestimate of the true biomass in the survey area. For this estimate, one haul in stratum Plateau Deep East was excluded from the bootstrap since it had been (randomly) placed in a known fishing location and its density estimate was over 100 times larger than that for any other haul in this stratum. Including this haul in the bootstrap resulted in a skewed biomass distribution and an unrealistically high biomass estimate in this stratum. The failure to complete the deeper stations in the same stratum was likely to have had only a minor impact on the overall biomass estimate since deeper stations in this stratum tend to show a similar if not slightly higher biomass density.

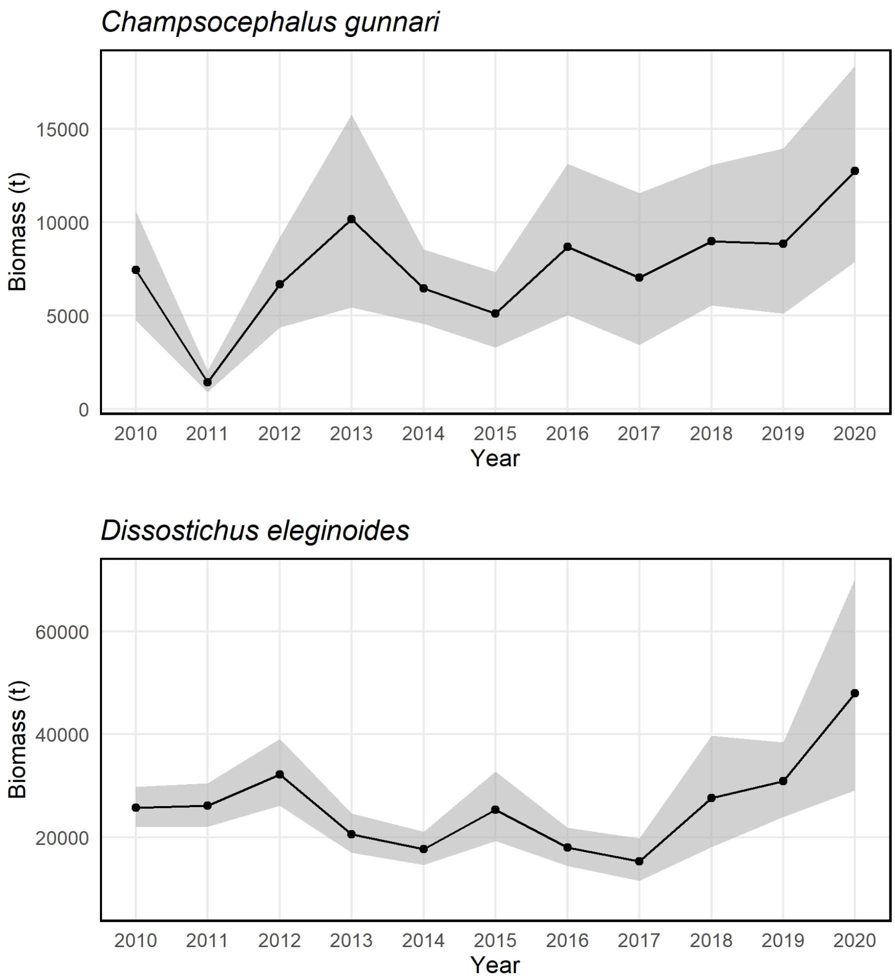



**Figure 2.4a:** Biomass estimates (tonnes, mean and 95% CIs) for *C. gunnari* and *D. eleginoides* from the surveys since 2010.

Amongst the managed bycatch species, the biomass estimates for *C. rhinoceratus* and Macrorurids were the highest seen in the last 10 years and the estimated biomass for *L. squamifrons* showed the first considerable increase since 2014 (Figure 2.4b). All three *Bathyraja* species have shown an increasing trend over the last few years. For *B. murrayi* the highest catches in the 10-year period also occurred in 2020 (Figure 2.4c).

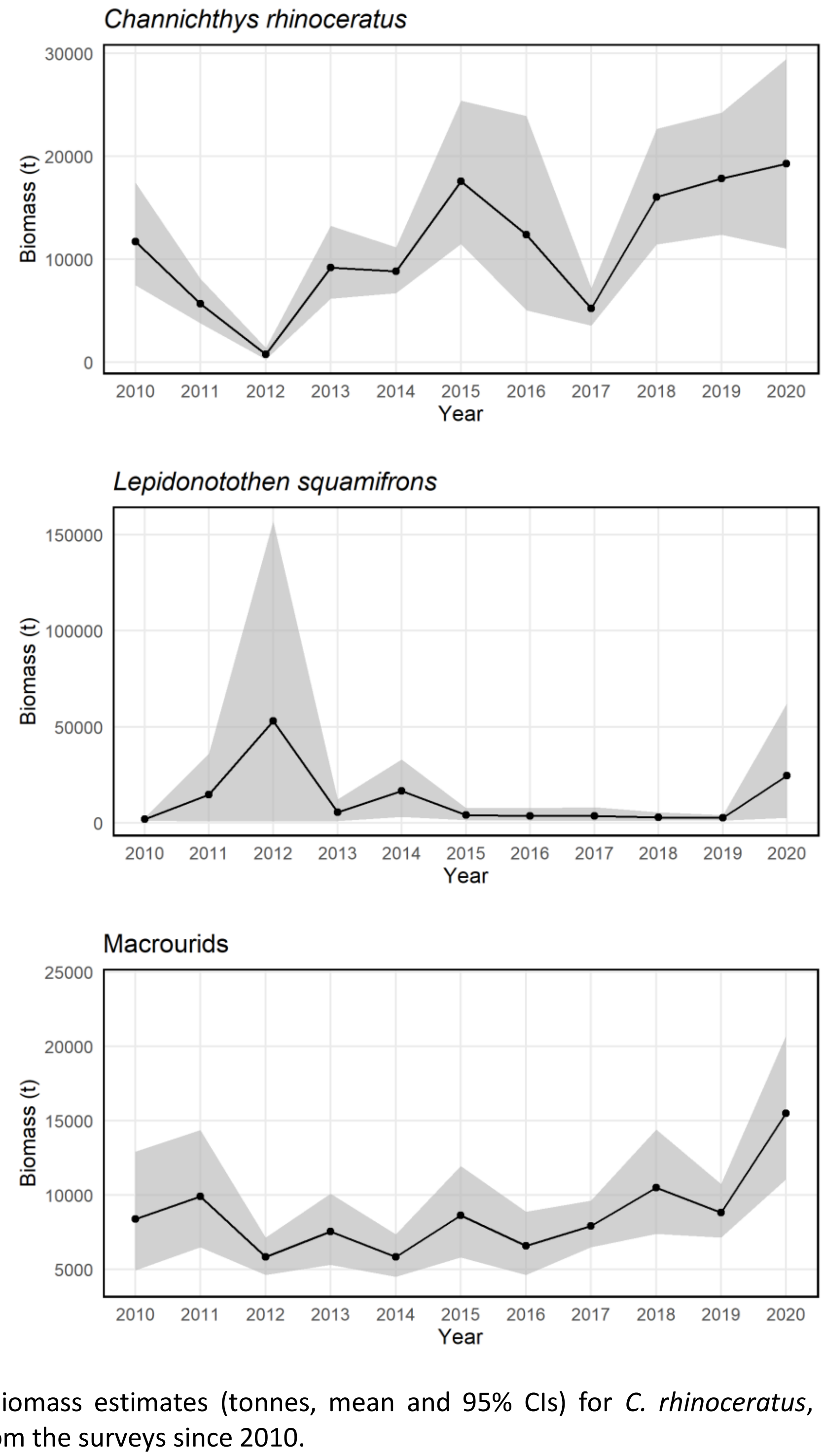



**Figure 2.4b:** Biomass estimates (tonnes, mean and 95% CIs) for *C. rhinoceratus*, *L. squamifrons* and Macrourids from the surveys since 2010.

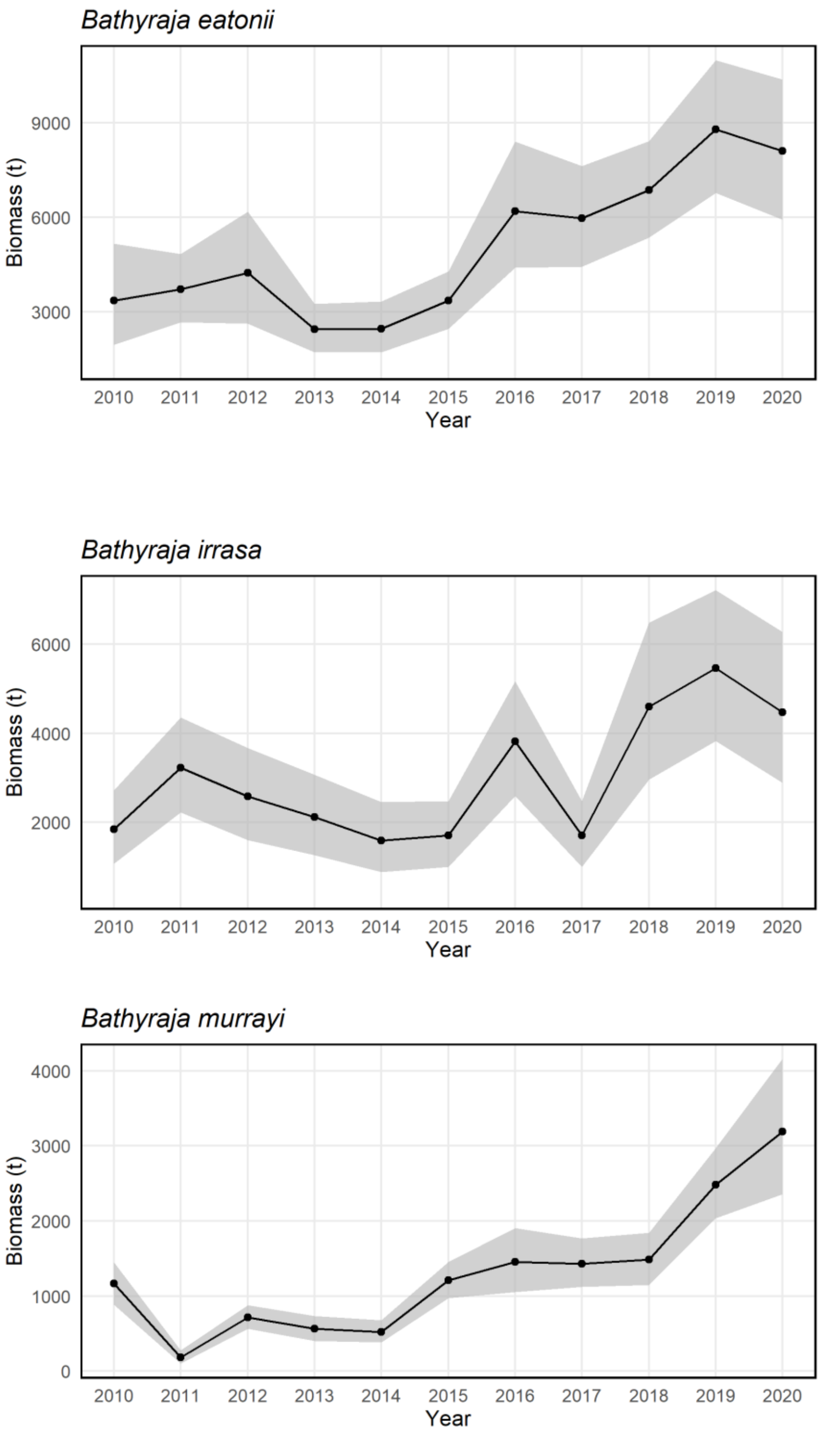



**Figure 2.4c:** Biomass estimates (tonnes, mean and 95% CIs) for the three species of skates (*B. eatonii, B. irrasa, B. murrayi*) from the surveys since 2010.

**Biological data**

During the survey between 2018 and 2020, between 15,000 and 22,000 fish were measured annually (Table 2.6). Otoliths were taken from 656, 283 and 763 *D. eleginoides*, and from other major catch species.

**Table 2.6:** Number of length measurements and otoliths taken by species in the 2018 to 2020 surveys.

| Species | 2018 | | 2019 | | 2020 | |
|---|---|---|---|---|---|---|
| | **Lengths** | **Otoliths** | **Lengths** | **Otoliths** | **Lengths** | **Otoliths** |
| Fish | | | | | | |
| *Champsocephalus gunnari* | 5658 | | 3558 | 25 | 6053 | |
| *Dissostichus eleginoides* | 3797 | 656 | 3925 | 283 | 4740 | 763 |
| *Channichthys rhinoceratus* | 7215 | 132 | 4827 | 17 | 2831 | |
| *Lepidonotothen squamifrons* | 1939 | 280 | 1128 | 110 | 2123 | 229 |
| *Macrourus caml* | 2594 | 234 | 554 | 26 | 474 | 55 |
| *Macrourus spp.* | 6 | | 30 | 4 | | |
| *Antimora rostrata* | 5 | | 47 | 1 | 12 | |
| *Gobionotothen acuta* | 23 | | 2 | | 93 | 19 |
| *Muraenolepis* sp. | 21 | | 2 | | 1 | |
| *Notothenia rossi* | *32* | | *8* | | *4* | *2* |
| Skates | | | | | | |
| *Bathyraja eatonii* | 461 | | 424 | | 385 | |
| *Bathyraja irrasa* | 105 | | 136 | | 105 | |
| *Bathyraja murrayi* | 406 | | 480 | | 598 | |
| **TOTAL** | **22262** | **1302** | **15121** | **955** | **17419** | **1068** |

The sex of 11,921, 7598 and 8766 fish was recorded (Table 2.7) and gonad maturity examined for most of these in the 2018 to 2020 surveys (Table2. 8 for 2020). Gonad maturity of bony fish was assessed on a scale of 1-6 and skates 1-3, with mature gonads represented in fish by 4 and skates by 3. Most fish were found to be immature. The majority of female and male *D. eleginoides* were found to be at stage 1 and 2 respectively. Most *C. gunnari*, *C. rhinoceratus*, *L. squamifrons* and *M. caml* were found at stages 1 to 3, with only *C. rhinoceratus* females and male *M. caml* showing some percentages of later stages. *Bathyraja* spp., were found in all 3 stages, with the majority being immature.

**Table 2.7:** Number of each sex identified for each species in the 2018-2020 surveys.

| **Species** | **2018** | **2019** | **2020** |
|---|---|---|---|
| Fish | | | |
| *Champsocephalus gunnari* | 3297 | 1685 | 2282 |
| *Dissostichus eleginoides* | 5268 | 1719 | 2209 |
| *Channichthys rhinoceratus* | 1561 | 2017 | 1581 |
| *Lepidonotothen squamifrons* | 1227 | 573 | 1219 |
| *Macrourus caml* | 2171 | 487 | 384 |
| *Macrourus carinatus* | 3 | 11 | |
| *Macrourus holotrachys* | 3 | | |
| *Macrourus whistoni* | | 16 | |
| *Antimora rostrata* | | 47 | |
| *Gobionotothen acuta* | | | 19 |
| *Notothenia rossi* | 2 | 3 | 4 |
| Skates | | | |
| *Bathyraja eatonii* | 461 | 424 | 385 |
| *Bathyraja irrasa* | 105 | 136 | 105 |
| *Bathyraja murrayi* | 406 | 480 | 598 |
| **TOTAL** | **11921** | **7598** | **8766** |

**Table 2.8:** Percentage of each stage (by sex) found in fishes examined for gonad maturity in the 2020 survey. Differences in the scale used to assess gonads in fish and skates mean that 4 and 3 represent mature gonads (blue numbers) in fish and skates respectively.

| **Species** | **Females** | | | | | | **Males** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **N** | **Stage (%)** | | | | | **N** | **Stage (%)** | | | | |
| | | **1** | **2** | **3** | **4** | **5** | | **1** | **2** | **3** | **4** | **5** |
| Fish[1] | | | | | | | | | | | | |
| *Champsocephalus gunnari* | 1522 | 71 | 27 | 2 | | | 760 | 74 | 24 | 2 | | |
| *Dissostichus eleginoides* | 1555 | 99 | 1 | | | | 649 | 83 | 17 | <1 | | |
| *Channichthys rhinoceratus* | 1176 | 60 | 27 | 10 | 2 | 1 | 404 | 59 | 31 | 10 | | |
| *Lepidonotothen squamifrons* | 893 | 67 | 23 | 10 | <1 | | 326 | 61 | 31 | 7 | | |
| *Macrourus caml* | 254 | 57 | 27 | 16 | | | 130 | 33 | 32 | 33 | 1 | 1 |
| *Gobionotothen acuta* | 18 | 1 | 8 | 8 | 1 | | 1 | 1 | | | | |
| Skates[2] | | | | | | | | | | | | |
| *Bathyraja eatonii* | 66 | 56 | 36 | 8 | | | 174 | 34 | 39 | 28 | | |
| *Bathyraja irrasa* | 10 | 70 | 10 | 20 | | | 52 | 33 | 46 | 21 | | |
| *Bathyraja murrayi* | 108 | 65 | 31 | 5 | | | 317 | 35 | 36 | 29 | | |

[1] Maturity scale for female fish: 1-Immature, 2-Maturing virgin or resting, 3-Developing, 4-Gravid, 5-Spent, 6-Resting
Maturity scale for male fish: 1-Immature, 2-Developing or resting, 3-Developed, 4-Ripe, 5-Spent, 6-Resting
[2] Maturity scale for skates: 1-Immature, 2-Maturing, 3-Mature

**Tagging**

A total of 609, 466 and 645 *D. eleginoides* were tagged during the surveys in 2018 to 2020, distributed across all strata. Tagged Toothfish ranged in size from 286 to 1275 mm. Three *Bathyraja* spp. were also tagged during the survey.

## 2.4 Acknowledgements

We are grateful to Austral Fisheries and Australian Longline for providing research support necessary to undertake these surveys at sea, and to the observers, Tamre Sarhan (AFMA), Henry Oak (AFMA) and Rob Leslie (CapFish), Henry Wilson (AFMA) and Michael Basson (CapMarine) for collecting the data. Thanks also to Troy Robertson and Peter Yates for validation of the data. Thanks to Paul Burch and Simon Wotherspoon for statistical advice and programs and to Dale Maschette for providing the biomass numbers for Mackerel Icefish.

# Chapter 3: Mackerel Icefish assessment in 2018 at Heard Island and McDonald Islands (HIMI)

Dale Maschette and Dirk Welsford

**This Chapter is based on:**

Maschette D. and Welsford D. (2018) A preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2, based on results from the 2018 random stratified trawl survey. Document WG-FSA-2018/56, CCAMLR, Hobart, Australia

# Abstract

The annual random stratified trawl survey was undertaken in Division 58.5.2 in the vicinity of Heard Island and McDonald Islands during April 2018. This paper provides an updated growth model and a preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) population structure, abundance and yield in Division 58.5.2 to the west of 79°20’E using standard CCAMLR methods (CMIX and Generalized Yield Model).

The 2018 survey showed a large 2+ cohort in the population. Catches of 443 t in the 2018/19 season and 320 t in the 2019/20 season respectively satisfied the CCAMLR decision rules.

# 3.1 Introduction

The fishery for Mackerel Icefish (*Champsocephalus gunnari)* around Heard Island and McDonald Islands in Division 58.5.2 began in 1997 (CCAMLR 2017). A random stratified trawl survey (RSTS) has been undertaken each year on the shallow plateau (<1000 m) in Division 58.5.2 to collect data on the distribution, abundance and population structure of Patagonian Toothfish, Mackerel Icefish and other species.

Prior to 2011, the population of Mackerel Icefish in Division 58.5.2 generally exhibited one or two cohorts which dominated in abundance and biomass, and these were separated in age by one or two years (Welsford 2010, Welsford 2015, Williams et al. 2001). Since the maximum age of Mackerel Icefish in this region is thought to be around five years, strong cohorts have resulted in large variation of population abundance and the amount of production available to the fishery (SC-CAMLR 2010). However, between 2011 and 2016 at least four and usually five cohorts were apparent in the population simultaneously, with no single cohort being overwhelmingly dominant (Welsford 2011, 2012, 2013, 2014, 2015, Maschette and Welsford 2016).

This study provides an analysis of data collected in the 2018 RSTS to estimate the current abundance and cohort structure in the Mackerel Icefish population in Division 58.5.2 and its implications for yields to the fishery in 2018/19 and 2019/20.

# 3.2 Methods

### 2018 survey

The design of the survey conducted in 2018 used the same principles as previous surveys in Division 58.5.2 (Nowara et al. 2018). The three strata where Mackerel Icefish are abundant (Gunnari Ridge, Plateau West and Plateau Southeast) were surveyed in daylight, when Icefish are close to the seafloor and most effectively sampled by demersal trawls (van Wijk et al. 2001). Survey hauls were allocated at random within each stratum, however a minimum spacing of 5 nautical miles between survey stations was specified to ensure hauls would not overlap. Station locations and catches are detailed in Nowara et al. (2018) with density estimates ranging from 0-42 tons per km$^2$. Survey diagnostic information as outlined in Maschette *et al.* (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of the Chapter.

### Assessment methods

The assessment method followed those agreed by CCAMLR (SC-CAMLR-XVI, para 5.70) for assessing yield in Mackerel Icefish, as published by de la Mare et al. (1998), and is identical to that used to estimate yields for Mackerel Icefish in Division 58.5.2 in previous years. Assessment diagnostic information as outlined in Maschette et al. (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of the Chapter.

### Cohort structure

A mixture analysis was undertaken using the CMIX procedure (de la Mare 1994, de la Mare et al. 2002) to estimate the density of fish in each age class and the contribution of each age class to the overall biomass estimated by scaling each age class by its mean weight at length. The survey data was pooled to a single survey data set. As in previous years the sampling effort across strata was uneven, as such the data is re-scaled so that the mean of the re-scaled data is the same as the stratified mean of the raw data. For each haul in *k* strata, the density data is re-scaled by the composite sampling fraction according to the following expression from de la Mare and Williams (1996):

$$D_{i,j} = d_{i,j}\frac{A_i}{\sum_k A_k} \times \frac{\sum_k n_k}{n_i}$$

where $D_{i,j}$ is the re-scaled density for haul *i* in stratum *j*, $d_{i,j}$ is the original density estimate for that haul, and $A_i$ and $n_i$ are the area and the number of hauls in stratum *i* respectively.

### Weight-at-length relationship

The parameters of the weight-at-length relationship, *a* and *b* were re-estimated by fitting the relationship:

$$W=aL^b$$

where *W* = weight (kg), *L* = length (mm) of individual Icefish measurements taken during the 2018 survey, and were fitted using the *nls*() function in R (R Development Core Team 2018).

### Length-at-age

Growth parameters were re-evaluated in 2017 (Maschette et al. 2017) using survey data between 2010–2017 and used in the assessment.

### Maturity

For the assessment, all fish (1 - 3 year olds) were assumed to be mature so that the status of the whole stock is monitored.

### Natural mortality

Natural mortality was assumed to be 0.4 (de la Mare 1998).

**Survey biomass and preliminary yield estimation**

Using the method described in Constable et al. (2005, Appendix 1), a bootstrap algorithm was implemented in R to estimate the uncertainty in the total biomass (tonnes) of Mackerel Icefish over the survey area. Prior to the bootstrap procedure, the observed densities from each haul were rescaled using the equation described above for cohort structure. The lower one-sided 95% confidence bound of the biomass estimate was then used as the estimate of the standing stock at the start of the projection period.

In combination with the biological parameters and other input settings shown in Table 3.7, the Generalised Yield Model (Constable and de la Mare 1996, Constable et al. 2002) was used to estimate the fishing mortality and corresponding catch that meets the short-term decision rule, i.e. that will result in a 75% escapement relative to a two-year projection with zero fishing mortality (Figure 3.1).

Few fish in the Mackerel Icefish population in Division 58.5.2 survive beyond age 4, with a drop in abundance between 3+ and 4+ cohorts observed in consecutive surveys (Welsford 2011, 2015). Consequently, the assessment scenarios run here only includes the biomass estimated from the 1+ to 3+ cohorts.

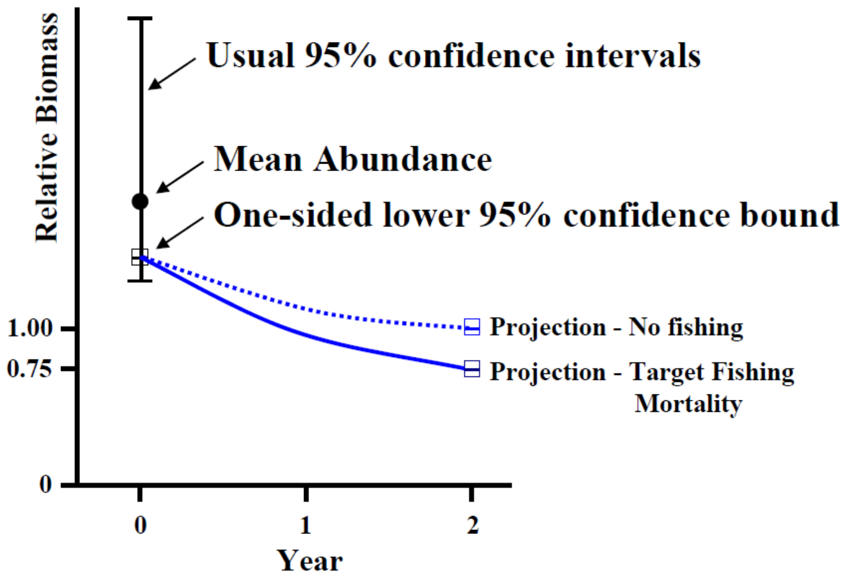



**Figure 3.1:** Decision rule for determining yield for Mackerel Icefish in year 1 and 2 after a survey (from Constable et al. 2005).

## 3.3. Results

### Cohort structure

The best CMIX fit to the survey length density data was achieved when the population was assumed to consist of 4 components, i.e. year classes 1+ through 4+ (Tables 3.1). The substantial 3+ cohort observed in the 2017 survey (Maschette and Welsford 2017) is still present as the 4+ cohort this year (Figure 3.2). Overall fish density was estimated to be the higher than last year due to the presence of a strong 2+ and a weaker 3+ cohort (Table 3.2).

**Table 3.1:** Results of CMIX analysis of Mackerel Icefish from the 2018 random stratified trawl survey in Division 58.5.2.

| | Mixture Components | | | |
|---|---|---|---|---|
| | **1 (1+)** | **2 (2+)** | **3 (3+)** | **4 (4+)** |
| Mean length (mm) | 180 | 293 | 356 | 400 |
| SD (mm) | 14.0 | 16.7 | 18.1 | 19.1 |
| Intercept of CV | 9.93 | | | |
| Slope of CV | 0.02 | | | |
| Total density ($n.km^{-2}$) | 18.6 | 866.7 | 309.7 | 542.7 |
| SD ($n.km^{-2}$) | 10.0 | 143.2 | 115.8 | 151.5 |
| Sum of observed densities | 1755.4 | | | |
| Sum of expected densities | 1736.9 | | | |

**Table 3.2:** Comparison of mean density of Mackerel Icefish ($n.km^{-2}$), and the CMIX estimate of overall and cohort density in the surveys conducted in 2016-2018 in Division 58.5.2. Note that the age of each year cohort increments by one year after the nominal birthdate of 1 December. For example, the 2+ cohort observed in 2016 is the same as 3+ cohort observed in 2017.

| Year | Month | Overall Density | | Cohort Density | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **Expected** | **Observed** | **1+** | **2+** | **3+** | **4+** | **5+** |
| 2016 | April | 2288.6 | 2361.5 | 3.5 | 1437.9 | 495.8 | 344.3 | 7.5 |
| 2017 | April | 1297.3 | 1338.1 | 29.9 | 90.5 | 1177.6 | - | - |
| 2018 | April | 1736.9 | 1755.4 | 18.6 | 866.7 | 309.7 | 542.7 | - |

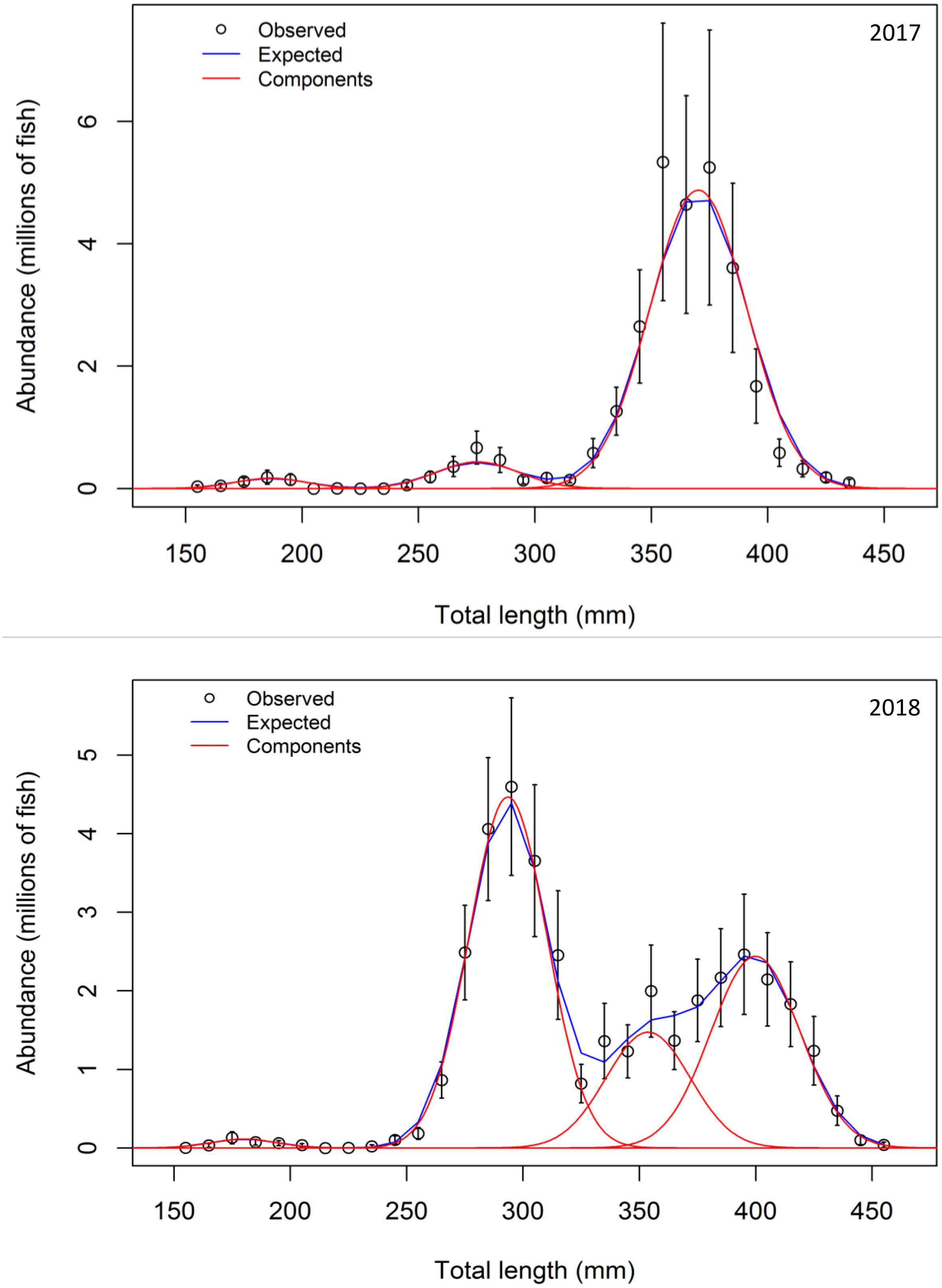



**Figure 3.2:** Observed and estimated length densities using CMIX for Mackerel Icefish in the surveys from April 2017 (upper panel) and April 2018 (lower panel). Shown are observed mean abundances at length (black circles, +SE), fitted total abundances at length (blue lines), and fitted abundances at length for the different components (red lines).

### Weight-at-length relationship

Due to a malfunction of the Icefish scales at the start of the RSTS, only 8 Mackerel Icefish were measured during the 2018 RSTS. The weight-at-length relationship was re-estimated based on 2 562 Icefish measured in the two weeks prior to the commencement of the RSTS. The re-estimated weight-at-length relationship closely followed that of last year, although fish larger than 350 mm tended to be slightly lighter in 2018 (Table 3.3, Figure 3.3).

**Table 3.3:** Estimates of the weight-at-length parameters of Mackerel Icefish fitted to data from each survey conducted in 2017 and 2018 in Division 58.5.2, and those estimated by de la Mare et al. (1998).

| Model | Parameter | |
|---|---|---|
| | ***a*** | ***b*** |
| de la Mare *et al.* (1998) | 2.69 E-10 | 3.515 |
| 2017 fit | 9.157E-10 | 3.316 |
| 2018 fit | 1.259E-09 | 3.260 |

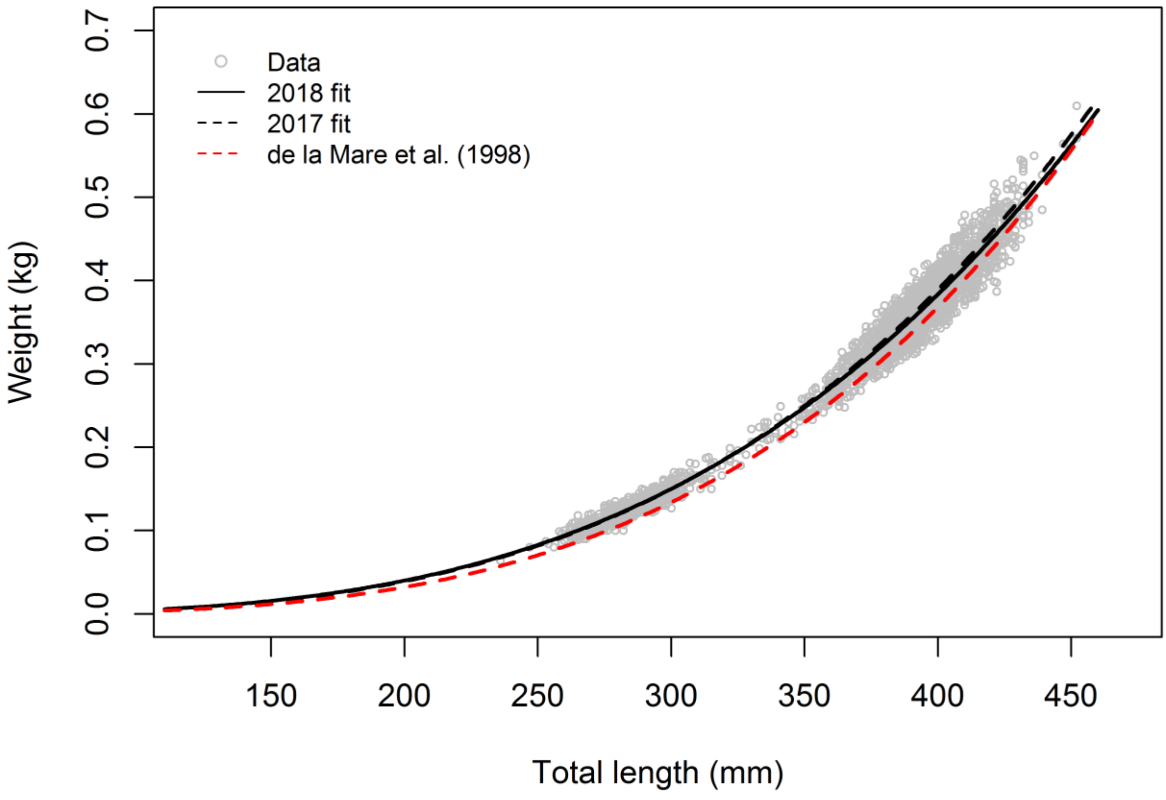



**Figure 3.3:** Weight-at-length data for Mackerel Icefish sampled during the 2018 random stratified trawl survey in Division 58.5.2 (grey dots) and fitted non-linear least squares regression (solid black line), fitted regression to the 2017 survey (dashed black line, Maschette & Welsford 2017) and by de la Mare et al. (1998, dashed red line).

Using the estimated weight-at-length relationship for 2018, the contribution by each age class to overall biomass present during the survey was estimated, indicating that fish up to 3+ constituted only around 50% of the biomass present across the three Icefish strata (Table 3.4).

**Table 3.4:** Proportion of Mackerel Icefish biomass at age in the 2018 random stratified trawl survey in Division 58.5.2.

| Age class | Mean length (mm) | Density (n.km$^{-2}$) | Mean weight (kg) | Proportion of biomass (%) |
|---|---|---|---|---|
| 1+ | 180 | 18.5 | 0.03 | 0.13 |
| 2+ | 294 | 866.7 | 0.14 | 29.69 |
| 3+ | 354 | 309.7 | 0.26 | 19.44 |
| 4+ | 400 | 542.7 | 0.38 | 50.74 |

**Survey biomass and preliminary yield estimation**

The biomass estimates with bootstrapped uncertainty for each Icefish survey stratum and overall are shown in Table 3.5.

The stock projection used the proportion of overall biomass made up by the 1+, 2+ and 3+ cohorts (49.26%, Table 3.4). This means that 2 964.5 of the overall 6 018 t lower 95% CI (Table 3.5) was used in the projection. An estimated 261.2 tonnes of Icefish have been captured after the survey was conducted as part of the 2017/18 fishery, however, based on length data collected 57% of the catch taken is assumed as 4+ fish (Consistent with the approach of Welsford 2010) which are not included in the forward projections. Therefore, the removals after the survey were scaled to reflect the likely impact only on the 2+ and 3+ in the catch, and estimated at 111.9 tonnes are presented in Table 3.6.

**Table 3.5:** Abundance (tonnes) of Mackerel Icefish in Division 58.5.2 estimated by bootstrapping hauls from the 2018 random stratified trawl survey. SE = standard error; LowerCI & UpperCI = lower and upper confidence intervals respectively; LOS 95% CI = lower one-sided 95% confidence interval.

| Stratum | Mean | SE | LowerCI | UpperCI | LOS 95% CI |
|---|---|---|---|---|---|
| Gunnari Ridge | 4042 | 1656 | 1235 | 7509 | 1623 |
| Plateau SE | 1702 | 319 | 1140 | 2364 | 1219 |
| Plateau W | 3234 | 646 | 2126 | 4508 | 2278 |
| Pooled | 8978 | 1947 | 5556 | 13087 | 6018 |

**Table 3.6:** Target fishing mortality rate and annual yields of Mackerel Icefish in Division 58.5.2, estimated to ensure 75% escapement over a 2-year projection period for the 1+, 2+ and 3+ cohorts in the Generalised Yield Model, using the parameters shown in Table 3.7.

| Scenario | Initial biomass estimate (t) | Target fishing mortality rate (yr$^{-1}$) | Catch after RSTS | Yield (tonnes) | |
|---|---|---|---|---|---|
| | | | | 2018/19 | 2019/20 |
| 2018 | 2964.5 | 0.14395 | 261.2 | 424 | 307 |
| 2018 no 4+ | 2964.5 | 0.14395 | 111.9 | 443 | 320 |

## 3.4 Discussion

**Robustness of harvest strategy**

As Mackerel Icefish are known to be a highly plastic species with differing population parameters across its geographic range (Kock 2005). Recent stock assessments indicate that population parameters vary through time within the same population. This is a challenge for stock assessment (SC-CAMLR, 2001). However, as can be seen in Figure 3.8 the current harvest strategy is apparently sufficiently conservative to avoid harvesting that would be inconsistent with CCAMLR's objective.

Estimating biological parameters regularly for this assessment also ensures that long term environmental changes, such as those due to climate change, which may impact population characteristics are accounted for in developing management advice.

**Management Advice**

The 2018 RSTS showed a large 2+ and 4+ cohort dominating the Mackerel Icefish population in Division 58.5.2. The preliminary assessment removes the 4+ cohort under the assumption that it will no longer be available to the fishery in the coming years and as such projects the 1+ - 3+ cohorts forward. The Generalized Yield Model projections indicated that catches of 443 t in the 2018/19 season and 320 t in the 2019/20 season, respectively, satisfy the CCAMLR decision rules.

As it has been observed in previous years, cohorts younger than age 3+ may not be well selected by the survey gear, and we therefore recommend that management advice be set for the 2018/19 season based on this assessment, and a revised assessment be conducted based on survey data collected in 2019.

## 3.5 Acknowledgements

We would like to express our thanks to the members of the Sub-Antarctic Resource Assessment Group and Philippe Ziegler for helpful comments on the analyses and text in this manuscript. We would also like to thank Austral Fisheries Pty Ltd, and the crew and observers aboard the FV *Atlas Cove* for conducting the survey hauls and collecting the data upon which this paper was based.

## 3.6 Assessment diagnostics

The 2018 Working Group of Statistics, Assessments and Modelling (WG-SAM) agreed to the following standard diagnostics presented in Maschette et al. (2018) for future Mackerel Icefish (*Champsocephalus gunnari*) assessments:

Survey information:

- Haul data - Location, and catch and CPUE data including strata.
- Haul by haul CPUE ($kg/km^2$) chart including strata.
- Number of fish measured and weighed from the survey used in the assessment.
- Time series of length frequency distribution.

Assessment:

- Distribution plot of bootstrap runs.
- Survey biomass time series plot (estimates of biomass with confidence intervals and lower one-sided $95^{th}$ percentile).
- CMIX plots.
- Code used for conducting calculations and assessment.
- Table of parameters used and their source.
- Previous lower $95^{th}$ stock assessment projection vs survey estimated time series.

A selection of this diagnostic information can be found in Figures 3.4 to 3.7 and Table 3.7.

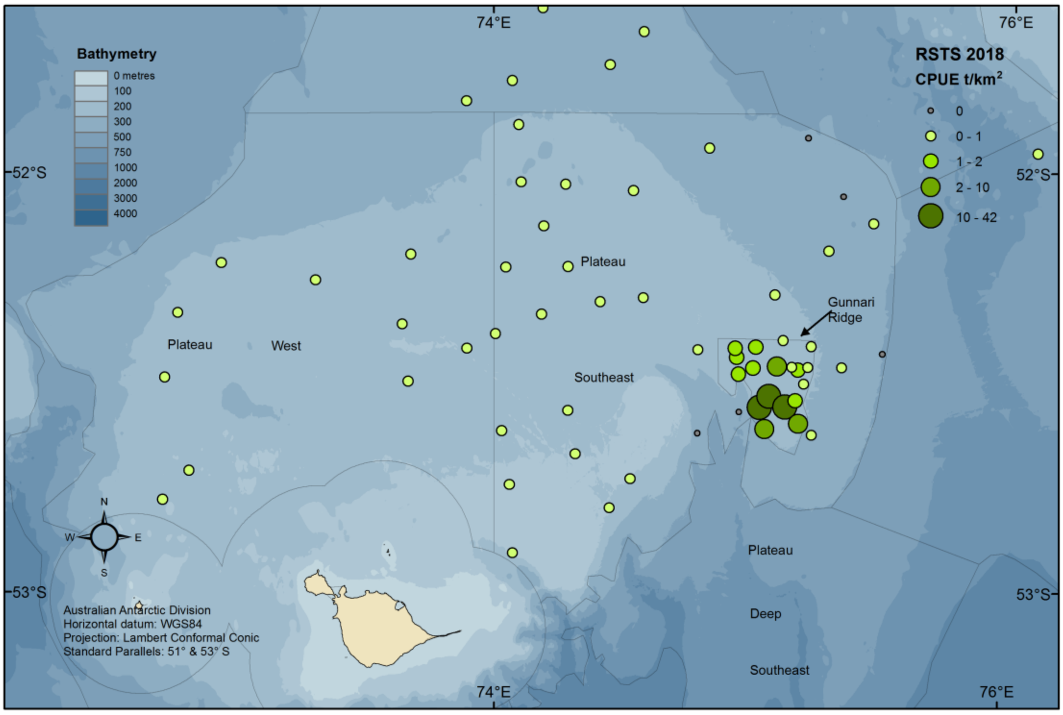



**Figure 3.4:** Catch rates (t/km2) in the 2018 RSTS for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2

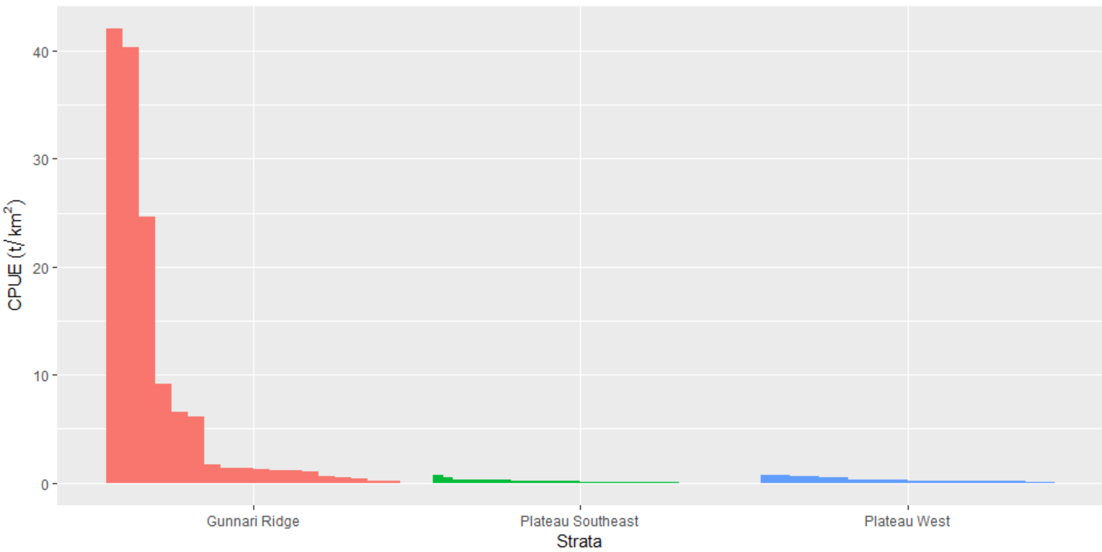



**Figure 3.5:** Catch rate (t/km$^2$) by haul within strata in the 2018 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

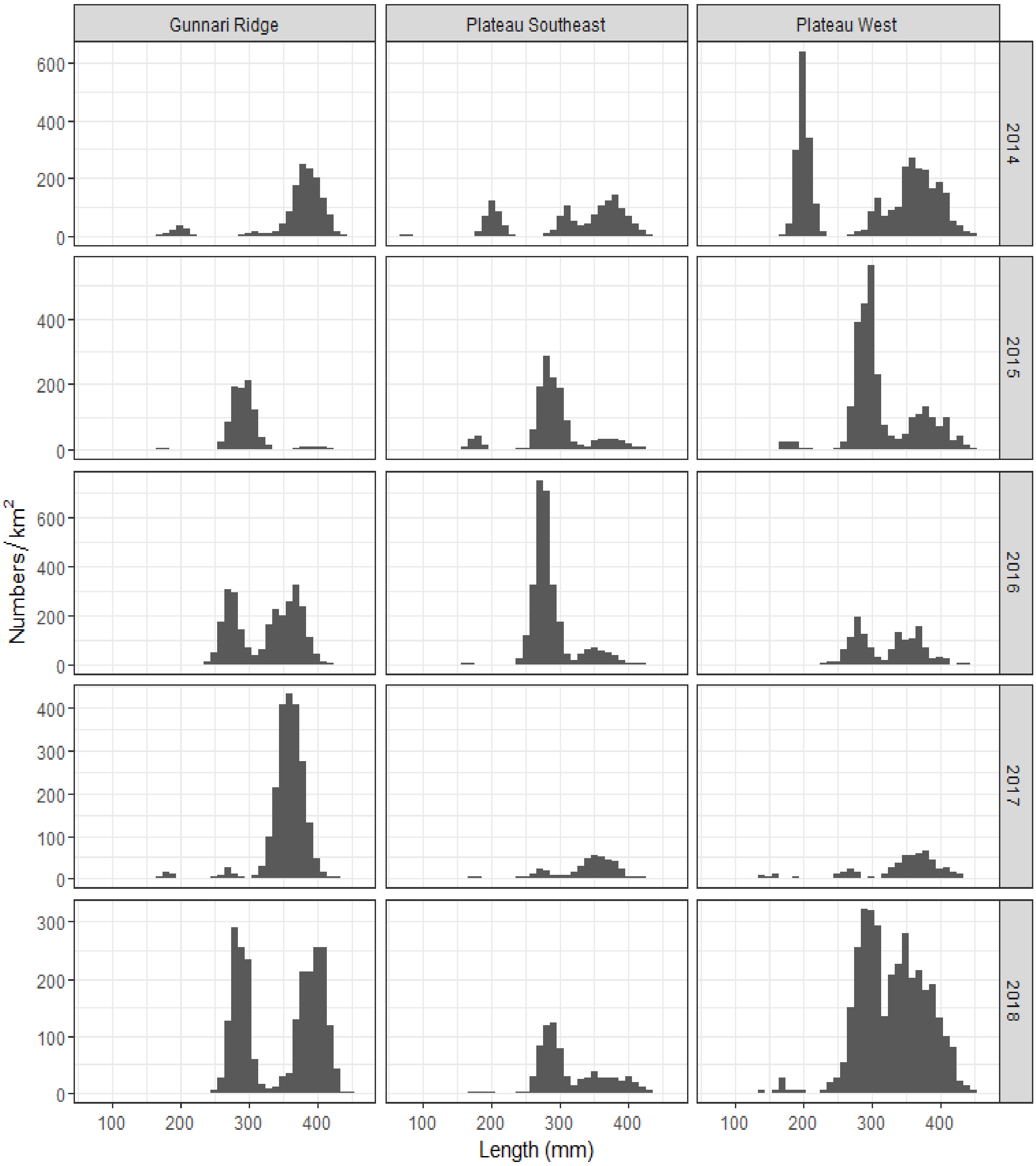



**Figure 3.6:** Fish length distribution by strata in the 2018 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

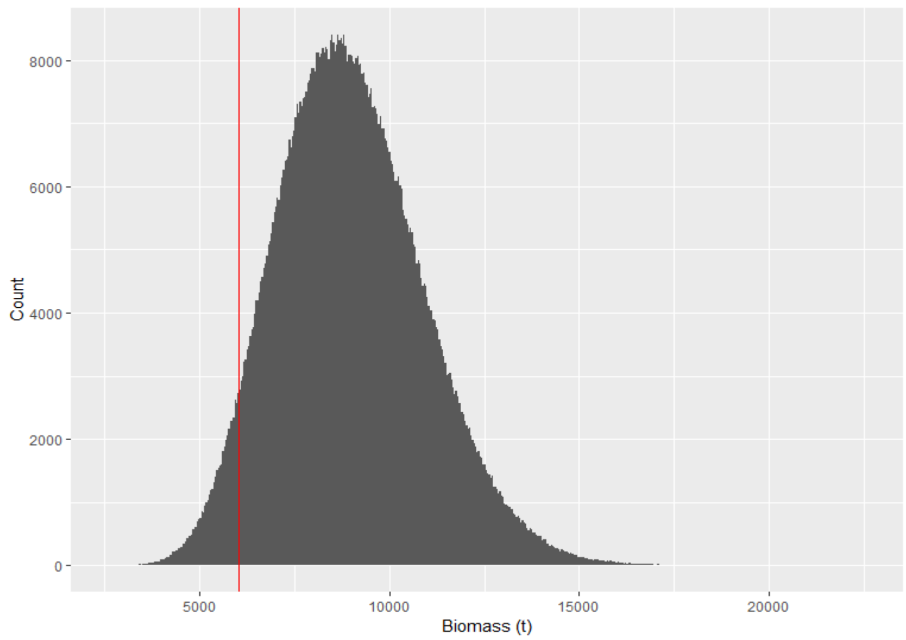



**Figure 3.7:** Distribution of bootstrapped biomass estimates for Mackerel Icefish (*Champsocephalus gunnari*) in 2018 for Division 58.5.2 with lower one-sided 95th confidence bound (red).

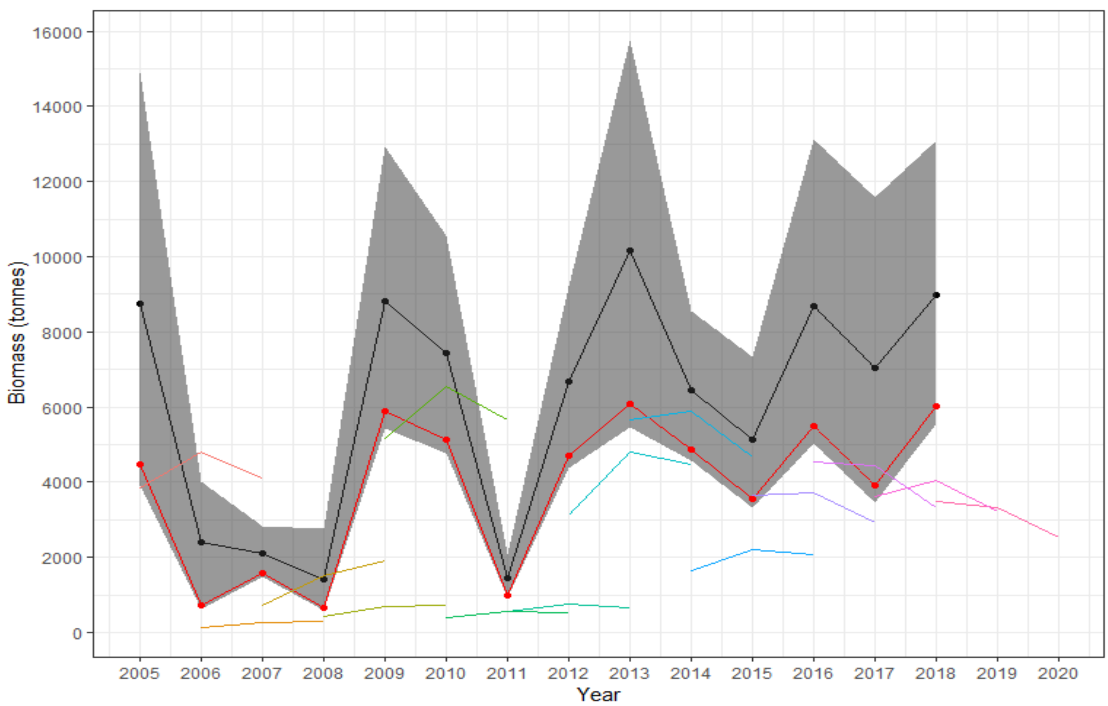



**Figure 3.8:** Mean time series of estimated biomass (including 4+ and 5+ cohorts; black) with confidence intervals (grey) and lower one-sided 95th confidence bound (red), and stock assessment projections (excluding 4+ and 5+ cohorts; colors) that were used to determine catch limits for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2 since 2005.

**Table 3.7:** Parameters used for the 2018 Mackerel Icefish (*Champsocephalus gunnari*) assessment in Division 58.5.2.

| Category | Parameter | Values | Source |
|---|---|---|---|
| Age Structure | Recruitment age | 2 years | de la Mare et al. 1997 |
| | Plus class accumulation | 10 years | de la Mare et al. 1997 |
| | Oldest age in initial structure | 11 years | de la Mare et al. 1997 |
| Initial population structure | Age class density | See Tables 3.1, 3.2 and 3.4 | This Chapter |
| | Biomass | 2964 | This Chapter |
| | Date of estimate (survey) | 7 Apr 18 | |
| Recruitment | | 0 | |
| Natural Mortality | Mean Annual M | 0.4 | de la Mare et al. 1997 |
| von Bertalanffy growth | $t_0$ | 0.067 | Maschette et al. 2017 |
| | $L_{inf}$ | 490 mm | Maschette et al. 2017 |
| | *k* | 0.368 | Maschette et al. 2017 |
| Weight at Length (kg, mm) | Weight-length parameter *a* | $1.259 \times 10^{-09}$ | This Chapter |
| | Weight-length parameter *b* | 3.26 | This Chapter |
| Maturity | Lm50 (set so that the status of the whole stock is being monitored) | 0 mm | |
| | Range: 0 to full maturity | 0 mm | |
| Fishery parameters | Age fully selected | 3 | de la Mare et al. 1997 |
| | Age first selected | 2.5 | de la Mare et al. 1997 |
| | Season | 1 Dec - 30 Nov | CCAMLR Season |
| | Catch between survey and season (tonnes) | 261 | CCAMLR Fishery report |
| Spawning Season | Set so that status of the stock is determined at the end of each year | 30 Nov - 30 Nov | |
| Simulation specifications | Number of runs in simulation | 1 | |
| Individual trial specifications | Years to remove initial age structure | 0 | |
| | Year prior to projection | 2017 | |
| | Reference Start Date in year | 1 Dec | |
| | Increments in year | 365 | |
| | Years to project stock in simulation | 2 | |
| | Reasonable upper bound for Annual F | 5 | |
| | Tolerance for finding F in each year | 0.000001 | |

# Chapter 4: Mackerel Icefish assessment in 2019 at Heard Island and McDonald Islands (HIMI)

Dale Maschette, Gabrielle Nowara and Dirk Welsford

**This Chapter is based on:**

Maschette D., Nowara G. and Welsford D. (2019) A preliminary assessment for Mackerel Icefish (Champsocephalus gunnari) in Division 58.5.2, based on results from the 2019 random stratified trawl survey. Document WG-FSA-2019/02, CCAMLR, Hobart, Australia

## Abstract

The annual random stratified trawl survey was undertaken in Division 58.5.2 in the vicinity of Heard Island and McDonald Islands during April 2019. Based on data from this survey, this paper provides a preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) population structure, abundance and yield in Division 58.5.2 to the west of 79° 20' E using standard CCAMLR methods (CMIX and Generalized Yield Model).

The 2019 survey showed a large 2+ and 3+ cohort in the population. Catches of 527 t in the 2019/20 season and 406 t in the 2020/21 season, respectively, satisfied the CCAMLR decision rules.

## 4.1 Introduction

The fishery for Mackerel Icefish (Champsocephalus gunnari) around Heard Island and McDonald Islands in Division 58.5.2 began in 1997 (CCAMLR 2017). A random stratified trawl survey (RSTS) has been undertaken each year on the shallow plateau (<1000 m) in Division 58.5.2 to collect data on the distribution, abundance and population structure of Patagonian Toothfish, Mackerel Icefish and other species.

Prior to 2011, the population of Mackerel Icefish in Division 58.5.2 generally exhibited one or two cohorts which dominated in abundance and biomass, and these were separated in age by one or two years (Welsford 2010, Welsford 2015, Williams et al. 2001). Since the maximum age of Mackerel Icefish in this region is thought to be around five years, strong cohorts have resulted in large variation of population abundance and the amount of production available to the fishery (SC-CAMLR 2010). However, between 2011 and 2016 at least four and often five cohorts were apparent in the population simultaneously, with no single cohort being overwhelmingly dominant (Maschette and Welsford 2019).

This study provides an analysis of data collected in the 2019 RSTS to estimate the current abundance and cohort structure in the Mackerel Icefish population in Division 58.5.2 and its implications for yields in the fishery in 2019/20 and 2020/21.

## 4.2 Methods

### 2019 survey

The design of the survey conducted in 2019 used the same principles as previous surveys in Division 58.5.2 (Nowara et al. 2019). The three strata where Mackerel Icefish are abundant (Gunnari Ridge, Plateau West and Plateau Southeast) were surveyed in daylight, when Icefish are close to the seafloor and most effectively sampled by demersal trawls (van Wijk et al. 2001). Survey hauls were allocated at random within each stratum, however a minimum spacing of 5 nautical miles between survey stations was specified to ensure hauls would not overlap. Station locations and catches are detailed in Nowara et al. (2019) with density estimates ranging from 0-114.8 tons per $km^2$. In the Gunnari Ridge strata, only 5 of the planned 18 survey hauls were conducted since the total allowable catch for the fishery in this season was reached before the survey could be completed (Nowara et al. 2019). Survey diagnostic information as outlined in Maschette et al. (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of this Chapter.

**Assessment methods**

The assessment method followed those agreed by CCAMLR (SC-CAMLR-XVI, para 5.70) for assessing yield in Mackerel Icefish, as published by de la Mare et al. (1998), and is identical to that used to estimate yields for Mackerel Icefish in Division 58.5.2 in previous years. Assessment diagnostic information as outlined in Maschette et al. (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of the Chapter.

**Cohort structure**

A mixture analysis was undertaken using the CMIX procedure (de la Mare 1994, de la Mare et al. 2002) to estimate the density of fish in each age class and the contribution of each age class to the overall biomass estimated by scaling each age class by its mean weight at length. The survey data were pooled to a single survey data set. As in previous years the sampling effort across strata was un-equal, as such the data is re-scaled so that the mean of the re-scaled data is the same as the stratified mean of the raw data. For each haul in *k* strata, the density data is re-scaled by the composite sampling fraction following de la Mare and Williams (1996):

$$D_{i,j} = d_{i,j}\frac{A_i}{\sum_k A_k} \times \frac{\sum_k n_k}{n_i}$$

where $D_{i,j}$ is the re-scaled density for haul *i* in stratum *j*, $d_{i,j}$ is the original density estimate for that haul, and $A_i$ and $n_i$ are the area and the number of hauls in stratum *i* respectively.

**Weight-at-length relationship**

The parameters of the weight-at-length relationship, *a* and *b* were re-estimated by fitting the relationship:

$$W=aL^b$$

where *W* is the weight (kg), *L* is the length (mm) of individual Icefish taken during the survey, and were fitted using the *nls*() function in R (R Development Core Team 2018).

**Length-at-age**

Growth parameters were re-evaluated in 2017 (Maschette et al. 2017) using survey data between 2010–2017 and used in the assessment.

**Maturity**

For the assessment, all fish (1 - 3 year olds) were assumed to be mature so that the status of the whole stock is monitored.

**Natural mortality**

Natural mortality was assumed to be 0.4 (de la Mare 1998).

**Survey biomass and preliminary yield estimation**

Using the method described in Constable et al. (2005, Appendix 1), a bootstrap algorithm was implemented in R to estimate the uncertainty in the total biomass (tonnes) of Mackerel Icefish over the survey area. Prior to the bootstrap procedure, the observed densities from each haul were rescaled using the equation described above for cohort structure. The lower one-sided 95% confidence bound of the biomass estimate was then used as the estimate of the standing stock at the start of the projection period.

In combination with the biological parameters and other input settings shown in Table 4.7, the Generalised Yield Model (Constable and de la Mare 1996, Constable et al. 2002) was used to estimate the fishing mortality and corresponding catch that meets the short-term decision rule, i.e. that will result in a 75% escapement relative to a two-year projection with zero fishing mortality (Figure 4.1).

Few fish in the Mackerel Icefish population in Division 58.5.2 survive beyond age 4, with a drop in abundance between 3+ and 4+ cohorts observed in consecutive surveys (Welsford 2011, Welsford 2015). Consequently, the assessment scenarios run here only includes the biomass estimated from the 1+ to 3+ cohorts.

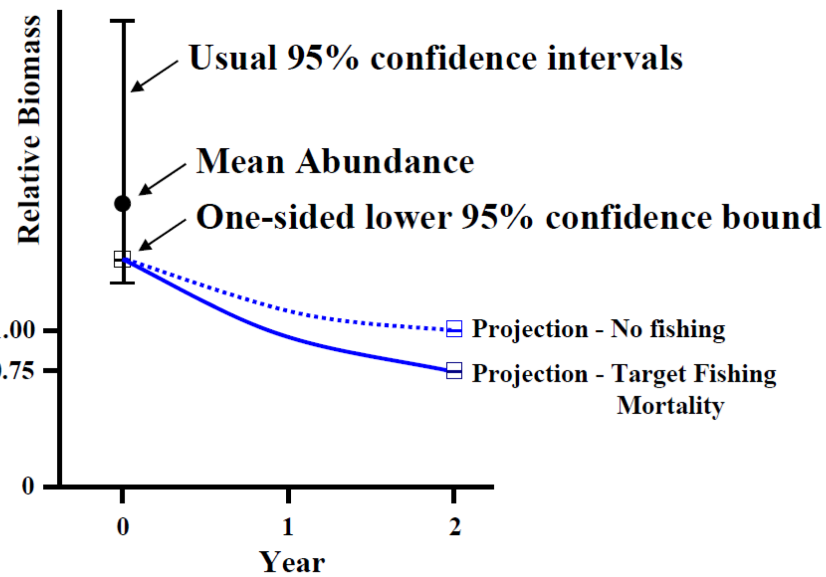



**Figure 4.1:** Decision rule for determining yield for Mackerel Icefish in year 1 and 2 after a survey (from Constable et al. 2005).

## 4.3 Results

### Cohort structure

The best CMIX fit to the survey length density data was achieved when the population was assumed to consist of 4 components, i.e. year classes 1+ through 4+ (Tables 4.1). The substantial 2+ cohort observed in the 2018 survey (Maschette and Welsford 2018) is still present as the 3+ cohort this year (Figure 2). Overall fish density was estimated to be higher than last year due to the presence of strong 2+ and 3+ cohorts (Table 4.2).

**Table 4.1:** Results of CMIX analysis of Mackerel Icefish from the 2019 random stratified trawl survey in Division 58.5.2.

| | Mixture Components | | | |
|---|---|---|---|---|
| | **1 (1+)** | **2 (2+)** | **3 (3+)** | **4 (4+)** |
| Mean length (mm) | 175 | 292 | 361 | 410 |
| SD (mm) | 10.8 | 14.3 | 16.4 | 17.8 |
| Intercept of CV | 5.54 | | | |
| Slope of CV | 0.03 | | | |
| Total density ($n.km^{-2}$) | 127.1 | 617.4 | 1988.9 | 740.4 |
| SD ($n.km^{-2}$) | 32.3 | 135.8 | 536.9 | 215.67 |
| Sum of observed densities | 3355.1 | | | |
| Sum of expected densities | 3471.9 | | | |

**Table 4.2:** Comparison of mean density of Mackerel Icefish ($n.km^{-2}$), and the CMIX estimate of overall and cohort density in the surveys conducted in 2017-2019 in Division 58.5.2. Note that the age of each year cohort increments by one year after the nominal birthdate of 1 December. For example, the 2+ cohort observed in 2017 is the same as 3+ cohort observed in 2018.

| Year | Month | Overall Density | | Cohort Density | | | |
|---|---|---|---|---|---|---|---|
| | | **Expected** | **Observed** | **1+** | **2+** | **3+** | **4+** |
| 2017 | April | 1297.3 | 1338.1 | 29.9 | 90.5 | 1177.6 | - |
| 2018 | April | 1736.9 | 1755.4 | 18.6 | 866.7 | 309.7 | 542.7 |
| 2019 | April | 3471.9 | 3355.1 | 127.1 | 617.4 | 1988.9 | 740.4 |

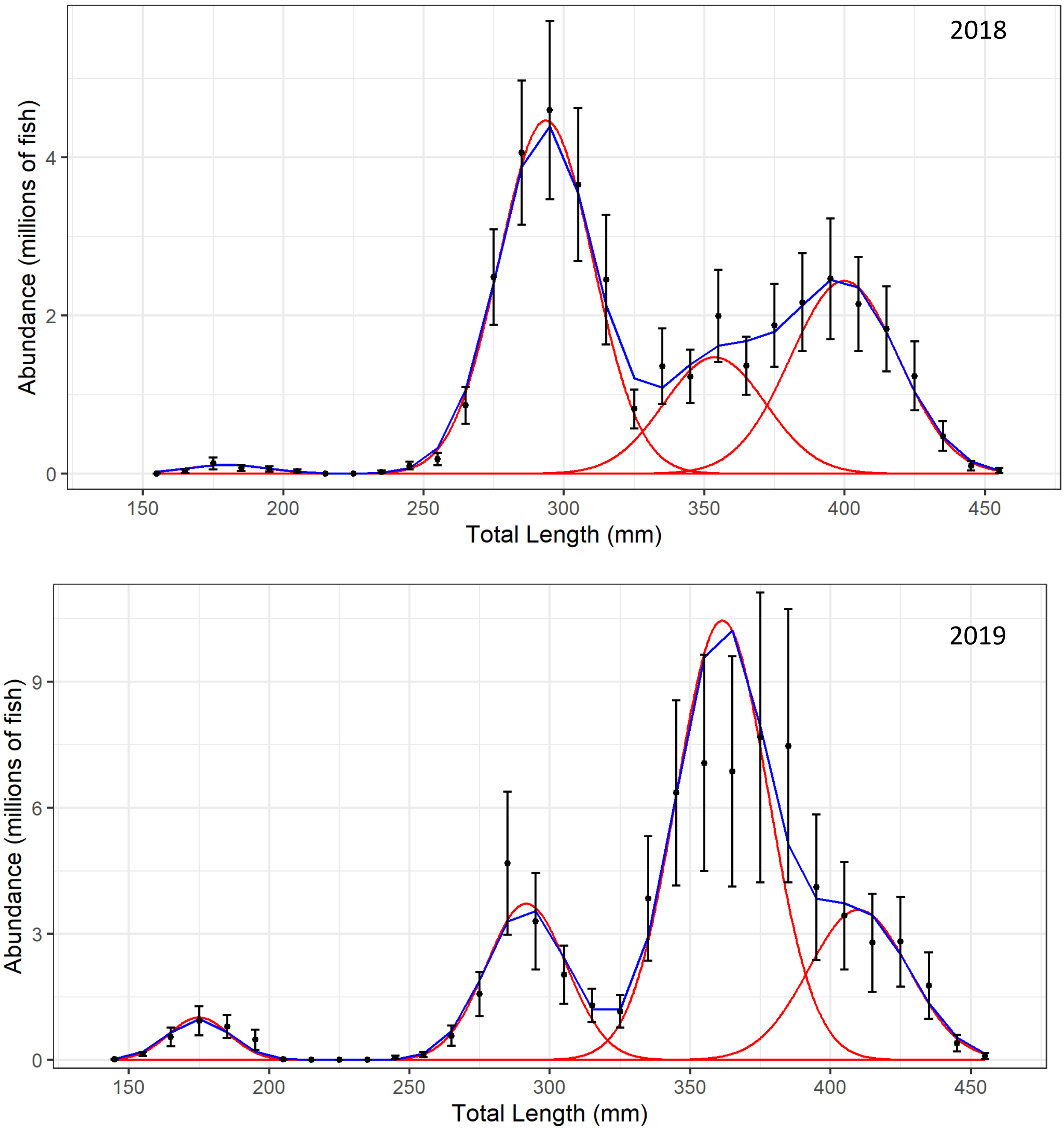



**Figure 4.2:** Observed and estimated length densities using CMIX for Mackerel Icefish in the surveys from April 2018 (upper panel) and April 2019 (lower panel). Shown are observed mean abundances at length (black circles, ± SE), fitted total abundances at length (blue lines), and fitted abundances at length for the different components (red lines).

### Weight-at-length relationship

The weight-at-length relationship was re-estimated based on 3 536 Icefish measured during the RSTS. The re-estimated weight-at-length relationship closely followed that of last year (Table 4.3, Figure 4.3).

**Table 4.3:** Estimates of the weight-at-length parameters of Mackerel Icefish fitted to data from each survey conducted in 2018 and 2019 in Division 58.5.2, and those estimated by de la Mare et al. (1998).

| **Model** | **Parameter** | |
|---|---|---|
| | ***a*** | ***b*** |
| de la Mare *et al.* (1998) | 2.69 E-10 | 3.515 |
| 2018 fit | 1.259E-09 | 3.260 |
| 2019 fit | 1.078E-09 | 3.286 |

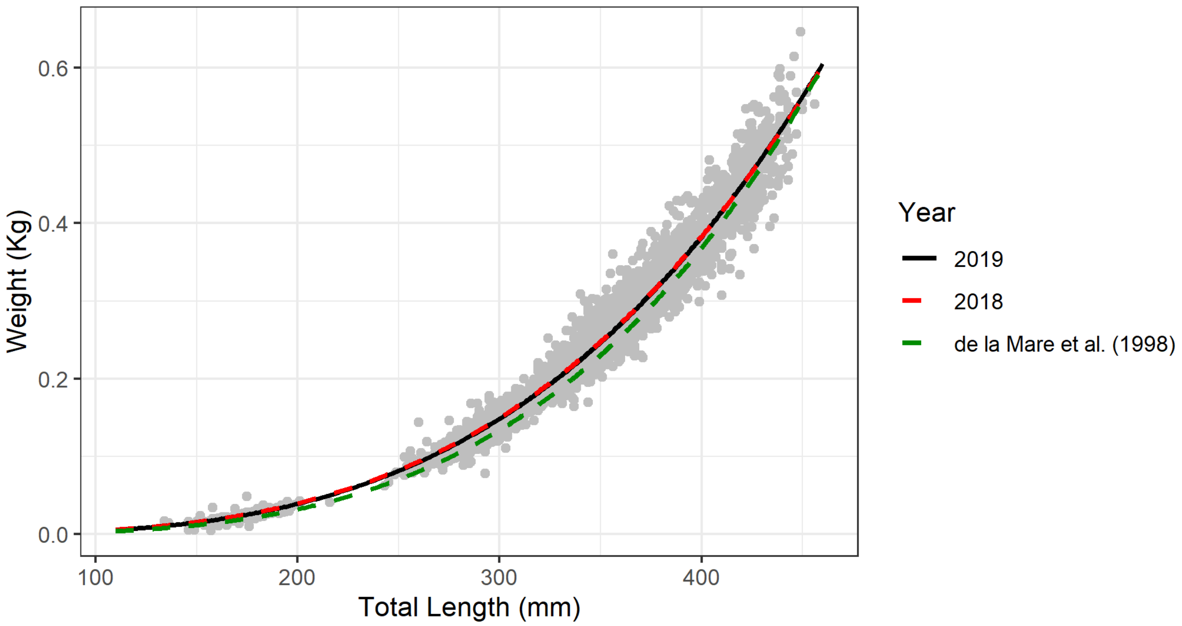



**Figure 4.3:** Weight-at-length data for Mackerel Icefish sampled during the 2019 random stratified trawl survey in Division 58.5.2 (grey dots) and fitted non-linear least squares regression (solid black line), fitted regression to the 2018 survey (dashed red line, Maschette & Welsford 2018) and by de la Mare et al. (1998, dashed green line).

Using the estimated weight-at-length relationship for 2019, the contribution of each age class to the overall biomass present during the survey was estimated, indicating that fish up to 3+ constituted around 67% of the biomass present across the three Icefish strata (Table 4.4).

**Table 4.4:** Proportion of Mackerel Icefish biomass at age in the 2019 random stratified trawl survey in Division 58.5.2.

| **Age class** | **Mean length (mm)** | **Density ($n.km^{-2}$)** | **Mean weight (kg)** | **Proportion of biomass (%)** |
|---|---|---|---|---|
| 1+ | 175 | 127.1 | 0.03 | 0.34 |
| 2+ | 292 | 617.4 | 0.14 | 8.96 |
| 3+ | 361 | 1988.9 | 0.27 | 57.93 |
| 4+ | 410 | 740.4 | 0.41 | 32.76 |

**Survey biomass and preliminary yield estimation**

The biomass estimates with bootstrapped uncertainty for each Icefish survey stratum and overall are shown in Table 4.5. The presence of two very large hauls compared to the remaining hauls in the Gunnari Ridge strata lead to a multi-modal distribution of the bootstrapped biomass (Figure 4.2). Consistent with the previous advice provided by WG-FSA when such a situation has arisen (see WG-FSA-13 paras. 4.2 - 4.3), these hauls were removed, resulting in a unimodal distribution of the bootstrapped biomass.

The stock projection used the proportion of overall biomass made up by the 1+, 2+ and 3+ cohorts (67.23%, Table 4.4). This means that 3 724 t of the overall 5 539 t lower 95% CI (Table 5) was used in the projection (Table 4.6).

**Table 4.5:** Abundance (tonnes) of Mackerel Icefish in Division 58.5.2 estimated by bootstrapping hauls from the 2019 random stratified trawl survey. SE = standard error; Lower CI & Upper CI = lower and upper confidence intervals respectively; LOS 95% CI = lower one-sided 95% confidence interval. * Bootstrap estimates after two large hauls had been removed from the Gunnari Ridge strata.

| Stratum | Mean | SE | Lower CI | Upper CI | LOS 95% CI |
|---|---|---|---|---|---|
| Gunnari Ridge | 20231 | 12655 | 123 | 44097 | 183 |
| Gunnari Ridge* | 156 | 88 | 21 | 322 | 56 |
| Plateau SE | 6088 | 2211 | 2737 | 11017 | 3061 |
| Plateau W | 2601 | 678 | 1365 | 3878 | 1553 |
| Pooled | 28920 | 14246 | 7129 | 60666 | 8310 |
| Pooled* | 8845 | 2317 | 5109 | 13942 | 5539 |

**Table 4.6:** Target fishing mortality rate and annual yields of Mackerel Icefish in Division 58.5.2, estimated to ensure 75% escapement over a 2-year projection period for the 1+, 2+ and 3+ cohorts in the Generalised Yield Model, using the parameters shown in Table 4.7.

| Scenario | Initial biomass estimate (t) | Target fishing mortality rate ($yr^{-1}$) | Catch after RSTS | Yield (tonnes) | |
|---|---|---|---|---|---|
| | | | | 2019/20 | 2020/21 |
| 2019 | 3724 | 0.14433 | 0 | 527 | 406 |

## 4.4. Discussion

**Robustness of harvest strategy**

Mackerel Icefish are known to be a highly plastic species with differing population parameters across its geographic range (Kock 2005). Recent stock assessments indicate that population parameters vary through time within the same population (Maschette and Welsford 2019), which can pose a challenge for stock assessment (SC-CAMLR 2001). However, the current harvest strategy appears sufficiently conservative to avoid harvesting that would be inconsistent with CCAMLRs objectives (Figure 4.8). Estimating biological parameters regularly for this assessment also ensures that long-term environmental changes, such as those predicted to occur due to global climate change, which may impact population characteristics are accounted for.

**Management Advice**

The 2019 RSTS showed a large 2+ and 3+ cohort dominating the Mackerel Icefish population in Division 58.5.2. This preliminary assessment removes the 4+ cohort as it is unlikely that it will be available to the fishery in the coming years and only uses the 1+ - 3+ cohorts in the forward projections using the Generalized Yield Model. These projections indicate that catches of 527 t in the 2019/20 season and 406 t in the 2020/21 season, respectively, satisfy the CCAMLR decision rules.

As in previous years, we recommend that management advice be set for the 2019/20 season based on this assessment, and a revised assessment be conducted based on survey data collected in 2020 since cohorts younger than age 3+ are not well selected by the survey gear.

## 4.5 Acknowledgements

We would like to express our thanks to the members of the Sub-Antarctic Resource Assessment Group and Philippe Ziegler for helpful comments on the analyses and text in this manuscript. We would also like to thank Austral Fisheries Pty Ltd, and the crew and observers aboard the FV *Atlas Cove* for conducting the survey hauls and collecting the data upon which this paper was based.

## 4.6 Assessment diagnostics

The 2018 Working Group of Statistics, Assessments and Modelling (WG-SAM) agreed to the following standard diagnostics presented in Maschette et al. (2018) for future Mackerel Icefish (*Champsocephalus gunnari*) assessments:

Survey information:

- Haul data - Location, and catch and CPUE data including strata.
- Haul by haul CPUE ($kg/km^2$) chart including strata.
- Number of fish measured and weighed from the survey used in the assessment.
- Time series of length frequency distribution.

Assessment:

- Distribution plot of bootstrap runs.
- Survey biomass time series plot (estimates of biomass with confidence intervals and lower one-sided $95^{th}$ percentile).
- CMIX plots.
- Code used for conducting calculations and assessment.
- Table of parameters used and their source.
- Previous lower $95^{th}$ stock assessment projection vs survey estimated time series.

A selection of this diagnostic information can be found in Figures 4.4 to 4.7 and Table 4.7.

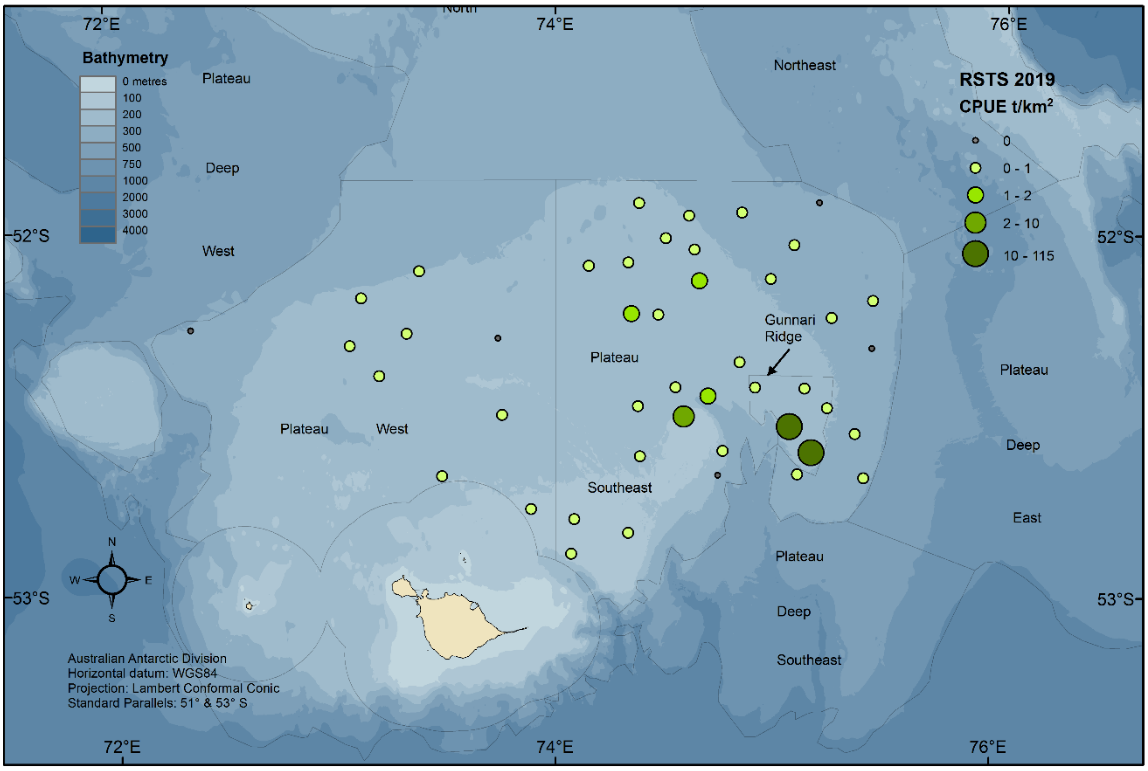



**Figure 4.4:** Catch rates (t/km2) in the 2019 RSTS for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2

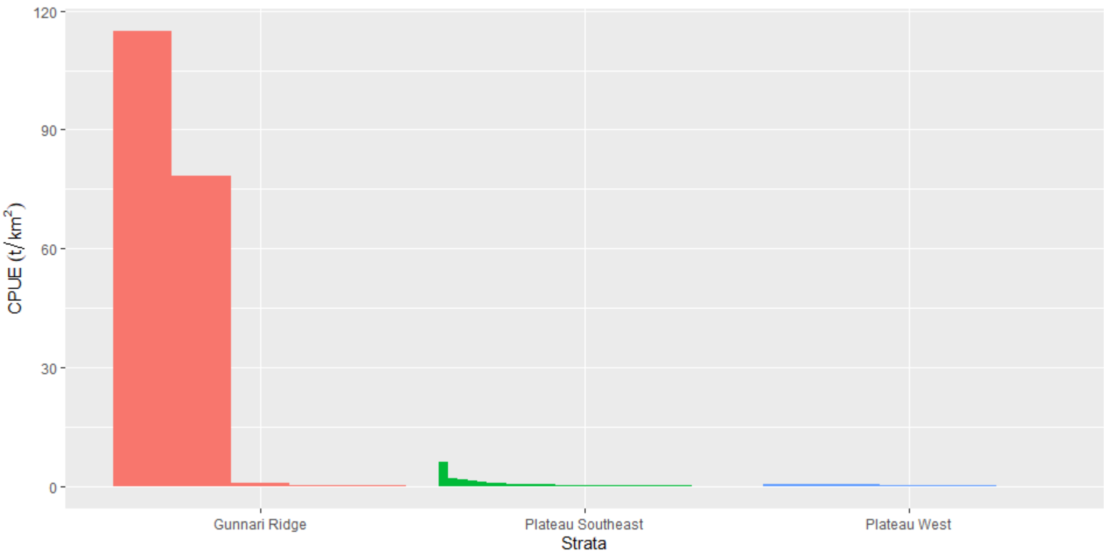



**Figure 4.5:** Catch rate (t/km$^2$) by haul within strata in the 2019 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

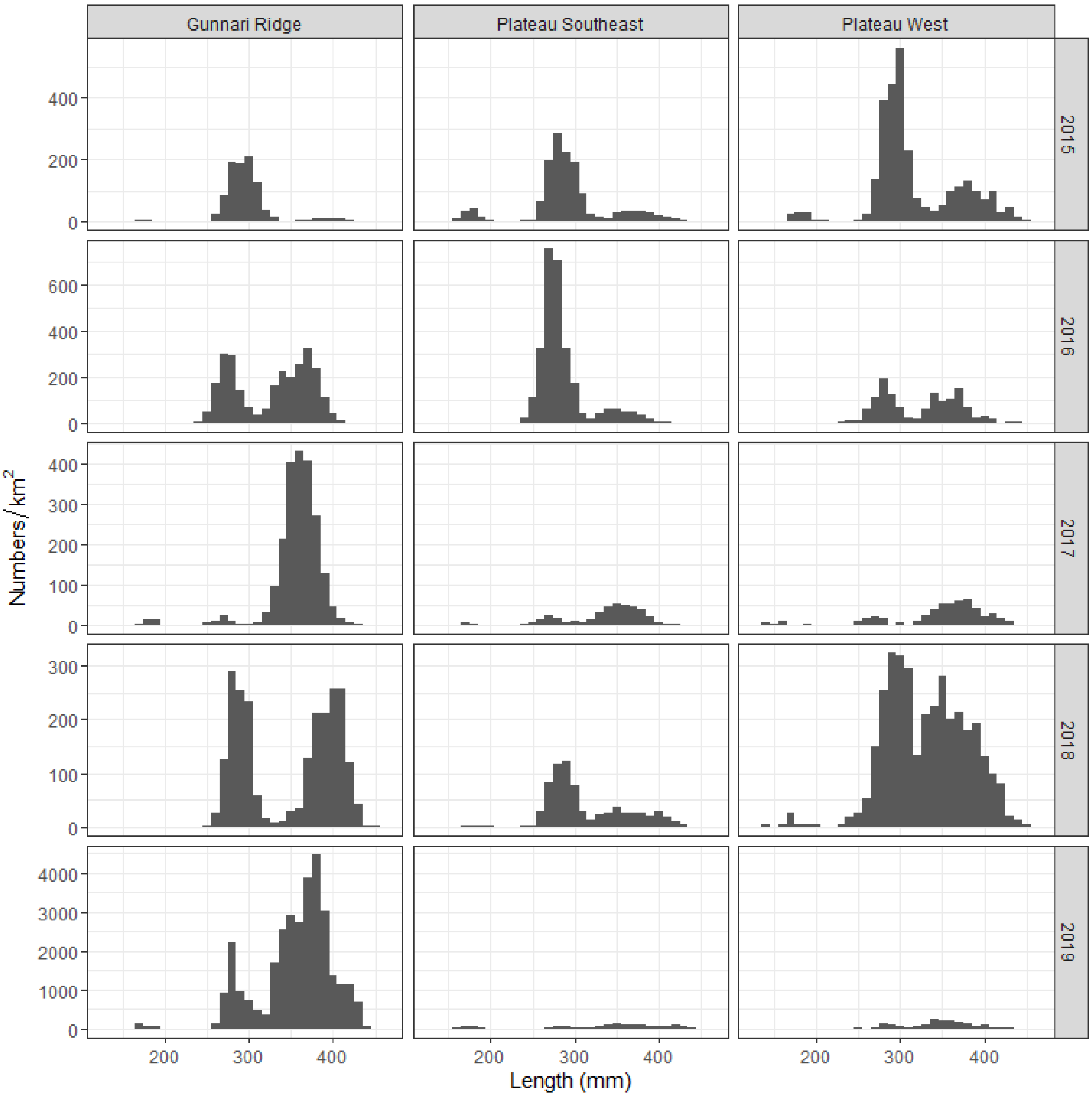



**Figure 4.6:** Fish length distribution by strata in the 2019 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

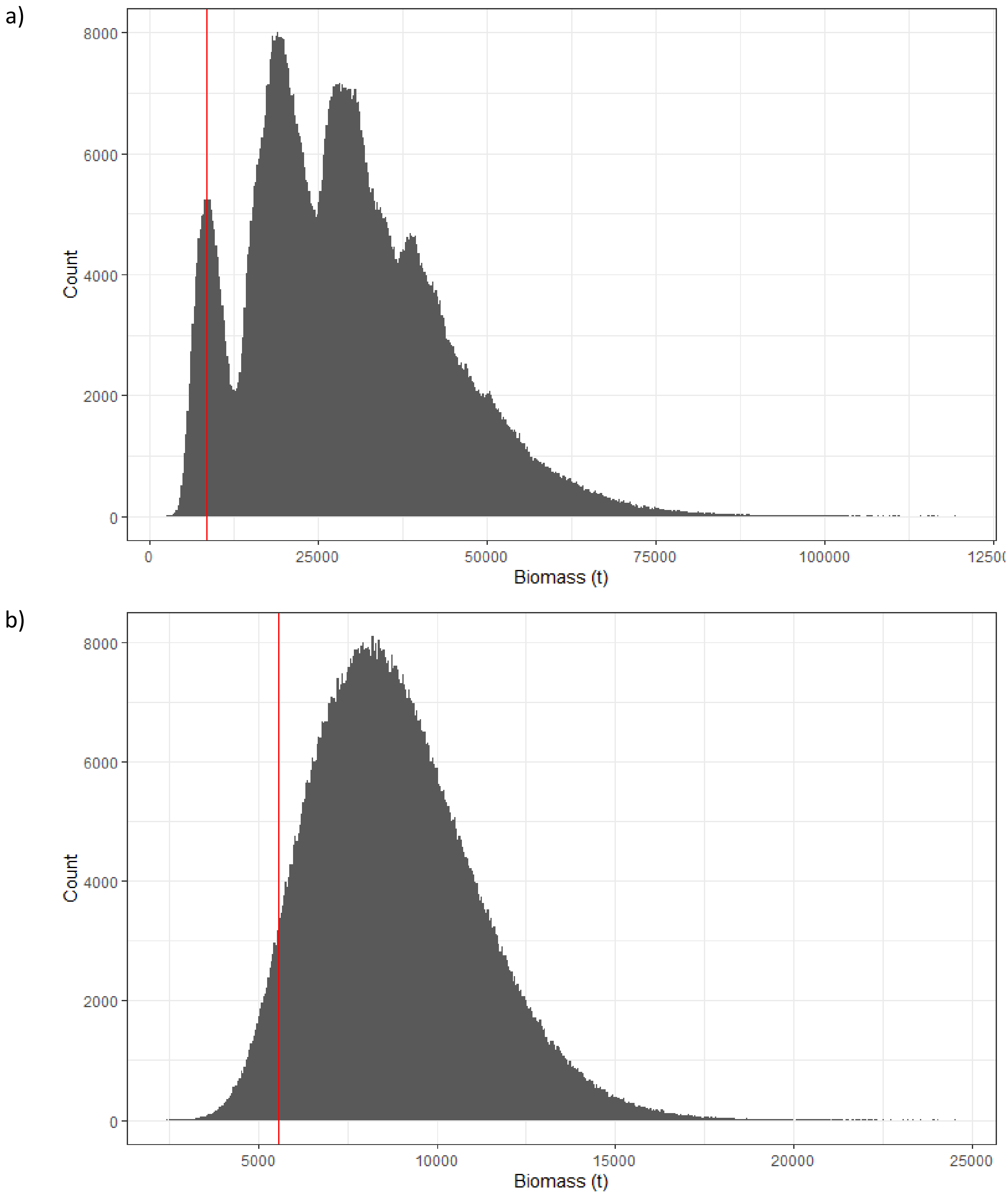



**Figure 4.7:** Distribution of bootstrapped biomass estimates for Mackerel Icefish (*Champsocephalus gunnari*) in 2019 for Division 58.5.2 with lower one-sided 95$^{th}$ confidence bound (red) for (a) all data and (b) with two hauls removed from Gunnari Ridge.

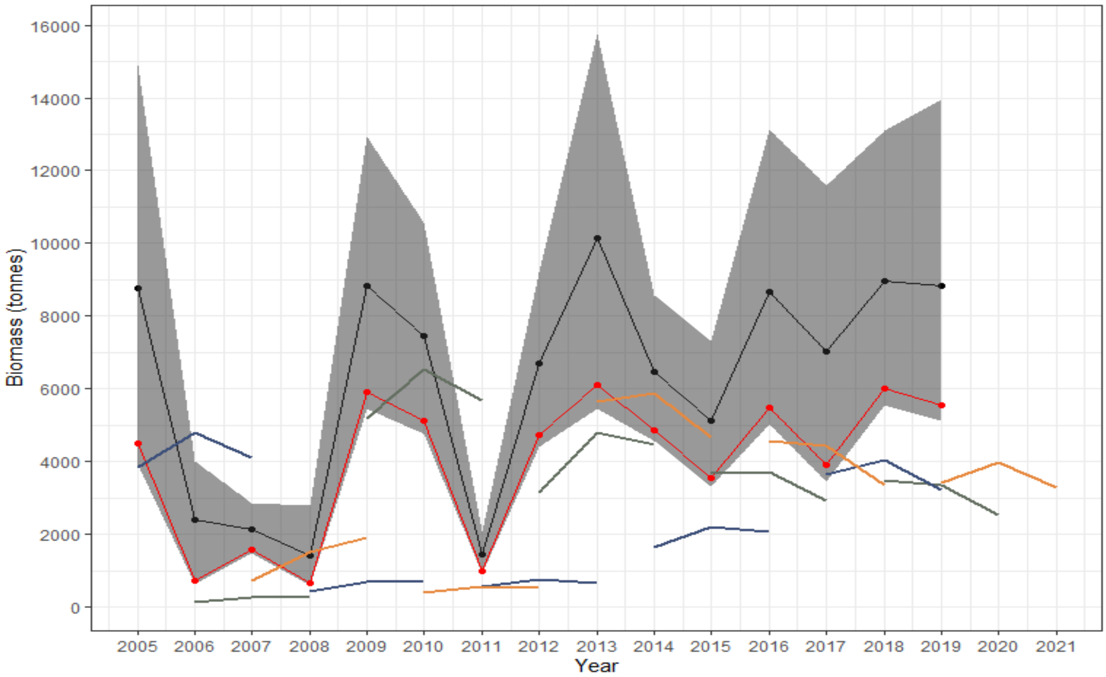



**Figure 4.8:** Mean time series of estimated biomass (including 4+ and 5+ cohorts; black) with confidence intervals (grey) and lower one-sided 95th confidence bound (red), and stock assessment projections (excluding 4+ and 5+ cohorts; colors) that were used to determine catch limits for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2 since 2005.

**Table 4.7:** Parameters used for the 2019 Mackerel Icefish (*Champsocephalus gunnari*) assessment in Division 58.5.2.

| Category | Parameter | Values | Source |
|---|---|---|---|
| Age Structure | Recruitment age | 2 years | de la Mare et al. 1997 |
| | Plus class accumulation | 10 years | de la Mare et al. 1997 |
| | Oldest age in initial structure | 11 years | de la Mare et al. 1997 |
| Initial population structure | Age class density | See Tables 4.1, 4.2 and 4.4 | This Chapter |
| | Biomass | 2964 | This Chapter |
| | Date of estimate (survey) | 4 Apr 19 | |
| Recruitment | | 0 | |
| Natural Mortality | Mean Annual M | 0.4 | de la Mare et al. 1997 |
| von Bertalanffy growth | $t_0$ | 0.067 | Maschette et al. 2017 |
| | $L_{inf}$ | 490 mm | Maschette et al. 2017 |
| | *k* | 0.368 | Maschette et al. 2017 |
| Weight at Length (kg, mm) | Weight-length parameter *a* | 1.078 x 10-09 kg | This Chapter |
| | Weight-length parameter *b* | 3.286 | This Chapter |
| Maturity | Lm50 (set so that the status of the whole stock is being monitored) | 0 mm | |
| | Range: 0 to full maturity | 0 mm | |
| Fishery parameters | Age fully selected | 3 | de la Mare et al. 1997 |
| | Age first selected | 2.5 | de la Mare et al. 1997 |
| | Season | 1 Dec - 30 Nov | CCAMLR Season |
| | Catch between survey and season (tonnes) | 0 | CCAMLR Fishery report |
| Spawning Season | Set so that status of the stock is determined at the end of each year | 30 Nov - 30 Nov | |
| Simulation specifications | Number of runs in simulation | 1 | |
| Individual trial specifications | Years to remove initial age structure | 0 | |
| | Year prior to projection | 2018 | |
| | Reference Start Date in year | 1 Dec | |
| | Increments in year | 365 | |
| | Years to project stock in simulation | 2 | |
| | Reasonable upper bound for Annual F | 5 | |
| | Tolerance for finding F in each year | 0.000001 | |

# Chapter 5: Mackerel Icefish assessment in 2020 at Heard Island and McDonald Islands (HIMI)

Dale Maschette, Simon Wotherspoon and Philippe Ziegler

**This Chapter is based on:**

Maschette D., Wotherspoon S. and Ziegler P. (2020) A preliminary assessment for Mackerel Icefish (Champsocephalus gunnari) in Division 58.5.2, based on results from the 2020 random stratified trawl survey. Document SC-CAMLR-39/01, CCAMLR, Hobart, Australia

## Abstract

The annual random stratified trawl survey was undertaken in Division 58.5.2 in the vicinity of Heard Island and McDonald Islands during April 2020. Based on data from this survey, this paper provides a preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) population structure, abundance and yield in Division 58.5.2 to the west of 79° 20' E using standard CCAMLR methods (CMIX and Generalized Yield Model). Additionally, recent work has been undertaken as part of the krill management strategy re-implementing the Generalized Yield Model software in R, and the two implementations resulted in highly consistent assessment results.

The 2020 survey showed a large 2+ cohort in the population and a high biomass. Based on the Grym implementation, catches of 1276 t in the 2020/21 season and 1047 t in the 2021/22 season satisfy the CCAMLR decision rules.


## 5.1 Introduction

The fishery for Mackerel Icefish (*Champsocephalus gunnari)* around Heard Island and McDonald Islands in Division 58.5.2 began in 1997 (CCAMLR 2017). A random stratified trawl survey (RSTS) has been undertaken each year on the shallow plateau (<1000 m) in Division 58.5.2 to collect data on the distribution, abundance and population structure of Patagonian Toothfish, Mackerel Icefish and other species.

Prior to 2011, the population of Mackerel Icefish in Division 58.5.2 generally exhibited one or two cohorts which dominated in abundance and biomass, and these were separated in age by one or two years (Welsford 2010, Welsford 2015, Williams et al. 2001). Since the maximum age of Mackerel Icefish in this region is thought to be around five years, strong cohorts have resulted in large variation of population abundance and the amount of production available to the fishery (SC-CAMLR 2010). However, between 2011 and 2016 at least four and often five cohorts were apparent in the population simultaneously, with no single cohort being overwhelmingly dominant (Maschette and Welsford 2019).

This study provides an analysis of data collected in the 2020 RSTS to estimate the current abundance and cohort structure in the Mackerel Icefish population in Division 58.5.2 and its implications for yields in the fishery in 2020/21 and 2021/22.

## 5.2 Methods

### 2020 survey

The design of the survey conducted in 2020 used the same principles as previous surveys in Division 58.5.2 (Lamb et al. 2020). The three strata where Mackerel Icefish are abundant (Gunnari Ridge, Plateau West and Plateau Southeast) were surveyed in daylight, when Icefish are close to the seafloor and most effectively sampled by demersal trawls (van Wijk et al. 2001). Survey hauls were allocated at random within each stratum, however a minimum spacing of 5 nautical miles between survey stations was specified to ensure hauls would not overlap. Station locations and catches are detailed in Lamb et al. (2020) with density estimates ranging from 0 - 39.1 tons per km$^2$. Survey diagnostic information as outlined in Maschette et al. (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of this Chapter.

**Assessment methods**

The assessment method followed those agreed by CCAMLR (SC-CAMLR-XVI, para 5.70) for assessing yield in Mackerel Icefish, as published by de la Mare et al. (1998), and is identical to that used to estimate yields for Mackerel Icefish in Division 58.5.2 in previous years. Additionally, recent work undertaken as part of the krill management strategy (SC-CAMLR-38 Table 1, para 3.34) re-implementing the Generalized Yield Model software in an open source software has resulted in the R package 'Grym' (Wotherspoon & Maschette, 2020). Briefly, the Grym implements the same projections as the GYM software but using an explicit solution with the composite trapezoidal quadrature rule rather than an adaptive Runge Kutta method, resulting in a more accurate projection (Maschette et al. 2020). Here we conduct and compare the 2-year projections of both the GYM software and the Grym. Assessment diagnostic information as outlined in Maschette et al. (2018) were endorsed by WG-SAM-18 (para. 3.11), and a selection is presented at the end of the Chapter.

**Cohort structure**

A mixture analysis was undertaken using the CMIX procedure (de la Mare 1994, de la Mare et al. 2002) to estimate the density of fish in each age class and the contribution of each age class to the overall biomass estimated by scaling each age class by its mean weight at length. The survey data were pooled to a single survey data set. As in previous years the sampling effort across strata was un-equal, as such the data is re-scaled so that the mean of the re-scaled data is the same as the stratified mean of the raw data. For each haul in *k* strata, the density data is re-scaled by the composite sampling fraction following de la Mare and Williams (1996):

$$D_{i,j} = d_{i,j} \frac{A_i}{\sum_k A_k} \times \frac{\sum_k n_k}{n_i}$$

where $D_{i,j}$ is the re-scaled density for haul *i* in stratum *j*, $d_{i,j}$ is the original density estimate for that haul, and $A_i$ and $n_i$ are the area and the number of hauls in stratum *i* respectively.

**Weight-at-length relationship**

The parameters of the weight-at-length relationship, *a* and *b* were re-estimated by fitting the relationship:

$$W=aL^b$$

where *W* is the weight (kg), *L* is the length (mm) of individual Icefish taken during the survey, and were fitted using the *nls*() function in R (R Development Core Team 2020).

**Length-at-age**

Growth parameters were re-evaluated in 2017 (Maschette et al. 2017) using survey data between 2010–2017 and used in the assessment.

**Maturity**

For the assessment, all fish (1 - 3 year olds) were assumed to be mature so that the status of the whole stock is monitored.

**Natural mortality**

Natural mortality was assumed to be 0.4 (de la Mare 1998).

**Survey biomass and preliminary yield estimation**

Using the method described in Constable et al. (2005, Appendix 1), a bootstrap algorithm was implemented in R to estimate the uncertainty in the total biomass (tonnes) of Mackerel Icefish over the survey area. Prior to the bootstrap procedure, the observed densities from each haul were rescaled using the equation described above for cohort structure. The lower one-sided 95% confidence bound of the biomass estimate was then used as the estimate of the standing stock at the start of the projection period.

In combination with the biological parameters and other input settings shown in Table 5.7), the Generalised Yield Model (Constable and de la Mare 1996, Constable et al. 2002) was used to estimate the fishing mortality and corresponding catch that meets the short-term decision rule, i.e. that will result in a 75% escapement relative to a two-year projection with zero fishing mortality (Figure 5.1).

Few fish in the Mackerel Icefish population in Division 58.5.2 survive beyond age 4, with a drop in abundance between 3+ and 4+ cohorts observed in consecutive surveys (Welsford 2011, Welsford 2015). Consequently, the assessment scenarios run here only includes the biomass estimated from the 1+ to 3+ cohorts.

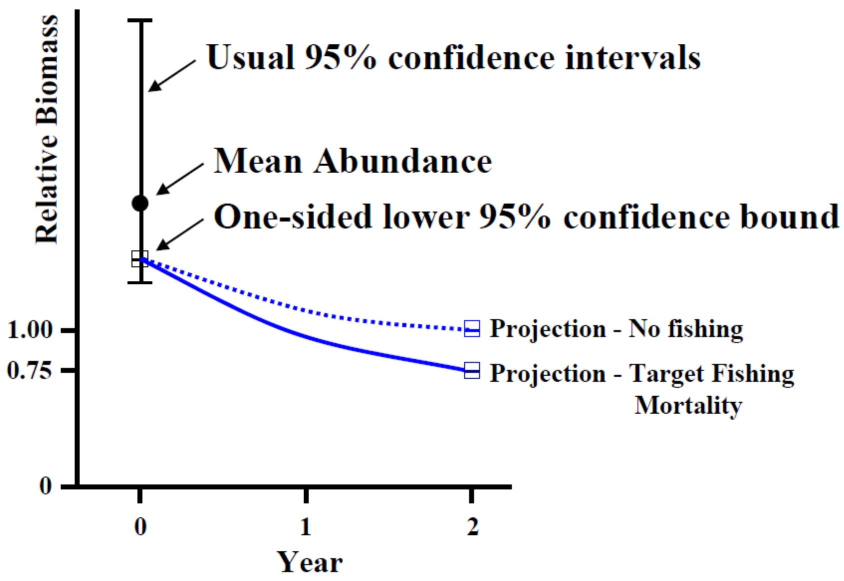



**Figure 5.1:** Decision rule for determining yield for Mackerel Icefish in year 1 and 2 after a survey (from Constable et al. 2005).

## 5.3 Results

### Cohort structure

The best CMIX fit to the survey length density data was achieved when the population was assumed to consist of 4 components, i.e. year classes 1+ through 4+ (Tables 5.1). The substantial 2+ cohort observed in the 2018 survey (Maschette and Welsford 2018) is still present as the 3+ cohort this year (Figure 2). Overall fish density was estimated to be higher than last year due to the presence of strong 2+ and 3+ cohorts (Table 5.2).

**Table 5.1:** Results of CMIX analysis of Mackerel Icefish from the 2020 random stratified trawl survey in Division 58.5.2.

| | **Mixture Components** | | | |
|---|---|---|---|---|
| | **1 (1+)** | **2 (2+)** | **3 (3+)** | **4 (4+)** |
| Mean length (mm) | 165 | 269 | 365 | 414 |
| SD (mm) | 15 | 18 | 21 | 22 |
| Intercept of CV | 10 | | | |
| Slope of CV | 0.03 | | | |
| Total density ($n.km^{-2}$) | 27 | 3725 | 1088 | 101 |
| SD ($n.km^{-2}$) | 14 | 743 | 324 | 107 |
| Sum of observed densities | 4863 | | | |
| Sum of expected densities | 4938 | | | |

**Table 5.2:** Comparison of mean density of Mackerel Icefish ($n.km^{-2}$), and the CMIX estimate of overall and cohort density in the surveys conducted in 2018-2020 in Division 58.5.2. Note that the age of each year cohort increments by one year after the nominal birthdate of 1 December. For example, the 2+ cohort observed in 2019 is the same as 3+ cohort observed in 2020.

| **Year** | **Month** | **Overall Density** | | **Cohort Density** | | | |
|---|---|---|---|---|---|---|---|
| | | **Expected** | **Observed** | **1+** | **2+** | **3+** | **4+** |
| 2018 | April | 1737 | 1755 | 19 | 867 | 310 | 543 |
| 2019 | April | 3472 | 3355 | 127 | 617 | 1989 | 740 |
| 2020 | April | 4938 | 4863 | 27 | 3725 | 1088 | 101 |

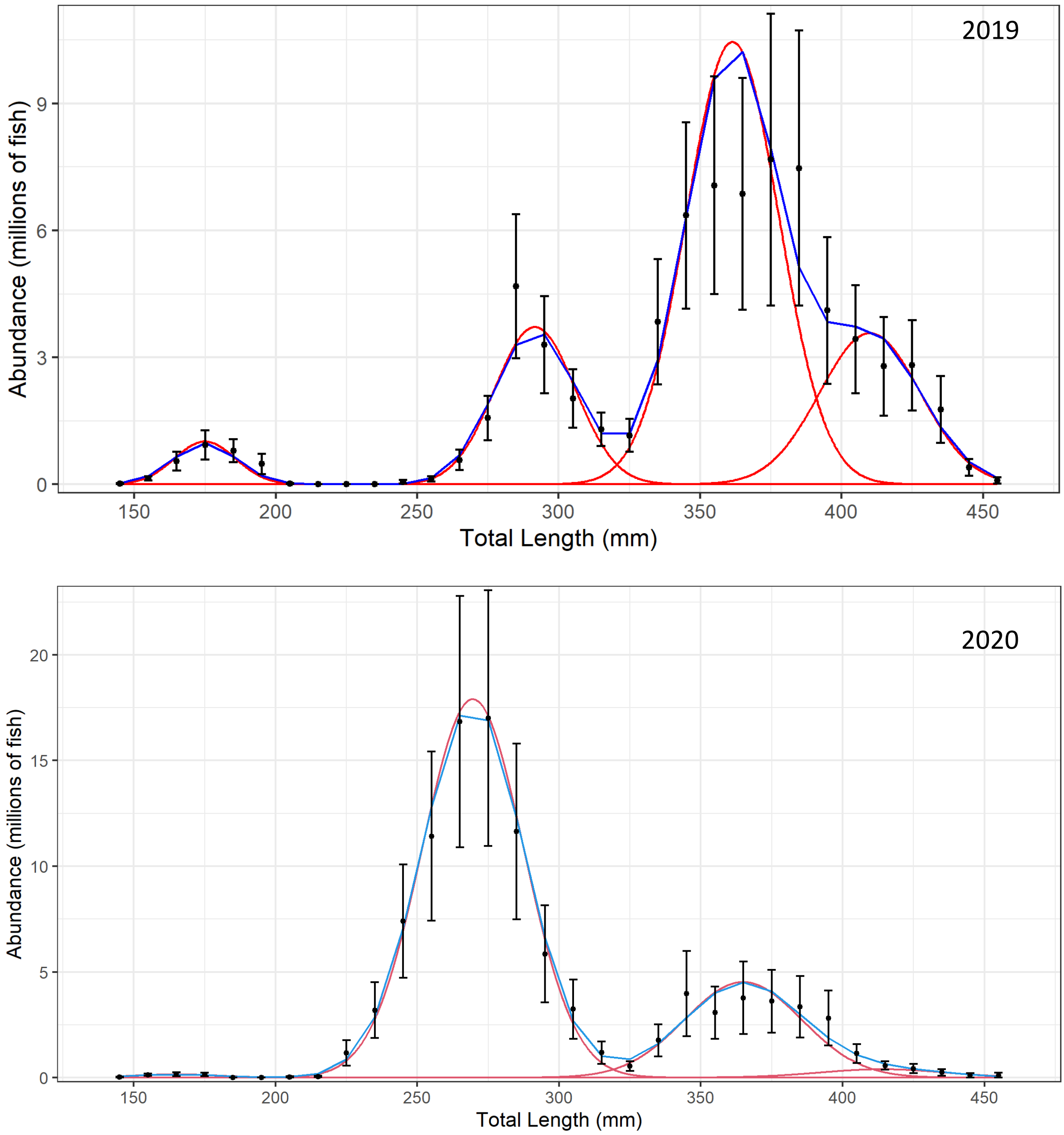



**Figure 5.2:** Observed and estimated length densities using CMIX for Mackerel Icefish in the surveys from April 2019 (upper panel) and April 2020 (lower panel). Shown are observed mean abundances at length (black circles, + SE), fitted total abundances at length (blue lines), and fitted abundances at length for the different components (red lines).

### Weight-at-length relationship

The weight-at-length relationship was re-estimated based on 16 973 Icefish measured during the RSTS. The re-estimated weight-at-length relationship closely followed that of last year (Table 5.3, Figure 5.3).

**Table 5.3:** Estimates of the weight-at-length parameters of Mackerel Icefish fitted to data from each survey conducted in 2019 and 2020 in Division 58.5.2, and those estimated by de la Mare et al. (1998).

| Model | Parameter | |
|---|---|---|
| | ***a*** | ***b*** |
| de la Mare *et al.* (1998) | 2.69 E-10 | 3.515 |
| 2019 fit | 1.078E-09 | 3.286 |
| 2020 fit | 1.150E-09 | 3.275 |

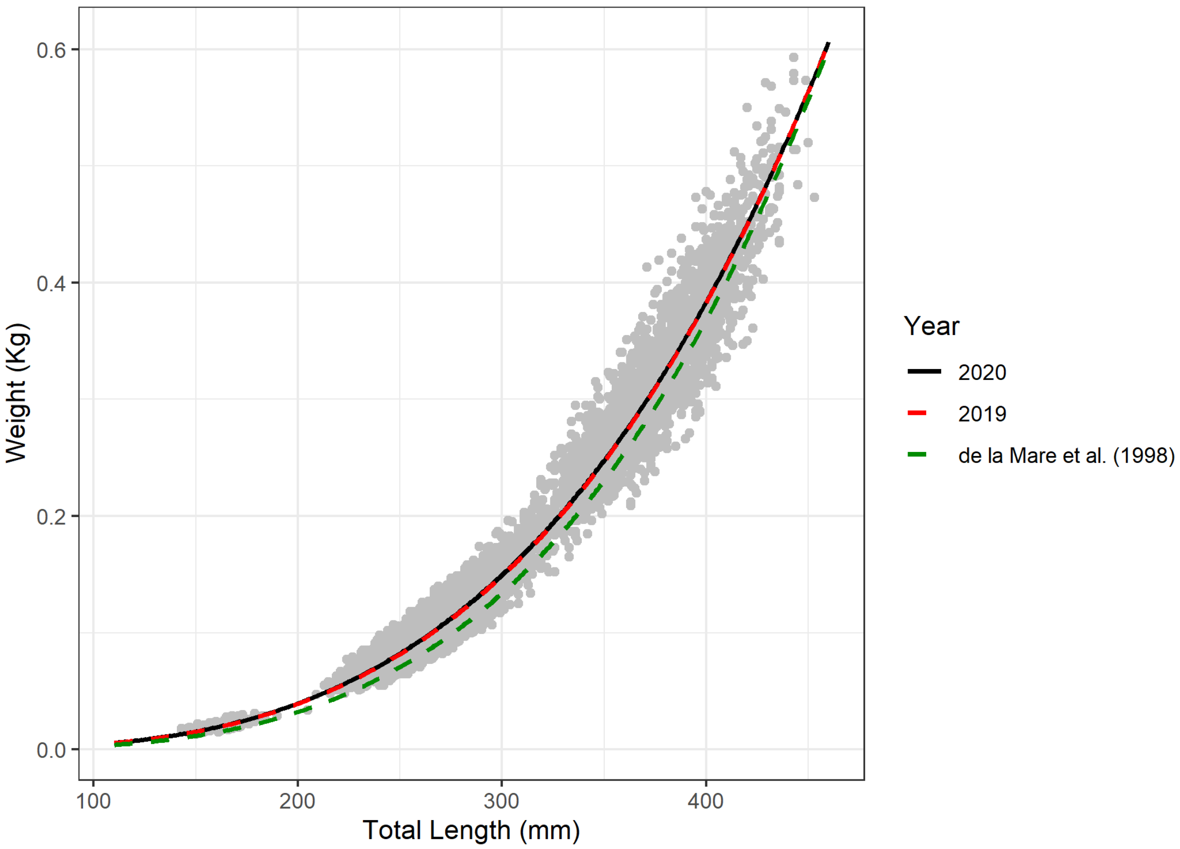



**Figure 5.3;** Weight-at-length data for Mackerel Icefish sampled during the 2020 random stratified trawl survey in Division 58.5.2 (grey dots) and fitted non-linear least squares regression (solid black line), fitted regression to the 2019 survey (dashed red line, Maschette & Welsford 2019) and by de la Mare et al. (1998, dashed green line).

Using the estimated weight-at-length relationship for 2020, the contribution of each age class to the overall biomass present during the survey was estimated, indicating that fish up to 3+ constituted around 94% of the biomass present across the three Icefish strata (Table 5.4).

**Table 5.4:** Proportion of Mackerel Icefish biomass at age in the 2020 random stratified trawl survey in Division 58.5.2.

| Age class | Mean length (mm) | Density (n.km$^{-2}$) | Mean weight (kg) | Proportion of biomass (%) |
|---|---|---|---|---|
| 1+ | 165 | 27 | 0.02 | 0.08 |
| 2+ | 270 | 3725 | 0.11 | 52.7 |
| 3+ | 365 | 1088 | 0.28 | 41.4 |
| 4+ | 414 | 101 | 0.43 | 5.8 |

### Survey biomass and preliminary yield estimation

The biomass estimates with bootstrapped uncertainty for each Icefish survey stratum and overall are shown in Table 5.5.

The stock projection used the proportion of overall biomass made up by the 1+, 2+ and 3+ cohorts (94.19%, Table 5.4). This means that 8 075 t of the overall 8 574 t lower 95% CI (Table 5.5) was used in the projection where the GYM and Grym implementations produced highly consistent results (Table 5.6).Projections of the GYM software indicated that catches of 1 272 t in the 2020/21 season and 1 041 t in the 2021/22 season satisfy the CCAMLR decision rules, while projections of the Grym indicated that catches of 1 276 t in the 2020/21 season and 1 047 t in the 2021/22 season satisfy the CCAMLR decision rules.

**Table 5.5:** Abundance (tonnes) of Mackerel Icefish in Division 58.5.2 estimated by bootstrapping hauls from the 2020 random stratified trawl survey. SE = standard error; Lower CI & Upper CI = lower and upper confidence intervals respectively; LOS 95% CI = lower one-sided 95% confidence interval.

| Stratum | Mean | SE | Lower CI | Upper CI | LOS 95% CI |
|---|---|---|---|---|---|
| Gunnari Ridge | 3037 | 1344 | 802 | 5845 | 961 |
| Plateau SE | 4194 | 1007 | 2395 | 6264 | 2650 |
| Plateau W | 5523 | 1887 | 2263 | 9235 | 2698 |
| Pooled | 12753 | 2713 | 7880 | 18372 | 8574 |

**Table 5.6:** Target fishing mortality rate and annual yields of Mackerel Icefish in Division 58.5.2, estimated to ensure 75% escapement over a 2-year projection period for the 1+, 2+ and 3+ cohorts using the Generalised Yield Model (GYM) and the Grym package, using the parameters shown in Table 5.7.

| Scenario | Initial biomass estimate (t) | Target fishing mortality rate (yr$^{-1}$) | Catch after RSTS | Yield (tonnes) | |
|---|---|---|---|---|---|
| | | | | 2020/21 | 2021/22 |
| GYM | 8075 | 0.1440 | 301 | 1272 | 1041 |
| Grym | 8075 | 0.1442 | 301 | 1276 | 1047 |

## 5.4 Discussion

**Robustness of harvest strategy**

Mackerel Icefish are known to be a highly plastic species with differing population parameters across its geographic range (Kock 2005). Recent stock assessments indicate that population parameters vary through time within the same population (Maschette and Welsford 2019), which can pose a challenge for stock assessment (SC-CAMLR 2001). However, the current harvest strategy appears sufficiently conservative to avoid harvesting that would be inconsistent with CCAMLRs objectives (Figure 5.8). Estimating biological parameters regularly for this assessment also ensures that long-term environmental changes, such as those predicted to occur due to global climate change, which may impact population characteristics are accounted for.

**Management Advice**

The 2020 RSTS showed a large 2+ cohort dominating the Mackerel Icefish population in Division 58.5.2. This preliminary assessment removes the 4+ cohort as it is unlikely that it will be available to the fishery in the coming years and only uses the 1+ - 3+ cohorts in the forward projections. Projections run with both the Generalised Yield Model (GYM) software and the Grym were highly consistent. Small differences are likely to be due to differences in programming language random number generators, and calculation of forward projections as discussed in the methods and Maschette et al. (2020).

These projections of the GYM software indicated that catches of 1 272 t in the 2020/21 season and 1 041 t in the 2021/22 season satisfy the CCAMLR decision rules. Projections of the Grym indicated that catches of 1 276 t in the 2020/21 season and 1 047 t in the 2021/22 season satisfy the CCAMLR decision rules.

Given the explicit solution using the composite trapezoidal quadrature rule leads to more exact solutions, we recommend the Grym be used both in this and future assessments of this fishery.

As in previous years, we recommend that management advice be set for the 2020/21 season based on this assessment, and a revised assessment be conducted based on survey data collected in 2021 since cohorts younger than age 3+ are not well selected by the survey gear.

## 5.5. Acknowledgements

We would like to express our thanks to the members of the Sub-Antarctic Resource Assessment Group for helpful comments on the analyses and text in this manuscript. We would also like to thank Austral Fisheries Pty Ltd, and the crew and observers aboard the FV *Atlas Cove* for conducting the survey hauls and collecting the data upon which this paper was based.

## 5.6. Assessment diagnostics

The 2018 Working Group of Statistics, Assessments and Modelling (WG-SAM) agreed to the following standard diagnostics presented in Maschette et al. (2018) for future Mackerel Icefish (*Champsocephalus gunnari*) assessments:

Survey information:

- Haul data - Location, and catch and CPUE data including strata.
- Haul by haul CPUE (kg/km$^2$) chart including strata.
- Number of fish measured and weighed from the survey used in the assessment.
- Time series of length frequency distribution.

Assessment:

- Distribution plot of bootstrap runs.
- Survey biomass time series plot (estimates of biomass with confidence intervals and lower one-sided 95$^{th}$ percentile).
- CMIX plots.
- Code used for conducting calculations and assessment.
- Table of parameters used and their source.
- Previous lower 95$^{th}$ stock assessment projection vs survey estimated time series.

A selection of this diagnostic information can be found in Figures 5.4 to 5.7 and Table 5.7.

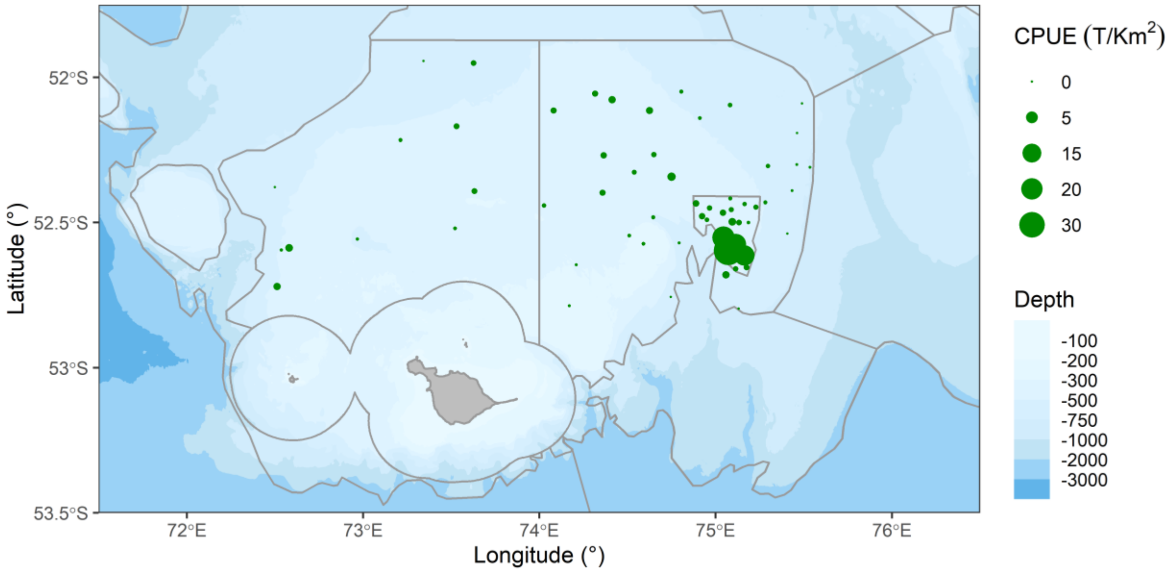



**Figure 5.4:** Catch rates (t/km2) in the 2020 RSTS for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2

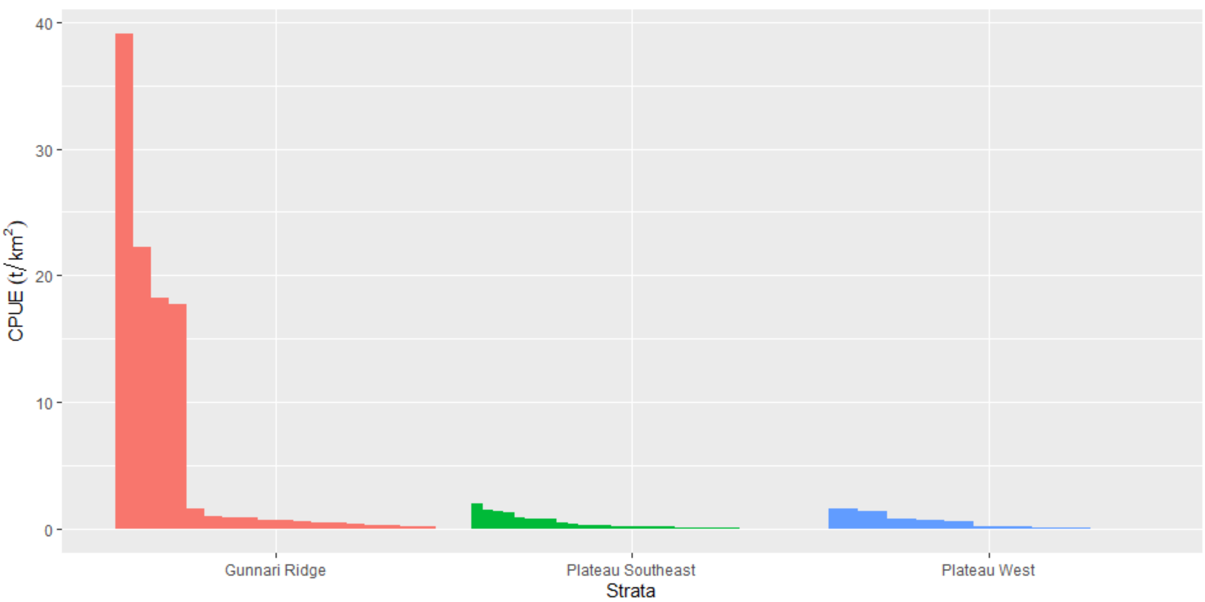



**Figure 5.5:** Catch rate (t/km$^2$) by haul within strata in the 2020 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

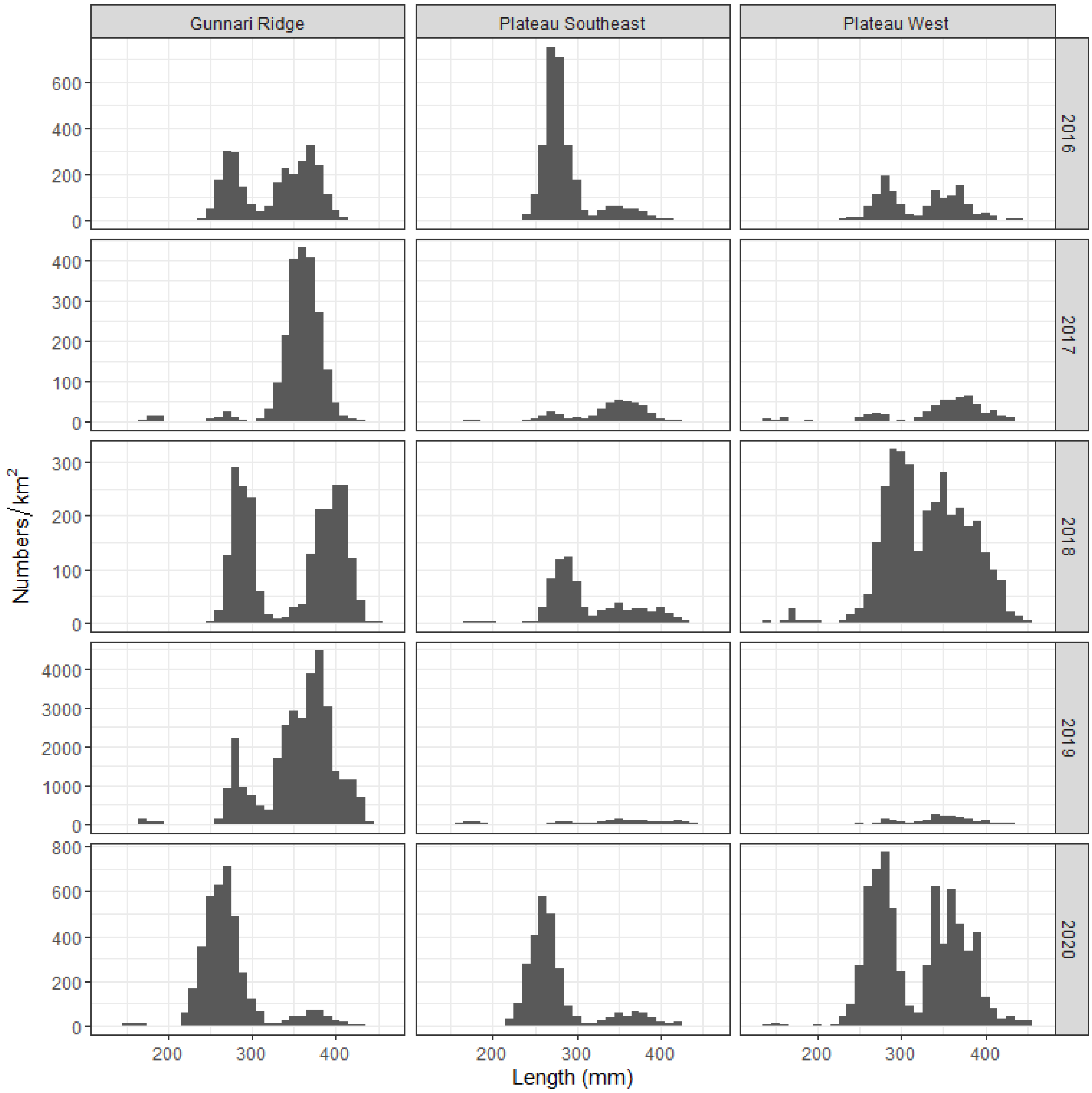



**Figure 5.6:** Fish length distribution by strata in the 2020 random stratified trawl survey (RSTS) for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2.

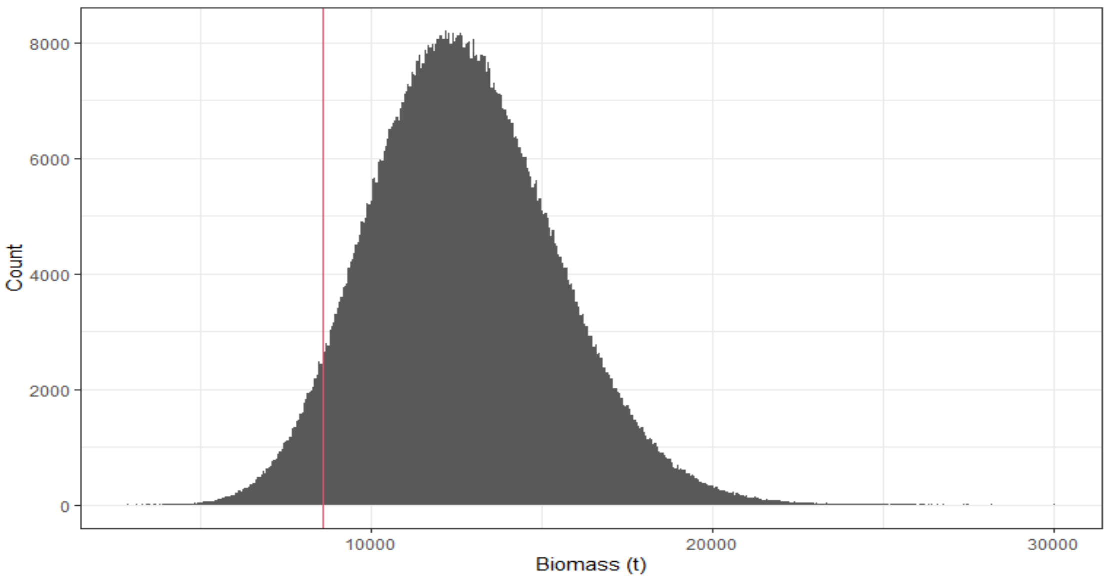



**Figure 5.7:** Distribution of bootstrapped biomass estimates for Mackerel Icefish (*Champsocephalus gunnari*) in 2020 for Division 58.5.2 with lower one-sided 95th confidence bound (red).

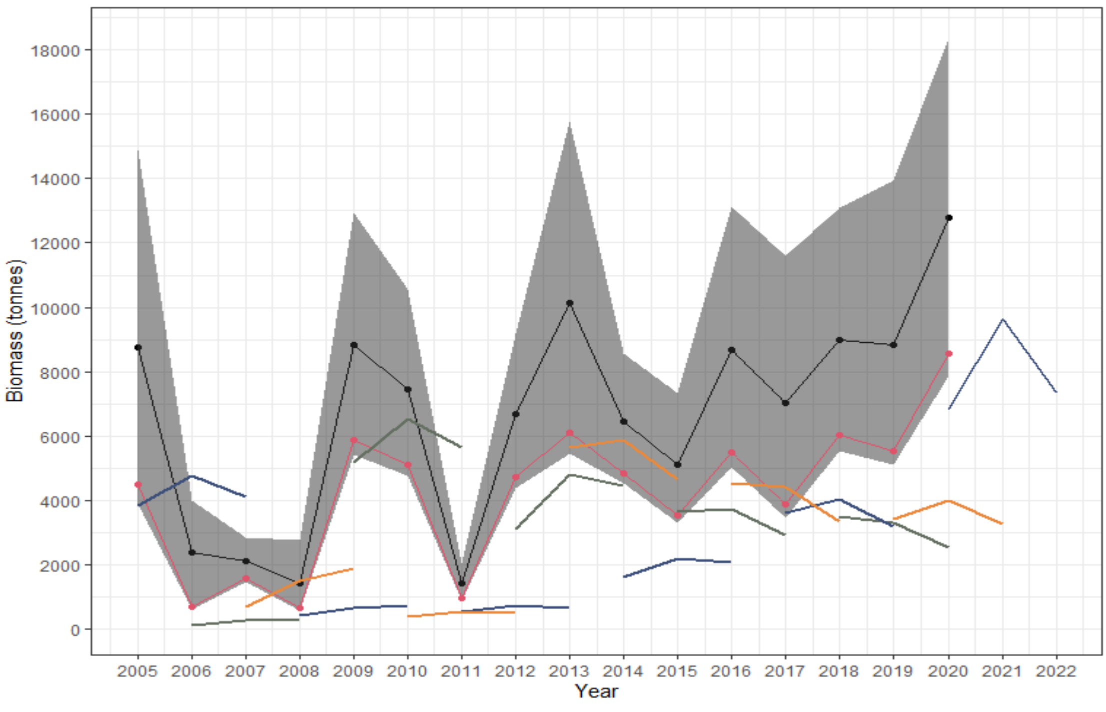



**Figure 5.8:** Mean time series of estimated biomass (including 4+ and 5+ cohorts; black) with confidence intervals (grey) and lower one-sided 95th confidence bound (red), and stock assessment projections (excluding 4+ and 5+ cohorts; colors) that were used to determine catch limits for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2 since 2005.

**Table 5.7:** Parameters used for the 2020 Mackerel Icefish (*Champsocephalus gunnari*) assessment in Division 58.5.2.

| Category | Parameter | Values | Source |
|---|---|---|---|
| Age Structure | Recruitment age | 2 years | de la Mare et al. 1997 |
| | Plus class accumulation | 10 years | de la Mare et al. 1997 |
| | Oldest age in initial structure | 11 years | de la Mare et al. 1997 |
| Initial population structure | Age class density | See Tables 3.1, 3.2 and 3.4 | This Chapter |
| | Biomass | 8075 | This Chapter |
| | Date of estimate (survey) | 1 Apr 20 | |
| Recruitment | | 0 | |
| Natural Mortality | Mean Annual M | 0.4 | de la Mare et al. 1997 |
| von Bertalanffy growth | $t_0$ | 0.067 | Maschette et al. 2017 |
| | $L_{inf}$ | 490 mm | Maschette et al. 2017 |
| | *k* | 0.368 | Maschette et al. 2017 |
| Weight at Length (kg, mm) | Weight-length parameter *a* | 1.150 x 10-09 kg | This Chapter |
| | Weight-length parameter *b* | 3.275 | This Chapter |
| Maturity | Lm50 (set so that the status of the whole stock is being monitored) | 0 mm | |
| | Range: 0 to full maturity | 0 mm | |
| Fishery parameters | Age fully selected | 3 | de la Mare et al. 1997 |
| | Age first selected | 2.5 | de la Mare et al. 1997 |
| | Season | 1 Dec - 30 Nov | CCAMLR Season |
| | Catch between survey and season (tonnes) | 0 | CCAMLR Fishery report |
| Spawning Season | Set so that status of the stock is determined at the end of each year | 30 Nov - 30 Nov | |
| Simulation specifications | Number of runs in simulation | 1 | |
| Individual trial specifications | Years to remove initial age structure | 0 | |
| | Year prior to projection | 2019 | |
| | Reference Start Date in year | 1 Dec | |
| | Increments in year | 365 | |
| | Years to project stock in simulation | 2 | |
| | Reasonable upper bound for Annual F | 5 | |
| | Tolerance for finding F in each year | 0.000001 | |

# Chapter 6: Estimation of fishing-induced mortality from gear loss in the Toothfish fishery at Heard Island and McDonald Islands (HIMI)

Philippe Ziegler and James Dell

**This Chapter is based on:**

Ziegler P. and Dell J. (2019) Planned updates for the integrated stock assessment for the Heard Island and McDonald Islands Patagonian Toothfish (Dissostichus eleginoides) fishery in Division 58.5.2. Document WG-SAM-2019/27, CCAMLR, Hobart, Australia

## Abstract

We estimate the annually amount of Patagonian Toothfish (Dissostichus eleginoides) caught on lost longline gears in CCAMLR Division 58.5.2 since 2006. We define lost gear as any portion of longline gear, greater than 100 hooks, which have not been retrieved within 7 days since being set.

## 6.1 Estimation of fishing mortality caused by longline gear loss

To estimate fishing mortality caused by longline gear loss, we defined “lost gear” as fishing gear that was lost and not retrieved during the normal hauling operation. In rare cases, entire longlines were lost, but more commonly longlines broke in one or several places. In this case, lost gear relates to the part of the longline that remained in the water and could not be found or was found only much later, such as accidentally during subsequent fishing operations or after targeted searching later in the fishing season.

We also specified that a minimum of 100 hooks needed to be lost to be defined as a “gear loss event” and count towards this analysis. This minimum value was chosen since incidental loss of small numbers of hooks and snoods may occur on longline operations, particularly at the transition between magazines.

Longlines attract and catch Toothfish only with bait on the hooks. Vessel skippers suggested that gear retrieved over two weeks after setting are normally stripped of all bait and catch due to predation by sea lice or other benthic detritivores. This was consistent with the maximum soak time of around 7 days when retrieved longline sets still yielded catch.

Fishing mortality from lost gear was estimated based on (1) the annual geometric mean catch rate, and (2) line-estimated catch rate where the lost sections of a longline was assumed to have the same catch rate as the recovered section of that line. For the line-estimated catch rate method, the annual geometric catch rate of Toothfish was used when less than 10 percent of the longline set was recovered.

The two methods estimated similar Toothfish fishing mortalities on lost longline gear for each year, with the exception of 2009 and 2012 when the line-estimated catch rate approach estimated a slightly higher mortality (Figure 6.1, Table 6.1). For the stock assessment, we propose to use the estimates using the annual geometric mean given the small differences, and likely impact on the stock assessment results, relative to the catch taken by the fishery, and for ease of estimation of future mortalities from gear loss.

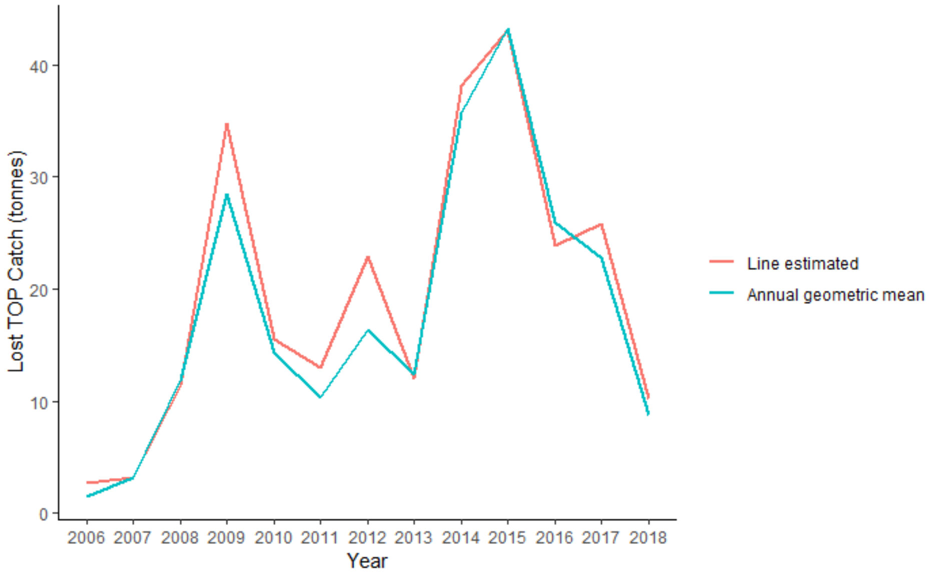



**Figure 6.1:** Estimated Patagonian Toothfish fishing mortality due to lost longline gear in Division 58.5.2 based on annual geometric mean of catch rates (blue) and line-estimated catch rates (red).

**Table 6.1:** Estimated numbers of hooks lost and estimated Toothfish fishing mortality (tonnes) due to lost gear based on the annual geometric mean of catch rates or line-estimated catch rates in Division 58.5.2.

| Year | Estimated hooks lost | Fishing mortality (tonnes) | |
|---|---|---|---|
| | | Annual geometric mean | Line-estimated |
| 2006 | 4 183 | 1.5 | 2.7 |
| 2007 | 8 955 | 3.1 | 3.1 |
| 2008 | 44 569 | 11.9 | 11.4 |
| 2009 | 112 736 | 28.4 | 34.8 |
| 2010 | 47 974 | 14.2 | 15.5 |
| 2011 | 38 550 | 10.3 | 13.0 |
| 2012 | 75 600 | 16.3 | 22.9 |
| 2013 | 44 569 | 12.4 | 12.0 |
| 2014 | 131 399 | 35.7 | 38.2 |
| 2015 | 195 903 | 43.2 | 43.1 |
| 2016 | 158 182 | 25.9 | 23.9 |
| 2017 | 120 652 | 22.8 | 25.8 |
| 2018 | 49 600 | 8.8 | 10.1 |
| **Total** | **1 032 872** | **234.7** | **256.5** |

# Chapter 7: Evaluation of the vessel tagging performance in the Toothfish fishery at Heard Island and McDonald Islands (HIMI)

Genevieve Phillips and Philippe Ziegler

**This Chapter is based on a paper submitted to SARAG in May 2021.**

# Abstract

Relative vessel tagging performance was calculated in the Patagonian Toothfish fishery at Heard Island and McDonald Islands (HIMI). The majority of vessels in the fishing fleet have tag-survival and tag-detection performance rates of greater than 0.9, and vessels with a lower estimated tagging performance are not active in the fishery any more. These results are encouraging and highlight the effectiveness of the tagging protocols and practices that have been applied across the fishing fleet.

Currently, the HIMI Toothfish stock assessment model assumes that all vessels have equal tag-survival and tag-detection rates. The failure to account for individual vessel tagging performance rates when using tag-recapture observations in the stock assessment could lead to an misspecification of the stock biomass. We therefore recommend to evaluate appropriate approaches that can account for tag-survival and tag-detection mortality in the integrated CASAL stock assessment for the HIMI fishery. However, given the high and consistent tag-release and tag-detection performance of fishing vessels which are currently active in the fishery and from which tagging data are used in the stock assessment, the impact of accounting for vessel-specific tagging performance is likely to be small.

## 7.1 Introduction

In the Patagonian Toothfish (*Dissostichus eleginoides*) fishery at Heard Island and McDonald Island (HIMI), tag release and recapture data are used in the CASAL integrated stock assessment as an important source of information for the estimation of spawning stock biomass and status and the determination of sustainable catch levels. Therefore, the processes around tag release and recapture by the fishing fleet need to be reflected appropriately in the model for accurate stock biomass estimation. If the number of tagged and released fish which survive is overestimated, or recaptured fish are missed when the catch is scanned, then stock biomass will be overestimated. Currently, the stock assessment model assumes that all vessels within the fishery perform similarly in terms of tag-survival and tag-detection rate. However, individual vessels are likely to vary in their tagging performance as has been shown in previous investigations in the Ross Sea (CCAMLR Subareas 88.1 and 88.2, Mormede and Dunn 2013) and East Antarctic Toothfish fisheries (CCAMLR Divisions 58.4.1 and 58.4.2, Delegation of Australia 2020e).

Here, we used the method developed and tested for robustness by Mormede and Dunn (2013) and applied in the Ross Sea fishery, to estimate relative tag-survival and tag-detection performance for individual vessels in the HIMI Patagonian Toothfish fishery.

Briefly, tagged fish recaptured in a fishing event by an individual vessel (case) are compared to the number of tagged fish recaptured by a subset of fishing events from other vessels (control). Data are scaled to each fishing event to account for differences between scanned fish numbers in the case and control fishing events. Spatial and temporal variability in release and recapture rates are accounted for in the control subset by ensuring the control data occurs within a specific timeframe and distance from the case data. In this analysis, we have limited the spatial zone to 20 km around a fishing event, and limited the temporal zone to fishing events within the same fishing season.

## 7.2 Methods

Following the method by Mormede and Dunn (2013), relative vessel performance for tag-survival and tag-detection were quantified at the level of a fishing event and the relative performance calculated over the time period chosen, i.e. fishing seasons from 1997-2020 inclusive.

Fishing events are defined as a longline haul, with the location of the event being the approximate mid-point of the haul (assuming a straight line from the start to the end of the haul). All distances are calculated taking into account the curvature of the Earth. Fishing events from each vessel are paired to those from vessels within the same fishing season and within 20 km of the reference vessel (control event). This method assumes that within the same timeframe (i.e. fishing season) and location (i.e. 20 km radius), any spatial and temporal factors affecting fish behaviour or probability of capture are minimal, so that differences in tag-release and tag-detection rates are likely to be due only to differences between processes relating to the vessels. These assumptions are based on findings (Ziegler et al. 2021) that Patagonian Toothfish have a low probability to make rapid within-season movements.

Relative tag-survival performance is calculated from the number of tagged fish that a vessel has released and that have subsequently been recaptured (by any vessel), compared to the numbers released by other vessels within the same spatio-temporal constraints.

Similarly, the relative tag-detection performance is calculated from the number of tagged fish a vessel recaptures in a fishing event, compared to fishing events by other vessels within the same spatio-temporal constraints. Vessels with less than 1000 scanned fish between 1997-2020 were excluded from this analysis.

The number of tagged fish released or recaptured is scaled to the total number of fish scanned by the vessels in question. By iterating over all fishing events for all vessels, a relative index for each vessel is generated, with a value of one representing the average performance of all vessels. The data are bootstrapped and plotted to show the relative performance of each vessel within the fishing fleet. The data are analysed for all combined fishing methods (trawl, longline and trap) and for longline only. In both cases, where within-season tag-recaptures were ignored. For this report, vessel names are removed to protect commercially-sensitive information.

## 7.3 Results

### Tag-survival performance

When combining all fishing methods, most vessels showed a good tag-survival performance (Table 7.1, Figure 7.1). One vessel had a performance index of 0.60, while all others had a relative performance of 0.93 or higher. Four vessels had performance indices of greater than 1.

**Table 7.1:** Median and 95% confidence intervals (CI) of relative survival rates of tagged fish by all vessels in the HIMI Toothfish fishery.

| Vessel | Median | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| H | 2.86 | 2.38 | 3.37 |
| B | 1.84 | 1.38 | 2.30 |
| E | 1.19 | 1.07 | 1.32 |
| A | 0.98 | 0.91 | 1.04 |
| F | 0.94 | 0.88 | 1.01 |
| C | 0.93 | 0.79 | 1.11 |
| D | 0.60 | 0.50 | 0.73 |

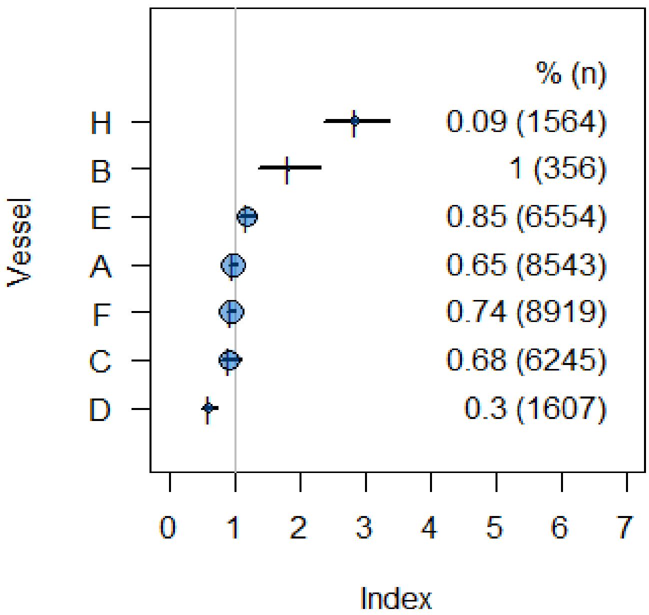



**Figure 7.1:** Indices of relative survival rates of tagged fish by all vessels in the HIMI Toothfish fishery. The circle and vertical bars indicate the index value. The area of each circle is proportional to the number of fish scanned by each vessel in the analysis. The grey vertical line represents an index of 1, where case and control performed identically (i.e. had the same tag-survival rate). Horizontal bars show the 90 % confidence interval, with confidence intervals > 7 truncated at 7. The numbers on the right represent the number of tag-releases and the percentage of the scanned fish (in brackets) from the case fishing events for each vessel included in the analysis.

When analysing longline hauls only, the ag-survival performance was similar for all vessels and only two vessels had a value of less than one (Figure 7.2, Table 7.2).

**Table 7.2:** Median and 95% confidence intervals (CI) of relative survival rates of tagged fish by longline vessels in the HIMI Toothfish fishery.

| Vessel | Median | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| B | 1.66 | 1.20 | 2.10 |
| E | 1.15 | 1.04 | 1.26 |
| C | 1.09 | 0.90 | 1.31 |
| A | 1.07 | 0.99 | 1.14 |
| F | 0.89 | 0.83 | 0.95 |
| D | 0.81 | 0.64 | 1.00 |

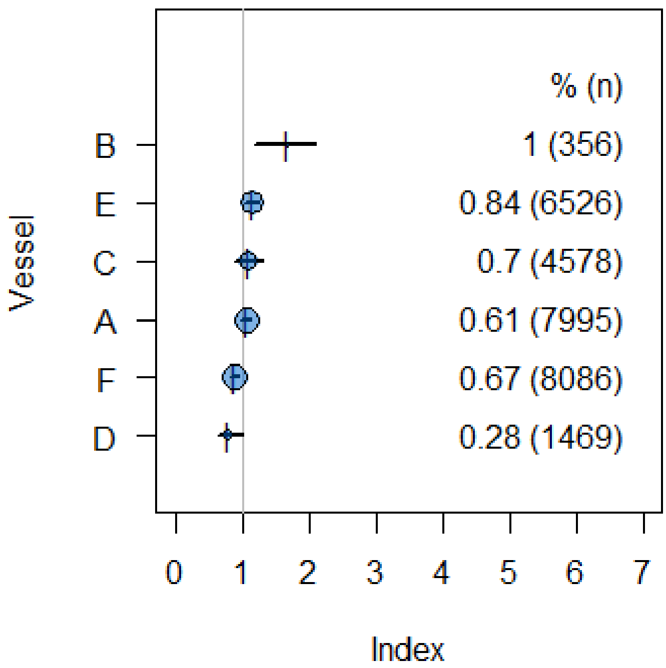



**Figure 7.2:** Indices of relative survival rates of tagged fish by longline vessels in the HIMI Toothfish fishery. The circle and vertical bars indicate the index value. The area of each circle is proportional to the number of fish scanned by each vessel in the analysis. The grey vertical line represents an index of 1, where case and control performed identically (i.e. had the same tag-survival rate). Horizontal bars show the 90% confidence interval, with confidence intervals >7 truncated at 7. The numbers on the right represent the number of tag-releases and the percentage of the scanned fish (in brackets) from the case fishing events for each vessel included in the analysis.

### Tag-detection performance

When combining fishing methods, all vessels had median tag-detection performance rates at or larger than one (Figure 7.3, Table 7.3).

**Table 7.3:** Median and 95% confidence intervals (CI) of relative detection rates of tagged fish by all vessels in the HIMI Toothfish fishery.

| Vessel | Median | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| H | 3.30 | 2.48 | 4.31 |
| B | 1.31 | 1.07 | 1.62 |
| C | 1.24 | 0.95 | 1.57 |
| D | 1.24 | 0.55 | 2.15 |
| E | 1.22 | 1.04 | 1.41 |
| A | 1.06 | 0.96 | 1.16 |
| F | 1.01 | 0.84 | 1.18 |

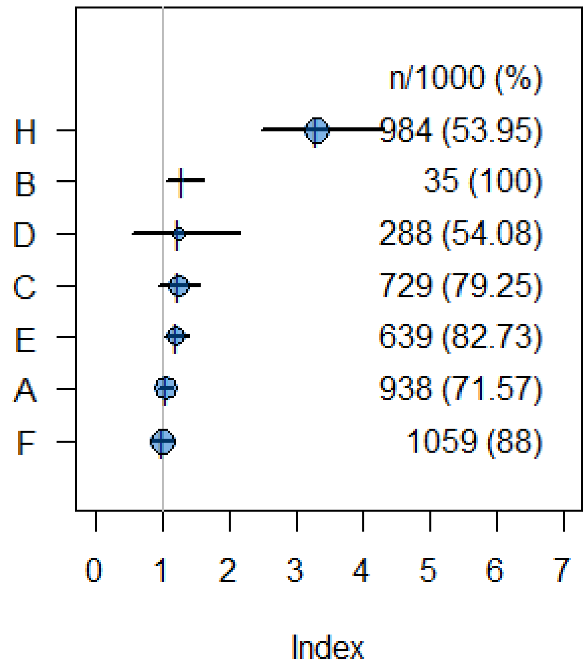



**Figure 7.3:** Indices of relative detection rates of tagged fish by all vessels in the HIMI Toothfish fishery. The circle and vertical bars indicate the index value. The area of each circle is proportional to the number of fish scanned by each vessel in the analysis. The grey vertical line represents an index of 1, where case and control performed identically (i.e. had the same tag-detection rate). Horizontal bars show the 90% confidence interval. The numbers on the right represent the number of scanned fish and the percentage of the scanned fish used in the analysis (in brackets) from the case fishing events for each vessel included in the analysis.

Longline vessels showed a fairly even tag-detection performance (Figure 7.4, Table 7.4), with all vessels having median tag-detection rates at or slightly larger than one.

**Table 7.4:** Median and 95% confidence intervals (CI) of relative detection rates of tagged fish by longline vessels in the HIMI Toothfish fishery

| Vessel | Median | Lower 95% CI | Upper 95% CI |
|---|---|---|---|
| B | 1.31 | 1.06 | 1.61 |
| E | 1.22 | 1.03 | 1.41 |
| D | 1.20 | 0.44 | 2.40 |
| A | 1.19 | 1.10 | 1.28 |
| C | 1.13 | 1.01 | 1.27 |
| F | 1.00 | 0.85 | 1.17 |

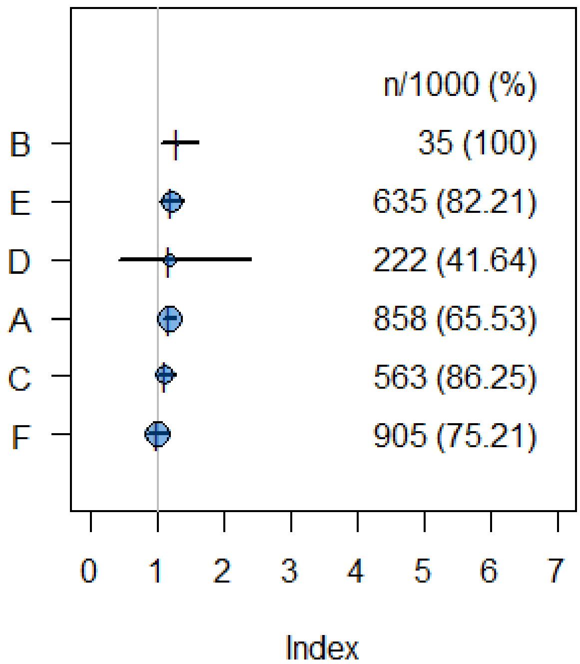



**Figure 7.4:** Indices of relative detection rates of tagged fish by longline vessels in the HIMI Toothfish fishery. The circle and vertical bars indicate the index value. The area of each circle is proportional to the number of fish scanned by each vessel in the analysis. The grey vertical line represents an index of 1, where case and control performed identically (i.e. had the same tag-detection rate). Horizontal bars show the 90% confidence interval. The numbers on the right represent the number of scanned fish and the percentage of the scanned fish used in the analysis (in brackets) from the case fishing events for each vessel included in the analysis.

## 7.4 Discussion

This is the first time that relative vessel tagging performance has been calculated in the Patagonian Toothfish fishery at Heard Island and McDonald Islands (HIMI). The majority of vessels in the fishing fleet have tag-survival and tag-detection performance rates of greater than 0.9, and vessels with a lower estimated tagging performance are not active in the fishery any more. These results are encouraging and highlight the effectiveness of the tagging protocols and practices that are applied across the fishing fleet. This contrasts strongly with other Southern Ocean Toothfish fisheries where some vessels have estimated relative tagging performances of as low as zero (Mormede and Dunn 2013).

Currently, the HIMI Toothfish stock assessment model assumes that all vessels have equal tag-survival and tag-detection rates. The failure to account for individual vessel tagging performance rates when using tag-recapture observations in the stock assessment could lead to an misspecification of the stock biomass. We therefore recommend to evaluate appropriate approaches that can account for tag-survival and tag-detection mortality in the integrated CASAL stock assessment for the HIMI fishery. However, given the high and consistent tag-release and tag-detection performance of fishing vessels which are currently active in the fishery and from which tagging data are used in the stock assessment, the impact of accounting for vessel-specific tagging performance is likely to be small.

# Chapter 8: Patagonian Toothfish stock assessment 2019 at Heard Island and McDonald Islands (HIMI)

Philippe Ziegler

**This Chapter is based on:**

Ziegler P. (2019a) Draft integrated stock assessment for the Heard Island and McDonald Islands Patagonian Toothfish (Dissostichus eleginoides) fishery in Division 58.5.2. Document WG-FSA-2019/32, CCAMLR, Hobart, Australia

## Abstract

This paper presents an updated assessment for the Patagonian Toothfish (*Dissostichus eleginoides*) fishery at Heard Island and McDonald Islands (HIMI) in CCAMLR Division 58.5.2 with catch until the end of 2019 and observations until the end of 2018. The updated assessment model is based on the best available estimates of model parameters, the use of abundance estimates from a random stratified trawl survey (RSTS), longline tag-release data from 2012-2017 and longline tag-recapture data from 2013-2018, and auxiliary commercial composition data to aid with the estimation of year class strength and selectivity functions of the trawl, longline and trap sub-fisheries.

Compared to the 2017 assessment that was accepted by WG-FSA-17 to be used for management advice, this assessment takes into account (1) update the model with catch data to 2019 and observations to the end of 2018 including new ageing data from the RSTS and commercial fishery from 2017-2018, (2) inclusion of fishing-induced mortality from longline gear loss, (3) updated growth parameters, (4) updated length-weight relationship parameters, (5) updated maturity-at-age parameters, and (6) a simplification of the longline selectivity functions. All model runs were conducted with the CASAL version 2.30-2012-03-21 rev. 4648 that was agreed on by WG-SAM-14.

The updated assessment model leads to a smaller estimate of the virgin spawning stock biomass $B_0$ than that obtained in 2017, with an MCMC estimate of 70 519 tonnes (95% CI: 65 634 - 76 626 tonnes). The estimated *SSB* status at the end of 2019 was 0.51 (95% CI: 0.49-0.53). The smaller biomass meant that the catch limit that satisfies the CCAMLR decision rules decreased from 3525 tonnes to 3030 tonnes.

Over the course of the projection period the median *SSB* status reaches a minimum of 40% before increasing to the target level at the end of the 35-year projection period, a pattern that is driven by the switch of the fishery from trawl to longline and below-average year class strength since 1998. The level of the predicted drop in *SSB* status by 2021, the time of the next stock assessment, was largely independent of the *YCS* period chosen as reference for the projections. With a comprehensive monitoring program of the fishery until then which include annual trawl surveys and extensive fish ageing to consolidate and estimate recent trends in *YCS*, the 2021 assessment will inform any decision whether further catch reductions will be necessary.

As the result of this assessment, we recommend a reduction of the catch limit from currently 3525 tonnes to 3030 tonnes for the Patagonian Toothfish fishery in Division 58.5.2.

## 8.1 Introduction

A number of stock assessments have been developed in recent years for the fishery for Patagonian Toothfish (*Dissostichus eleginoides*) at Heard Island and McDonald Islands (HIMI) in CCAMLR Division 58.5.2 (Candy and Constable 2008, Candy and Welsford 2009, Candy and Welsford 2011, Ziegler et al. 2013, Ziegler et al. 2014, Ziegler and Welsford 2015, Ziegler 2017a).

Following this work, this paper presents a revised integrated stock assessment for *D. eleginoide*s in Division 58.5.2, using the CASAL assessment model framework (Bull et. al. 2012). As in Ziegler (2017a), a bridging analysis was conducted starting with the assessment model that was used to provide management advice in 2017 (WG-FSA-17, para. 3.44-3.54). This bridging analysis updates model data and parameter estimates, leading step-wise to the 2019 assessment model.

The assessment also addresses recommendations from WG-FSA-17 (para. 3.48), WG-SAM-19 (p. 3.6-3.6) and the CCAMLR Independent Stock Assessment Review (2018).

## 8.2 Stock hypothesis

The Kerguelen Plateau is located in the Southern Indian Ocean and stretches from around 45°S to over 60°S. Almost the entire Kerguelen Plateau is situated within the area managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), with only a small extension, the William's Ridge, on the eastern side of the northern part of the Plateau extending into the Southern Indian Ocean Fisheries Agreement (SIOFA) Statistical Area 7.

On the northern part of the plateau (north of Fawn Trough or roughly 57°S), two large fisheries for Patagonian Toothfish are located in CCAMLR Division 58.5.1 which covers the French Exclusive Economic Zones (EEZ) around Kerguelen Islands, and Division 58.5.2 which covers the Australian EEZ around Heard Island and McDonald Islands (HIMI). On the southern part of the Kerguelen Plateau, Antarctic Toothfish (*D. mawsoni*) which is better adapted to the colder waters around the Antarctic continent, is the dominant Toothfish species.

Based on available genetic information (Toomey et al. 2016), catch composition (Péron et al. 2016) and tag-recapture data from survey and the commercial Toothfish fishery (Burch et al. 2017, Ziegler 2019b), Patagonian Toothfish are continuously distributed on the northern part of the Kerguelen Plateau and populations are linked. Within this area, the populations are likely structured with juveniles settling in shallow waters around the islands and potential exchange between Kerguelen Islands and HIMI (Figure 8.1). As fish grow larger and older, they move to deeper waters, and major spawning grounds are located on the western and southern side of the plateau.

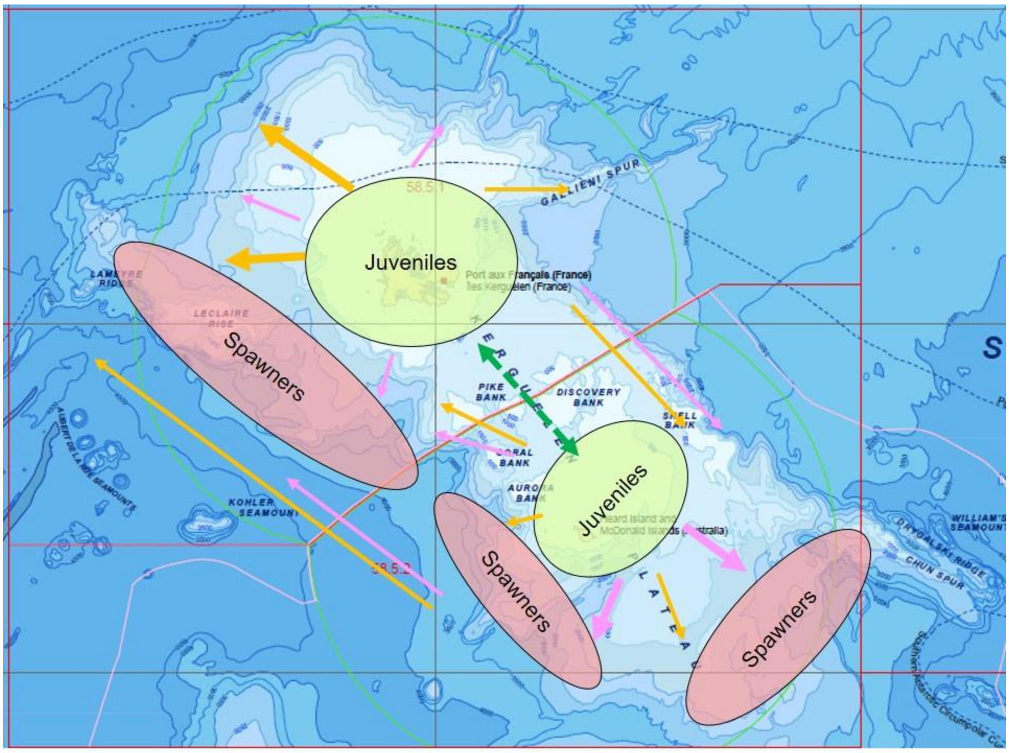



**Figure 8.1:** Schematic Toothfish population structure on the northern part of the Kerguelen Plateau with Kerguelen Island to the north and Heard Island and McDonald Islands to the south. Juveniles settle in shallow waters on the plateau around the islands with potential exchange between areas (dark green arrows). Males (orange arrows) and females (pink arrows) then move into deeper waters as they grow larger and older, with major spawning grounds on the western and southern side of the plateau. Most adult fish move only short distances, but long-distance movement occur over the entire plateau, with some level of fish exchange between the Australian and French EEZ (green lines). CCAMLR Divisions are marked by red lines.

## 8.3 Data

### Catch data

Data from random stratified trawl surveys (RSTS) and the commercial fishery in Division 58.5.2 were available for the period from 1997-2018 (Table 1). The haul-by-haul data from the RSTS, longline, trawl and trap included information on *inter alia* fishing date, haul latitude and longitude, fishing depth, gear type, effort, and total catch in weight and numbers. Relevant biological data collected by observers included the total length and weight of all sampled fish. Biological data were excluded if the quality of the record had been flagged as being poor. Observers also collected fish otoliths that were used for ageing fish. For the assessment, catches were summarised by RSTS and commercial sub-fisheries, and fishing season.

Fishing-induced mortality from lost longline gear was estimated from the numbers of hooks that were lost. Gear loss was included when more than 100 hooks were lost at a time since incidental loss of small numbers of hooks and snoods may occur on longline operations without loss of any line, particularly at the transition between magazines. The numbers of lost hooks were then multiplied with the mean of catch per hook for that year as recommended by WG-SAM-19 (para. 3.5), which resulted in similar or slightly higher mortality than when multiplying the numbers of lost hooks with line-specific catch rates (Figure 8.2, Table 8.1).


**Figure 8.2:** Estimated annual Toothfish fishing mortality due to lost longline gear in Division 58.5.2 based on line-estimated catch rates (red) and annual mean of catch rates (blue).

In 2018, the Spanish vessel *FV Tronio* fished on William's Ridge in SIOFA area 7, catching an estimated 339 tonnes of Patagonian Toothfish (SERAWG-01/12). In 2019, a second Spanish vessel, the *FV Ibsa Quinto*, also fished on William's Ridge, with a yet unknown catch volume.

Illegal, unreported and unregulated (IUU) catches in CCAMLR Division 58.5.2 were potentially large in the late 1990s and early 2000s. IUU catches were estimated based on sightings of IUU vessels, their known fishing capacities, and catch and effort data from the licensed fishery (Table 1). No IUU vessel has been sighted after 2005 and it is likely that no IUU catches have been taken since then.

### Random stratified trawl surveys (RSTS)

The RSTS have been conducted in Division 58.5.2 to estimate the abundance and size structure of *D. eleginoides* and *Champsocephalus gunnari* (Mackerel Icefish) in 1990, 1992, 1993, and annually since 1997. However, the structure and intensity of the surveys has varied over these years as the objective for the surveys has changed, and information for survey design and power has improved (Welsford et al. 2006). For example, the initial three surveys in the early 1990s were conducted to gain a basic understanding of the distribution and abundance of fish stocks in the region, occurred at different seasons, and used a relatively small number of trawls. The surveys in 1997-1998 targeted Icefish and are not suitable to estimate Toothfish abundance. Major surveys incorporating a wider range of Toothfish habitats started in 1999, although for the first four years different stratum plans based on specific research questions for Toothfish and Icefish resulted in varying effort to survey Toothfish. The large shallow strata sampled in the 1999 survey were subdivided in 2001 and the deeper strata in 2002, after which the strata boundaries have been stable. In 2000, only a relative small area was surveyed, and the northern plateaus were not sampled in 2003. After reviewing the statistical power of the surveys in 2003, trawl allocation to strata with greater fish abundance was increased (Candy et al. 2004).

**Table 8.1**: Catch limits, reported catch for the random stratified trawl survey (RSTS), trawl, longline and trap, estimated fishing-induced mortality from lost longline gear, reported or estimated catches in the SIOFA area, estimated IUU catch, and total removals in tonnes by calendar year for Division 58.5.2.

| Year [a] | Catch limits | Division 58.5.2 Reported catch | | | | | Gear loss | SIOFA catch | Estimated IUU catch | Total removals |
|---|---|---|---|---|---|---|---|---|---|---|
| | | RSTS | Trawl | Longline | Trap | Total | | | | |
| 1996 | 297 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3000 | 3000 |
| 1997 | 3800 | 0 | 1866 | 0 | 0 | 1866 | 0 | 0 | 7117 | 8983 |
| 1998 | 3700 | 1 | 3784 | 0 | 0 | 3785 | 0 | 0 | 4150 | 7935 |
| 1999 | 3690 | 93 | 3452 | 0 | 0 | 3545 | 0 | 0 | 427 | 3972 |
| 2000 | 3585 | 9 | 3556 | 0 | 0 | 3565 | 0 | 0 | 1154 | 4719 |
| 2001 | 2995 | 45 | 2942 | 0 | 0 | 2987 | 0 | 0 | 2004 | 4991 |
| 2002 | 2815 | 35 | 2717 | 0 | 0 | 2752 | 0 | 0 | 3489 | 6241 |
| 2003 | 2879 | 13 | 2580 | 270 | 0 | 2863 | 0 | 0 | 1274 | 4137 |
| 2004 | 2873 | 65 | 2218 | 566 | 0 | 2849 | 0 | 0 | 531 | 3380 |
| 2005 | 2787 | 21 | 2101 | 636 | 0 | 2758 | 0 | 0 | 265 | 3023 |
| 2006 | 2584 | 12 | 1785 | 659 | 72 | 2528 | 2 | 0 | 112 | 2641 |
| 2007 | 2427 | 12 | 1775 | 625 | 0 | 2412 | 4 | 0 | 0 | 2415 |
| 2008 | 2500 | 4 | 1614 | 825 | 0 | 2443 | 13 | 0 | 0 | 2455 |
| 2009 | 2500 | 20 | 1268 | 1173 | 13 | 2474 | 36 | 0 | 0 | 2502 |
| 2010 | 2550 | 28 | 1239 | 1216 | 32 | 2515 | 17 | 0 | 0 | 2529 |
| 2011 | 2550 | 6 | 1142 | 1317 | 33 | 2498 | 12 | 0 | 0 | 2508 |
| 2012 | 2730 | 41 | 1322 | 1356 | 0 | 2719 | 25 | 0 | 0 | 2735 |
| 2013 | 2730 | 8 | 555 | 2116 | 40 | 2719 | 15 | 0 | 0 | 2731 |
| 2014 | 2730 | 13 | 93 | 2638 | 0 | 2744 | 40 | 0 | 0 | 2780 |
| 2015 | 4410 | 26 | 180 | 4073 | 0 | 4279 | 50 | 0 | 0 | 4322 |
| 2016 | 3405 | 52 | 107 | 2640 | 0 | 2799 | 30 | 0 | 0 | 2825 |
| 2017 | 3405 | 20 | 3 | 3334 | 0 | 3357 | 27 | 0 | 0 | 3380 |
| 2018 | 3525 | 41 | 8 | 3091 | 0 | 3140 | 12 | 339 | 0 | 3488 |
| 2019 | 3525 | NA | NA | NA | NA | NA | NA | NA | NA | 3525 [b] |

[a] Fishing seasons run from 1 December - 30 November of the following year. Here, years are denoted after the year with the majority of the season, e.g. 1996/97 is 1997.
[b] For the assessment, it was assumed that the catch limit for 2019 was fully taken, with a survey catch of 20 tonnes.

Since 2003, an annual survey has consisted of between 120-160 trawl hauls, each taking approximately 30 mins tow time on the seabed to complete. The entire fishable area in Division 58.5.2 down to 1000 m is divided into ten strata (of which one is excluded from sampling since it is closed to fishing), each covering areas of similar depth and/or fish abundance (Nowara et al. 2017). A list of random co-ordinates for starting position and prescribed headings for each station in each stratum is provided to the fishing vessel conducting the survey, including first choice and reserve positions. In the surveys until 2014, the sampling area of the main trawl fishing ground, which is around 450 km$^2$, was subdivided into squares of 2 x 2.4 nautical miles (0.5 x 0.5 degrees). Sampling occurred in a randomly selected subset of 20 out of the total of 30 of these squares, with details provided in the survey instructions. Since the 2015 survey, the main trawling ground has been subdivided into two sub-strata, and as in the other strata vessels have been provided with random co-ordinates for starting positions and headings. The number of stations in the main trawl ground has also been increased to 25.

Survey observations were separated into a survey biomass index and survey proportions-at-age. The annual survey biomass and *CVs* for 2001-2002 and 2004-2018 ('Survey group 1' in Ziegler et al. 2014, Ziegler and Welsford 2015, Ziegler 2017a) were estimated as the sum of biomass estimates in each surveyed stratum which were derived from a stratified bootstrap of the estimated fish density in survey hauls. In the assessments up to 2013, this survey group had been assumed to fully sample the fish stock vulnerable to the fishing gear as quantified by the fishing selectivity function, with survey catchability *q* set to 1. For the 2014 assessment, catchability for this survey group had been estimated using a prior that was derived from comparing abundance estimates of the survey with abundance estimates calculated from the tag-recaptures data on the main trawl ground (Ziegler et al. 2014). De la Mare et al. (2015) further investigated the ability to estimate survey *q* from survey and tag-based abundance estimates, but concluded from simulations that a potential bias in the estimate of survey catchability could arise from the need to concurrently estimate fishing selectivity and that this potential bias could not be corrected given the available data. Similar to the assessments in 2015 and 2017, a uniform-log prior for survey *q* was therefore used in this assessment to account for the multiplicative space within which catchability is applied (Punt and Hilborn 2001).

**Commercial sub-fisheries**

Data from commercial hauls were pooled into 'sub-fisheries' based on systematic trends in the catch-at-length distributions of fish in hauls following the method developed by Candy et al. (2013). The definition of sub-fisheries is typically based on gear-specific selectivity and fish availability in different locations, and sub-fisheries have individual selectivity functions to achieve a better model fit.

The method by Candy et al. (2013), takes account of the shape of the entire catch-at-length distribution of single or grouped hauls and fits a Generalised Additive Mixed Model (GAMM) with cubic smoothing splines for a combination of covariates (e.g. gear type, depth strata and region). The analysis showed that a split between all gear types and some further splits for longline hauls were appropriate for the Toothfish fishery in Division 58.5.2 (Figure 8.3). Alternative depth and regional splits of longline hauls indicated that depth splits at 1500 m and 1200 m provided similar results, with significantly different splines between shallow and deep hauls. A depth split at 1500 m was used similar to the 2017 assessment here. Splines from the respective depth strata on eastern and western fishing grounds were similar, indicating that separate selectivities for longline by fishing regions was not needed in the assessment.

Based on this analysis, the commercial sub-fishery structure for the assessment consisted of two trawl (Trawl1 and Trawl2), one trap (Trap), one shallow longline (LL1) and one deep longline sub-fishery (LL2). IUU catches from Table 8.1 were included in the assessment and assumed to have been taken by longline, with a selectivity function similar to that of the longline sub-fishery LL1. Similarly, the SIOFA catches were assumed to have been taken with a selectivity function similar to LL1.

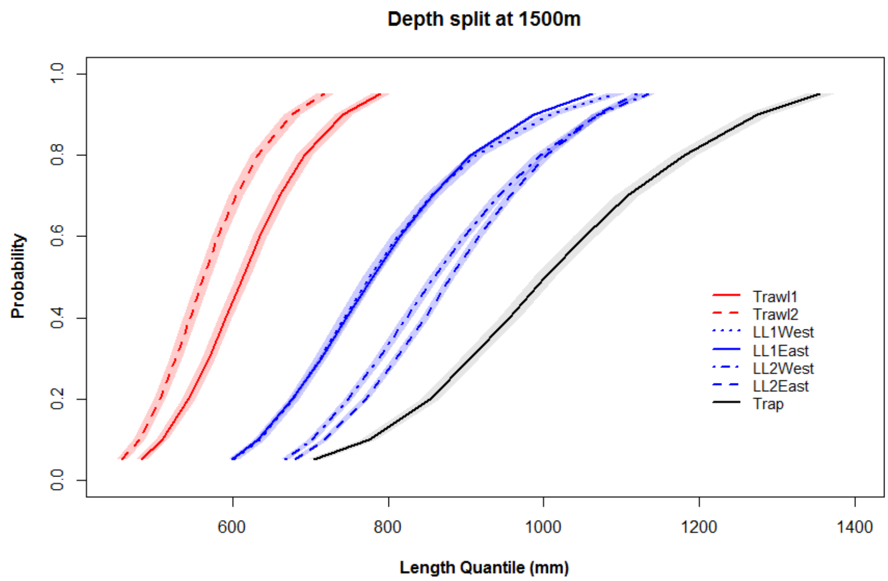



**Figure 8.3**: Predicted splines for length quantiles of trawl, trap and longline (LL). Longline hauls were split by fishing areas (west and east of around 74°E), and 1500 m depth, whereas '1' is shallow and '2' is deep. The shaded areas represent the 95% confidence intervals (or two standard errors) of the spline for trawl (red) and trap (black), or of the difference between pairs of splines for longline (blue). The analysis is based on hauls pooled by block size of 1/8° latitude * 1/4° longitude (about 4 * 4 nm).

### Tagging data

Tagging of *D. eleginoides* in Division 58.5.2 commenced in 1998 soon after the fishery had started. Initially, all tag-releases and recaptures were from trawl. However, trawl effort has been highly concentrated on a small fishing ground, and Candy and Constable (2008) investigated the inclusion of trawl tag-release and recapture data in the stock assessment. They concluded that these tag-recapture data were likely to only estimate the local biomass in the relatively small fishing area where trawl had been concentrated, rather than that of the population biomass in the entire Division 58.5.2.

Longlining started in 2003 on shallower fishing grounds in the eastern part of the Division and has expanded substantially to deeper fishing grounds and up to the northwest corner over the years. Within this trend, the spatial effort distribution has varied substantially between years (Figure 8.4, WG-FSA-15/55). While tagged Toothfish are unlikely to mix completely within the fished part of the population (Williams et al. 2003, Welsford et al. 2007, Welsford et al. 2014), only longline-caught fish that have been tagged and released from 2012 onwards have been used in the previous assessment (Ziegler 2017a) since longline effort had been spatially more spread out from that year onwards. For this assessment, the selection of years of release was the same as in the previous assessment, but the inclusion of releases from earlier years was explored in a sensitivity analysis. This approach was endorsed by the CCAMLR Independent Stock Assessment Review (2018).

Annual tag-release and recapture numbers from longline have increased since 2008, and particularly since 2015 due to a higher catch limit and an increase in tagging rates from 2 fish per 3 tonnes to 2 fish per tonne (Table 8.2). In total, over 34 000 fish have been tagged and released and over 3400 have been recaptured since 2008.

**Table 8.2:** Numbers of longline tag-releases and tag-recaptures that were used in the assessment models. Numbers with grey shading were only used the sensitivity analyses. Within-season recaptures are not used in the assessment.

| Releases | | Recaptures | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Numbers | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | Total |
| 2008 | 891 | 25 | 14 | 3 | 8 | 23 | 19 | 24 | 9 | 5 | 5 | 135 |
| 2009 | 1249 | 7 | 49 | 44 | 9 | 21 | 39 | 46 | 13 | 22 | 4 | 254 |
| 2010 | 1216 | - | 2 | 41 | 5 | 12 | 52 | 36 | 9 | 14 | 10 | 181 |
| 2011 | 1197 | - | - | 0 | 20 | 19 | 35 | 39 | 27 | 28 | 28 | 196 |
| 2012 | 1434 | - | - | - | 1 | 22 | 40 | 39 | 21 | 44 | 33 | 200 |
| 2013 | 1471 | - | - | - | - | 4 | 52 | 94 | 37 | 48 | 43 | 278 |
| 2014 | 1808 | - | - | - | - | - | 9 | 76 | 58 | 78 | 45 | 266 |
| 2015 | 7713 | - | - | - | - | - | - | 80 | 261 | 336 | 284 | 961 |
| 2016 | 5321 | - | - | - | - | - | - | - | 31 | 221 | 296 | 548 |
| 2017 | 6740 | - | - | - | - | - | - | - | - | 54 | 337 | 391 |
| 2018 | 5645 | - | - | - | - | - | - | - | - | - | 46 | 46 |
| Total | 34 686 | 32 | 65 | 88 | 43 | 101 | 246 | 434 | 466 | 850 | 1131 | 3456 |

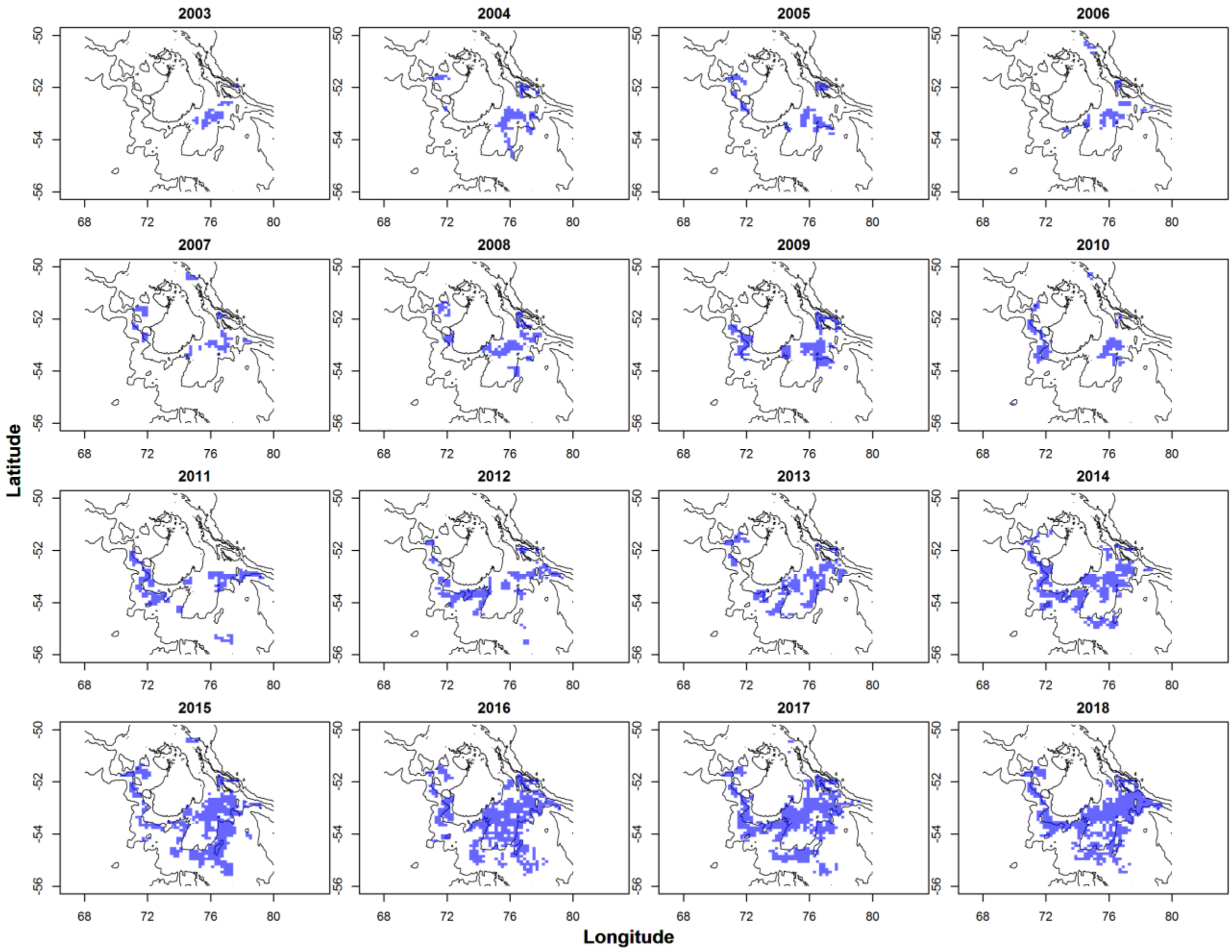



**Figure 8.4:** Annual variations in spatial distribution of longline fishing effort for Patagonian Toothfish in Division 58.5.2 from 2003 to 2018. Blue cells correspond to locations where at least one longline haul event occurred.

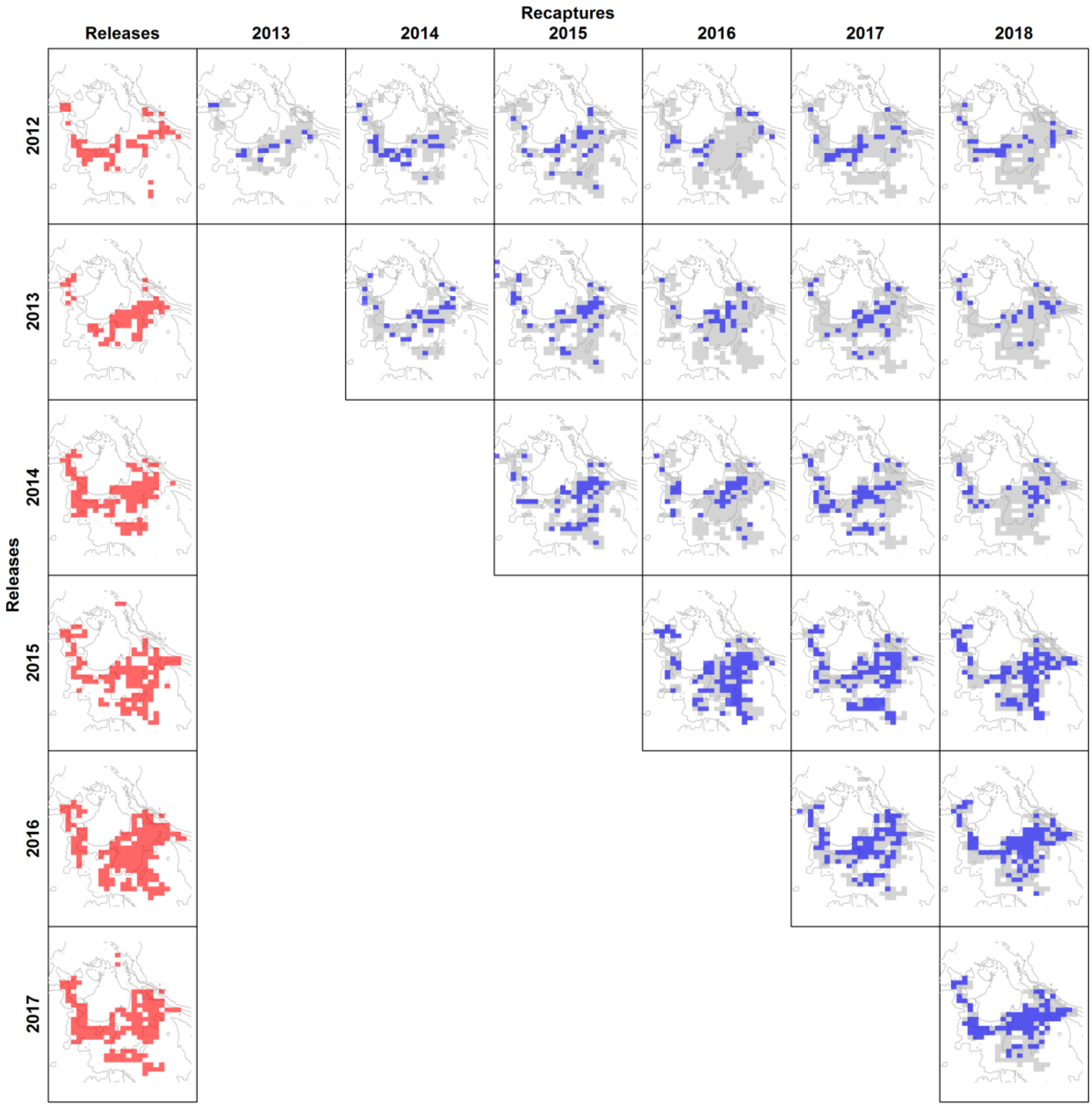



**Figure 8.5:** Distribution of longline releases of Patagonian Toothfish in Division 58.5.2 since 2012 (red), and distributions of subsequent recaptures (blue) and longline fishing effort from 2013 to 2018. Cells correspond to locations where at least one tagged fish was released (red) or recaptured (blue), or where at least one longline haul event occurred (grey).

The spatial overlap between longline releases and their subsequent recaptures showed a high level of overlap, whereas the spatial extent of longline fishing effort increased over the years (Figure 8.5).

In the assessment model, the numbers of longline tag-releases and tag-recaptures used were capped at 6 years at liberty to account for tag-shedding rates in CASAL being specified for fish tagged with a single tag, while all released fish are double tagged (Candy 2011b; Dunn et al. 2011), and within-season recaptures were excluded (Table 8.3). Tag-release mortality was assumed to be 0.1 (Agnew et al. 2006), and a no-growth period after tagging of 0.5 years was assumed (Agnew et al. 2005).

The tag-detection rate during longline fishing was assumed to be to 100%, and tag-shedding rates were estimated following the method proposed by Adam & Kirkwood (2001) as estimated by Ziegler (2017b). The parameter of annual tag loss rate in CASAL's single-tag model was then approximated for a maximum time at liberty of 6 years as *l* = 0.021 for 2007-2011 and *l* = 0.006 for 2012-2015. The same tag-shedding rate of *l* = 0.006 was also assumed for all tagged fish released since 2015.

**Length and ageing data**

A large number of Toothfish have been measured annually for length in the RSTS and the commercial fishery (Table 8.3, Figure 8.6). Since the last assessment (Ziegler 2017a), an additional 1699 otoliths collected from the surveys and commercial fishery in 2017 and 2018 have been aged, helping to create a dataset of over 19 000 age estimates. All ages have been estimated by technicians that have been trained following the recommendation of the 2012 Toothfish ageing workshop (SC-CAMLR 2012) and the protocols for thin sectioning developed at the Australian Antarctic Division (Welsford et al. 2012, Farmer et al. 2014).

**Table 8.3:** Number of Toothfish measured for length or age and used in the assessment for the RSTS and commercial fisheries. Where numbers are in bold, the ages have been used to calculate age-length keys (ALKs). * Not randomly sampled.

| Year | Length | | | Age | | |
|---|---|---|---|---|---|---|
| | RSTS | Commercial | Total | RSTS | Commercial | Total |
| 1997 | 0 | 11 387 | 11 387 | 0 | 55* | 55 |
| 1998 | 169 | 11 229 | 11 398 | 0 | **286** | 286 |
| 1999 | 2294 | 14 623 | 16 917 | 2 | **623** | 625 |
| 2000 | 2258 | 20 483 | 22 741 | 20 | **807** | 827 |
| 2001 | 2505 | 27 079 | 29 584 | 2 | **909** | 911 |
| 2002 | 2965 | 18 476 | 21 441 | 4 | **829** | 833 |
| 2003 | 2301 | 27 298 | 29 599 | 13 | **675** | 688 |
| 2004 | 2462 | 33 509 | 35 971 | 4 | **336** | 340 |
| 2005 | 2355 | 28 899 | 31 254 | 1 | **370** | 371 |
| 2006 | 2081 | 31 427 | 33 508 | **119** | **1100** | 1219 |
| 2007 | 2050 | 22 843 | 24 893 | **547** | **588** | 1135 |
| 2008 | 1281 | 31 475 | 32 756 | **652** | **107** | 759 |
| 2009 | 1922 | 44 342 | 46 264 | **642** | **77** | 719 |
| 2010 | 5893 | 30 485 | 36 378 | **918** | **129** | 1047 |
| 2011 | 2484 | 35 568 | 38 052 | **520** | **316** | 836 |
| 2012 | 6062 | 37 026 | 43 088 | **549** | **140** | 689 |
| 2013 | 2912 | 42 736 | 45 648 | **266** | **1249** | 1515 |
| 2014 | 2769 | 50 417 | 53 186 | **571** | **526** | 1099 |
| 2015 | 3869 | 73 739 | 77 608 | **656** | **559** | 1215 |
| 2016 | 5630 | 57 078 | 62 708 | **315** | **537** | 852 |
| 2017 | 2592 | 65 768 | 68 360 | **304** | **522** | 826 |
| 2018 | 3787 | 68 813 | 72 600 | **323** | **550** | 873 |
| Total | 60 641 | 784 706 | 845 347 | 6 427 | 12 778 | 19 205 |

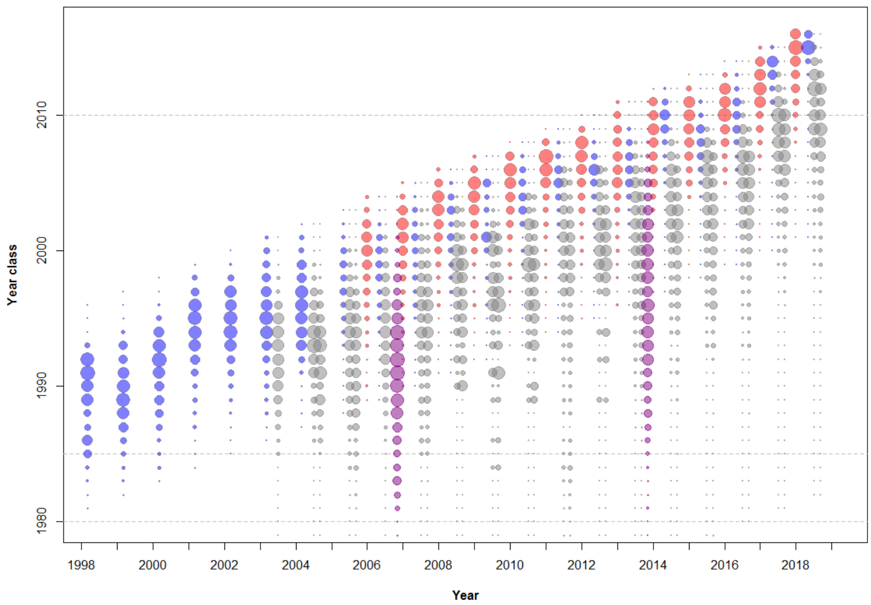



**Figure 8.6:** Bubble plot of age observations by year for the survey (red), trawl (Trawl1 and Trawl2, blue), longline (LL1 and LL2, grey) and trap (purple).

Year-specific ALKs, grouped by 50 mm length bins from 150 to 2000 mm. were calculated separately for the survey and the commercial catch from all respective age-length samples. Tables A1 and A2 show an ALK obtained by pooling data over all years showing the overall age-length relationship for survey and commercial catches.

For all surveys where ALKs were available (2006-2018), catch-at-length data were used to estimate proportions-at-length, weighted by stratum area. These were then converted to proportions-at-age, using survey ALKs. The initial ESS for these survey proportions-at-age were derived by assuming a relationship between the observed proportions-at-age $O_j$ and their CVs $c_j$ as estimated from bootstrap sampling that accounted for haul-specific proportions-at-length, the ALK and random ageing error. The estimated effective sample size was then derived using a robust non-linear least squares fit of $\log(c_j) \sim \log(O_j)$ assuming a multinomial distribution.

For the commercial fishery, representative ALKs were available for all years from 1998 - 2018. Catch-at-length data grouped by 50 mm length bins from 150 to 2000 mm were used to estimate catch proportions-at-length and converted to proportions-at-age using commercial ALKs. Similarly to the survey data, initial ESS for all years and sub-fisheries except Trap were estimated by fitting a robust non-linear least squares model to the observed proportions-at-age against their CVs assuming a multinomial distribution. For Trap, ESS was set to 1 to allow for the estimation of trap selectivity while the information content of the data was considered to be poor due to high inter-annual variability in areas and depths fished.

### Length-at-age estimation

Similar to previous assessments, length-at-age data was re-estimated using all randomly sampled and aged fish from 1997-2018. Fish records with a poor quality flag, missing data, doubtful length measurements, or poor age reads (e.g. a poor readability score) were excluded. For otoliths with multiple reads, the median age was taken (rounded to the next integer age).

Similarly to the 2017 assessment (Ziegler and Welsford 2015) and as recommended by the CCAMLR Independent Stock Assessment Review (2018), a von Bertalanffy (VB) growth function was re-estimated that accounted for length-bin sampling and gear selectivity. The definition of the likelihood function was based on variable probability sampling due to the pre-specified length-dependent fishing selectivity function and the effect of length-bin sampling on sampling probabilities following the approach of Candy et al. (2007). Accounting for a dome-shaped selectivity function reflected the combined effects of fish selection by the trawl, longline and trap gear, with lower selectivity of fish smaller than about 500 mm and larger than 1200 mm (Figure 8.7). Accounting for length-bin sampling was needed because aged fish were not randomly selected from the catch, with an over-representation of aged fish smaller than 500 mm and fish between 1000-1500 mm compared to the catch.

The contribution of the almost 1700 newly-aged fish, with a relatively high proportion of old fish, were used to update the 2019 growth model. This model predicted a slightly lower $L_\infty$ and higher $K$, and thus lower estimates of length-at-age for younger and older fish, compared to the 2017 growth model (Figure 8.8 and Table 8.4). Accounting for length-bin sampling substantially reduced the estimated growth rates, while accounting for dome-shape selectivity had only a minor effect on growth estimates, particularly for the age classes up to 35 years used in the assessment.

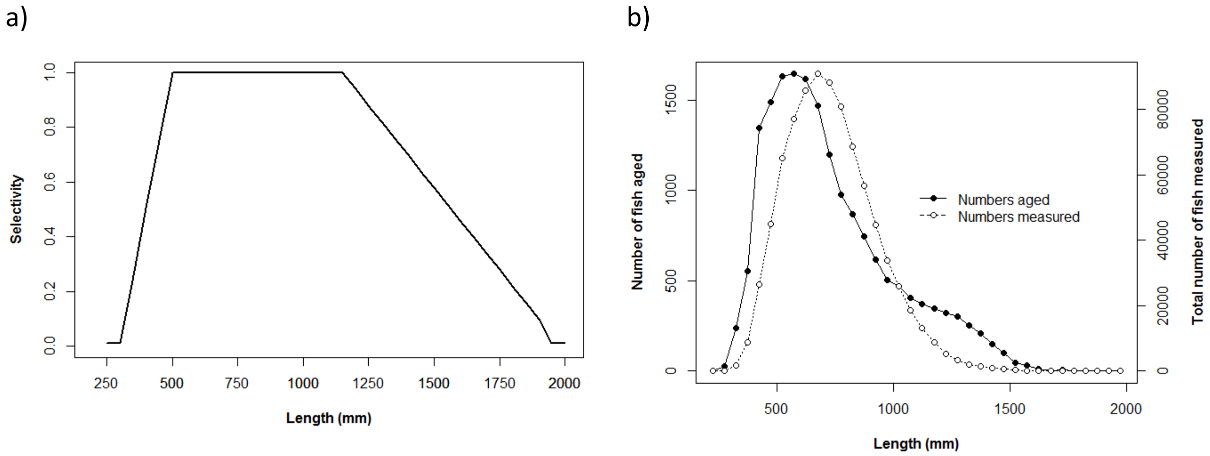



**Figure 8.7**: (a) Selectivity function used in the estimation of growth, and (b) number of fish sampled by 50 mm length bins for ageing (black circles) and overall in the fishery (open circles).

**Table 8.4**: Parameters estimates of the von Bertalanffy growth functions that accounted for dome-shaped selectivity and length-bin sampling and were used in the 2015, 2017 and 2019 stock assessments.

| **Model** | $L_\infty$ | $K$ | $t_0$ | $CV$ |
|---|---|---|---|---|
| 2015 Growth (Ziegler & Welsford 2015) | 2116 | 0.030 | -5.31 | 0.128 |
| 2017 Growth (Ziegler 2017a) | 1604 | 0.049 | -3.64 | 0.131 |
| 2019 Growth | 1504 | 0.058 | -3.30 | 0.135 |

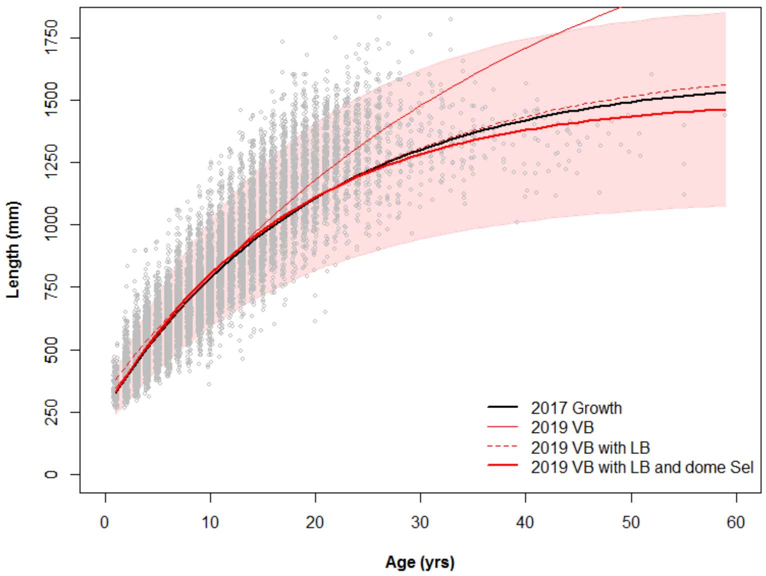



**Figure 8.8:** Length-at-age data (grey), growth model used in the 2017 assessment ('2017 Growth', black line), simple von Bertalanffy model ('2019 VB', thin red line), von Bertalanffy model that accounted for length-bin sampling ('2019 VB with LB', red dashed line), and final von Bertalanffy model that accounted for length-bin sampling and dome-shaped selectivity and was used in the 2019 assessment ('2019 with LB and dome Sel', bold red line) with approximate 95% confidence intervals of the data based on CV (red shade). Sample size N = 19 620.

### Length-weight relationship

The length-weight relationship, originally derived from Constable et al. (1999), was re-estimated for this assessment. The estimated relationships varied slightly between 1997-2009 but has been highly consistent after 2009, and the length-weight relationship fitted to all data from 1997-2018 estimated a slightly smaller weight-at-length than what was found by Constable et al. (1999, Figures 8.9 and 8.10, Table 8.6).

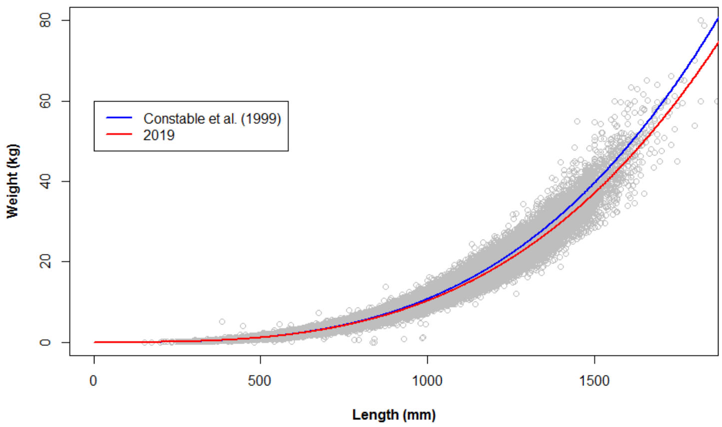



**Figure 8.9:** Estimated length-weight relationship (red line) fitted to observations from all years 1997-2018 (grey dots), and length-weight relationship estimated by Constable et al. (1999) (blue line).

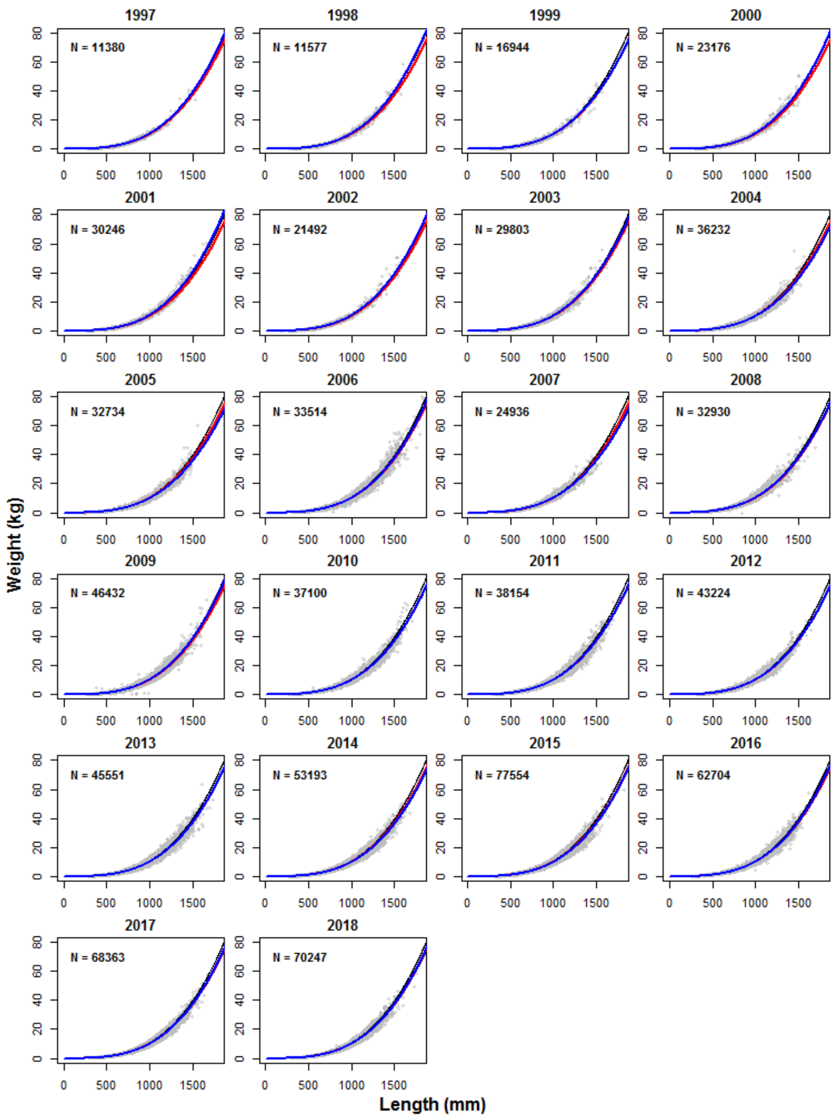



**Figure 8.10:** Estimated annual (blue lines) and combined (red lines) length-weight relationships for the years 1997-2018, and observations (grey dots). N denotes sample sizes.

**Maturity-at-age**

Between 2006 and 2015, an age-converted maturity-at-length function was used in the stock assessment. In 2017, a re-estimated maturity function by Yates et al. (2017) was applied, with $a_{50}$ = 13.9 years and $a_{to95}$ = 13.7 years (Figure 8.11). Yates et al. (2017) considered all stages ≥ 2 as mature since a large proportion of fish that were macroscopically determined to be stage 2 were found to contain cells of higher stages when gonads were examined histologically. This finding indicated that many fish that had spawned, as confirmed by the presence of post-ovulatory follicles, return to a resting stage which is macroscopically indistinguishable from maturing fish. Furthermore, the occurrence of females of all size classes with low gonadosomatic index (GSI) and low macroscopic gonad stage during the spawning season suggested that a proportion of mature fish did not spawn every year.

The assumption that all stages ≥ 2 are mature may bias the estimation of age-at-maturity in the population to some degree as some of stage-2 fish have not spawned in the past. Kock and Kellermann (1991) argued that the progression from cortical alveoli stage to hydration in notothenioid fishes can take up to 2 years. When adding an offset of 2 years to all stage-2 fish, the estimated age-at-maturity parameters were similar although contracted, with $a_{50}$ = 13.7 years and $a_{to95}$ = 10.6 years. The influence of the offset on the maturity parameter estimates was relatively small since maturity of young fish was strongly determined by a large number of stage-1 fish.

WG-FSA-17 considered that this revised maturity-at-age function which predicted that some young fish in the age range of 1–7 would be mature, was inconsistent with the expectation of the life-history characteristics of a long-lived deep-water species. Following WG-SAM-19/27 and the recommendation by WG-SAM-19 (para. 3.6), the maturity function for this assessment assumed that:

(1) Fish aged ≤ 5 years: immature

(2) Fish aged > 5 years and < 10 years: Maturity increases linearly to the proportion as estimated under (3) for fish aged 10 years

(3) Fish aged ≥ 10 years: Maturity follows a function assuming fish of all maturity stages ≥ 2 are mature, with an age offset of 2 years added to all stage-2 fish.

The assumption that all fish up to the age of 5 years are immature is consistent with that taken for *D. eleginoides* in the 2017 assessment for Subarea 48.3 (Earl and Fischer 2017). However, older fish are estimated to mature later by this revised maturity-at-age function compared to fish in Subarea 48.3 (Figure 8.12), and the maturity is in-between the estimated maturity for male and female *D. mawsoni* in the Ross Sea (Parker and Grimes (2010) which was used in the 2017 stock assessment (Mormede 2017a, 2017b).

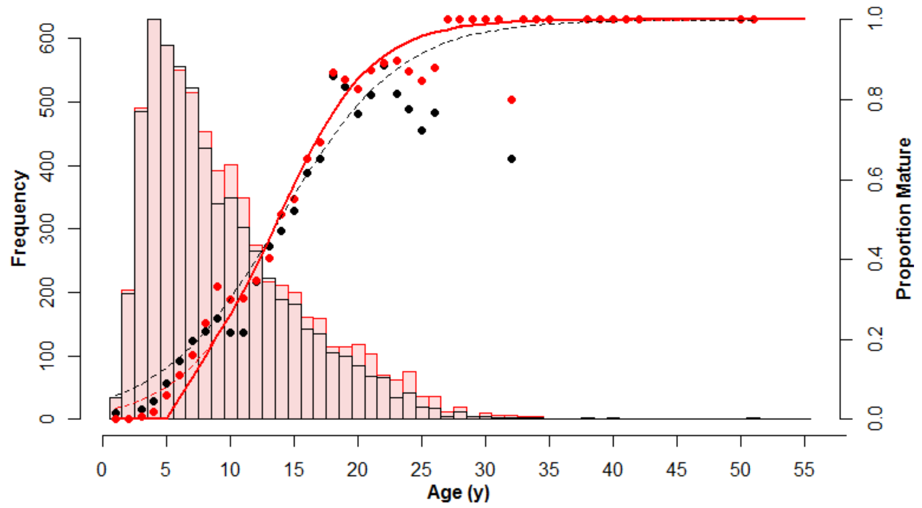



**Figure 8.11:** Maturity-at-age functions fitted to data assuming all fish of stage ≥ 2 are mature (black points and dashed black line, used in the 2017 assessment) and when an offset of 2 years to all fish of stage 2 was added (red points and dashed red line), and adjusted function assuming that all fish up to the age of 5 years are immature and maturity then increase linearly up to the estimated value at the age of 10 years (red solid line, used in this assessment). Shown are also age-frequency histograms and proportions of fish that were mature pooled in 1-year age bins (points).

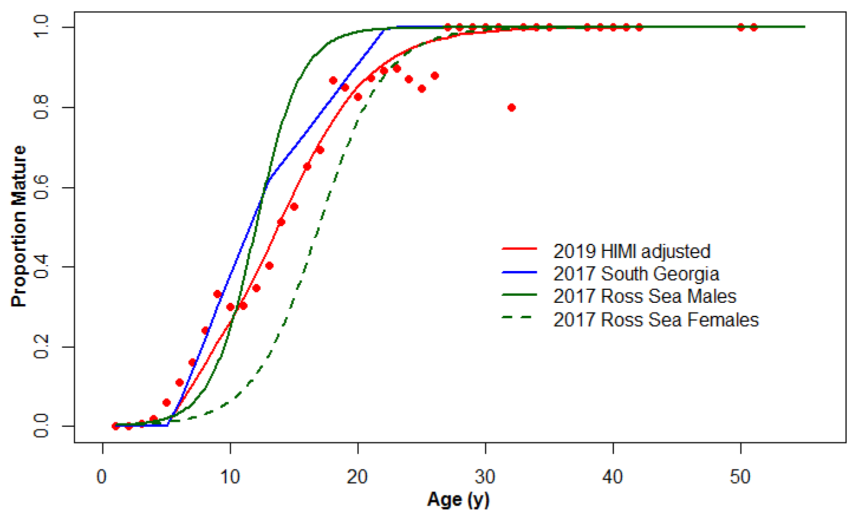



**Figure 8.12:** Adjusted maturity-at-age based used in the 2019 stock assessment when assuming all fish of stage ≥ 2 are mature with an added age offset of 2 years to all fish of stage 2 (red line), and functions used in the 2017 assessment for Subarea 48.3 (blue, WG-FSA-17/53) and in the 2017 assessment for male (green solid line) and female (green dashed line) *D. mawsoni* in the Ross Sea (Parker and Grimes 2010). Shown are also the proportions of fish that were mature pooled in 1-year age bins (red points) in samples from Division 58.5.2.

### Other biological parameters

Other biological parameters are specified in Table 6. Natural mortality was estimated to be 0.155 (Candy 2011a, Candy et al. 2011) and assumed constant across all age classes, and the stock recruitment relationship was assumed to follow a Beverton-Holt function with steepness *h* = 0.75 (Dunn et al. (2006).

### Ageing error matrix

In 2014, the method of Candy et al. (2012) to estimate the ageing error matrix (AEM) was revised by Burch et al. (2014) to address some issues regarding true ages not being the mode at the extremes of the matrix and a lack of smoothness in the probabilities for ages above 25 years. At the same time, the reference collection was expanded to include an additional 50 otoliths, read by four or more readers, that had a mean fish age of 25 years or greater. For this assessment, the same ageing error matrix was used as for the 2015 and 2017 assessments (see 8.8 Appendix).

## 8.4 Methods

### Model configuration

Basic descriptions of the CASAL model population dynamics can be found in Candy and Constable (2008), Candy and Welsford (2009, 2011), Ziegler et al. (2013, 2014), Ziegler and Welsford (2015) and Ziegler (2017a). The single-sex CASAL assessment model (Bull et al. 2012) was age-structured with age classes from 1-35 years. CASAL 2.30-2012-03-21 rev. 4648 was used in all instances, following the recommendation of WG-SAM-14 (WG-SAM-14, para. 2.29).

The assessment models were run for the period from 1982-2019. The annual cycle was divided into three time steps or seasons during which (1) fish recruitment, the first half of natural mortality, and fishing, (2) the second part of natural mortality and spawning, and (3) ageing occurred.

### Selectivity functions

Either double-normal (DN) or double-normal-plateau (DNP) fishing selectivity functions were fitted for the survey and each sub-fishery. The DNP function was calculated as *f(x)* for age *x* (Bull et al. 2012):

$$f(x) = \begin{cases} a_{\max} 2^{-\left[(x-a_1)/\sigma_L\right]^2} & x \le a_1 \\ a_{\max} & a_1 < x \le a_1 + a_2 \\ a_{\max} 2^{-\left[\{x-(a_1+a_2)\}/\sigma_U\right]^2} & x > a_1 + a_2 \end{cases} \quad (1)$$

where $a_1$ and $a_1$+ $a_2$ define the age range at which the ogive takes the value $a_{max}$, and $\sigma_L$ and $\sigma_R$ define the shape of the left-hand and right-hand side of the DNP function such that the ogive takes the value 0.5$a_{max}$ at $a = a_1 - \sigma_L$ and $a = a_1 + a_2 + \sigma_R$. In all cases, $a_{max}$ was not estimated but set to 1, i.e. only four parameters were estimated for all DNPs. When the parameter $a_2$ is estimated to be very small (~ 0.1 year), the DNP collapses to a DN and was replaced with a DN function in the assessment model. This was the case for the survey, the trawl and longline sub-fisheries and for longline (see below), while the trap sub-fishery was fitted with DNP functions.

## Model estimating procedure

The assessment models estimated the unfished spawning biomass $B_0$, survey catchability $q$, annual year class strength (*YCS*), and the parameters of the selectivity functions for the survey and all sub-fisheries.

All models included penalties for *YCS* and catch. A penalty for *YCS* was intended to force the average of estimated *YCS* towards 1. Strong catch penalties prohibited the model from returning an estimated fishable biomass for which the catch in any given year would exceed the maximum exploitation rate set at $U$ = 0.995 for each sub-fishery.

Process error was estimated and added in a number of iterations for each model in the bridging analysis (see below). Iterative data re-weighting followed the method TA1.8 described by Francis (2011a and 2011b) to allow for correlations within the observed composition data. The reweighting was applied first to the commercial catch composition data of all sub-fisheries, then to the survey composition data, and lastly to the tag-recapture data.

For catch-at-age composition data, the weight $w_j$ for each age $j$ observed by a sub-fishery or the survey was estimated as:

$$w_j = \frac{1}{\text{var}_i\left[(O_{iy} - E_{iy}) / \sqrt{(v_{iy} / N_{iy})}\right]} \qquad (2)$$

where $O_{iy}$ is the observed and $E_{iy}$ is the expected proportions for age or length class $i$ in year $y$, $v_{iy}$ is the variance of the expected age or length distribution, and $N_{iy}$ was the number of multinomial cells. The weight was then multiplied with the sample size from the previous step before re-running the model. For the re-weighting of the tagging data, Equation (2) was used again.

Initially, a point estimate (maximum posterior density MPD) and its approximate covariance matrix for all free the parameters as the inverse Hessian matrix were estimated. For the final model, these estimates were used as starting point for Monte Carlo Markov Chains (MCMCs) sampling. For the MCMCs, the first 500 000 iterations were dismissed (burn-in), and every 1000$^{th}$ sample taken from the next 1 million iterations. MCMC trace plots were used to determine evidence of non-convergence.

## Bridging analysis

Similar to previous assessments, a bridging analysis was conducted. The analysis started with the 2017 assessment model that was used to provide management advice in 2017 (WG-FSA-17, para. 3.44-3.54) and led step-wise to the 2019 assessment model (Table 8.5).

The starting point of the bridging analysis, the 2017 assessment model, included survey abundance-at-length and abundance-at-age, tag-releases for 2012-2016, and catch-at-age from sub-fisheries for Trawl1, Trawl2, longline LL1 and LL2, and Trap. Year class strength was estimated for the period from 1986-2011 (Table 8.6).

In Model 1, the model was extended to 2019. The catch in 2019 was assumed to be fully taken, with similar catch proportions as in 2018. Complete data sets from 2017 and 2018 for survey index and proportions-at-age, commercial sub-fisheries catch-at-age, and tag-releases and tag-recaptures were added. Annual ALKs were used as recommended in the CCAMLR Independent Stock Assessment Review (2018), i.e. low commercial age-length samples were not pooled as in the previous assessment and in fact 1997 was dropped since only old fish had been aged. The period of estimated year class strength was extended to 1986-2013.

**Table 8.5**: Step-wise, cumulative changes from the 2017 assessment model to the 2019 assessment model.

| Step | Description |
|---|---|
| 0 | 2017 Assessment model (as in Ziegler 2017a) |
| 1 | Update model to the end of the 2018/19 season including catch, survey, commercial catch-at-age and tag-recapture data |
| 2 | Include estimated fishing-induced mortality from longline gear loss |
| 3 | Update growth parameters |
| 4 | Update length-weight relationship |
| 5 | Update maturity estimates |
| 6 | Simplified longline selectivity functions |

In Model 2, estimated fishing-induced mortality from longline gear loss was included.

In Model 3, the parameters of the growth function (see above) were updated.

In Model 4, the parameters of the length-weight relationship (see above) were updated.

In Model 5, the parameters of the maturity function (see above) were updated.

In Model 6, the DNP selectivity functions for both longline sub-fisheries were replaced with DN functions as the parameters $a_2$ was estimated at the lower boundary (0.1 year) in Model 5.

A number of sensitivity runs were conducted to evaluate the impact of assumptions such as tag-recapture data, natural mortality, initial tag loss, and estimated *YCS*.

### Calculations of catch limits

Catch projection trials accounted for uncertainty surrounding parameter estimates of the model as well as future recruitment variability. In order to integrate across uncertainty in the model parameters, MCMC samples were used for CASAL's projection procedure to obtain 1000 random time series samples of estimated numbers of age-1 recruits for the period from 1982-2013, corresponding to *YCS* estimates from 1981-2012. The median of the square root of the variance of the yearly numbers of these age-1 recruits from 1986-2013 provided a robust estimate of the $\sigma_R$ for recruitment required for the lognormal random recruitment generation.

The estimated *CVs* were used to generate the random recruitment from 2012 until the end of the 35-year projection period. Based on this sample of projections for spawning stock biomass, long-term catch limits were calculated following the CCAMLR decision rules:

- Choose a yield $\gamma_1$, so that the probability of the spawning biomass dropping below 20% of its median pre-exploitation level over a 35-year harvesting period is 10% (depletion probability).

- Choose a yield $\gamma_2$, so that the median escapement of the spawning biomass at the end of a 35-year period is 50% of the median pre-exploitation level.
- Select the lower of $\gamma_1$ and $\gamma_2$ as the yield.

The depletion probability was calculated as the proportion of samples from the Bayesian posterior where the predicted future spawning biomass was below 20% of $B_0$ in the respective sample at any time over the 35-year projected period. The level of escapement was calculated as the proportion of samples from the Bayesian posterior where the projected future status of the spawning biomass was below 50% of $B_0$ in the respective sample at the end of the 35-year projection period.

Catch limit estimates were based on the assumption of constant annual catches. Future surveys were assumed to be conducted every year with a catch of 20 tonnes. The entire remaining future catch was assumed to be taken by longline, with a catch split based on the overall catch distribution of longline sub-fisheries in the last three years, i.e. 50% of the total catch was attributed to LL1 and 50% to LL2 selectivities.

**Table 8.6**: Population parameters and their values for all evaluated Models 1 to 6 in the bridging analysis. New changes in each model are highlighted in bold with grey shading and then maintained. All introduced changes were maintained for subsequent model steps.

| **Parameters** | **0. Model 2017** | **1. Updated data to 2. Gear loss** | **3. Growth** | **4. Length-weight** | **5. Maturity to 6. LL Selectivity** |
|---|---|---|---|---|---|
| Assessment period | 1982-2016 | 1982-2019 | 1982-2019 | 1982-2019 | 1982-2019 |
| $B_0$ | Estimated | Estimated | Estimated | Estimated | Estimated |
| $R_0$ | Derived from $B_0$ | Derived from $B_0$ | Derived from $B_0$ | Derived from $B_0$ | Derived from $B_0$ |
| $\sigma_R$ for projections | Calculated from *YCS* 1986-2011 | Calculated from *YCS* 1986-2013 | Calculated from *YCS* 1986-2013 | Calculated from *YCS* 1986-2013 | Calculated from *YCS* 1986-2013 |
| Stock–recruitment Steepness *h* | Beverton-Holt *h* = 0.75 | Beverton-Holt *h* = 0.75 | Beverton-Holt *h* = 0.75 | Beverton-Holt *h* = 0.75 | Beverton-Holt *h* = 0.75 |
| Estimated *YCS* | 1986-2011 | 1986-2013 | 1986-2013 | 1986-2013 | 1986-2013 |
| Age classes | 1 - 35 y | 1 - 35 y | 1 - 35 y | 1 - 35 y | 1 - 35 y |
| Length classes | 300 - 2000 mm (50 mm bins) | 300 - 2000 mm (50 mm bins) | 300 - 2000 mm (50 mm bins) | 300 - 2000 mm (50 mm bins) | 300 - 2000 mm (50 mm bins) |
| Size-at-age: vB | Ziegler (2017a) | Ziegler (2017a) | This document | This document | This document |
| $L_\infty$ | 1605 | 1605 | 1504 | 1504 | 1504 |
| *K* | 0.049 | 0.049 | 0.058 | 0.058 | 0.058 |
| *t0* | -3.64 | -3.64 | -3.30 | -3.30 | -3.30 |
| *CV* | 0.131 | 0.131 | 0.135 | 0.135 | 0.135 |
| Ageing error matrix | Burch et al. (2014) | Burch et al. (2014) | Burch et al. (2014) | Burch et al. (2014) | Burch et al. (2014) |
| Weight at length *L* (mm to t) | Constable et al. (1999) *c* = 2.59E-12 *d* = 3.2064 | Constable et al. (1999) *c* = 2.59E-12 *d* = 3.2064 | Constable et al. (1999) *c* = 2.59E-12 *d* = 3.2064 | This document *c* = 3.61E-12 *d* = 3.1518 | This document *c* = 3.61E-12 *d* = 3.1518 |
| Maturity | Yates et al. (2018) Logistic: $a_{50}$ = 13.9 $a_{to95}$ = 13.7 | Yates et al. (2018) Logistic: $a_{50}$ = 13.9 $a_{to95}$ = 13.7 | Yates et al. (2018) Logistic: $a_{50}$ = 13.9 $a_{to95}$ = 13.7 | Yates et al. (2018) Logistic: $a_{50}$ = 13.9 $a_{to95}$ = 13.7 | This document Logistic: $a_{50}$ = 13.7 $a_{to95}$ = 10.6 Adjusted for ages up to 10 y |
| Natural mortality *M* | Candy et al. (2011a) 0.155 | Candy et al. (2011a) 0.155 | Candy et al. (2011a) 0.155 | Candy et al. (2011a) 0.155 | Candy et al. (2011a) 0.155 |
| Survey *q* | Estimated | Estimated | Estimated | Estimated | Estimated |
| Tagging data | | | | | |
| Tag detection | Ziegler (2017a) 1 | Ziegler (2017a) 1 | Ziegler (2017a) 1 | Ziegler (2017a) 1 | Ziegler (2017a) 1 |
| Tag-release mortality | Agnew et al. (2006) 0.1 | Agnew et al. (2006) 0.1 | Agnew et al. (2006) 0.1 | Agnew et al. (2006) 0.1 | Agnew et al. (2006) 0.1 |
| No-growth period | Agnew et al. (2005) 0.5 y | Agnew et al. (2005) 0.5 y | Agnew et al. (2005) 0.5 y | Agnew et al. (2005) 0.5 y | Agnew et al. (2005) 0.5 y |
| Tag shedding | Ziegler (2017b) 2012-2015: 0.006 | Ziegler (2017b) 2012-2017: 0.006 | Ziegler (2017b) 2012-2017: 0.006 | Ziegler (2017b) 2012-2017: 0.006 | Ziegler (2017b) 2012-2017: 0.006 |
| Emigration correction (included in tag shedding parameter) | Burch et al. (2017) 0.01 | Burch et al. (2017) 0.01 | Burch et al. (2017) 0.01 | Burch et al. (2017) 0.01 | Burch et al. (2017) 0.01 |

| | 0: Model 2017 | 1. Updated data | 2. Gear loss | 3. Growth to 5. Maturity | 6. LL Selectivity |
|---|---|---|---|---|---|
| **Priors for estimated parameters** | | | | | |
| $B_0$ | Uniform-log | Uniform-log | Uniform-log | Uniform-log | Uniform-log |
| Starting value | 90000 | 90000 | 90000 | 90000 | 90000 |
| Bounds | 30000-250000 | 30000-250000 | 30000-250000 | 30000-250000 | 30000-250000 |
| Survey *q* | Uniform-log | Uniform-log | Uniform-log | Uniform-log | Uniform-log |
| Bounds | 0.1-1.5 | 0.1-1.5 | 0.1-1.5 | 0.1-1.5 | 0.1-1.5 |
| *YCS* | Lognormal | Lognormal | Lognormal | Lognormal | Lognormal |
| Starting value | $\mu$=1, *CV*=0.6 | $\mu$=1, *CV*=0.6 | $\mu$=1, *CV*=0.6 | $\mu$=1, *CV*=0.6 | $\mu$=1, *CV*=0.6 |
| Bounds | 0.001-200 | 0.001-200 | 0.001-200 | 0.001-200 | 0.001-200 |
| Fishing selectivities: | | | | | |
| Double-normal: | Uniform | Uniform | Uniform | Uniform | Uniform |
| Sub-fisheries | Survey, Trawl1, Trawl2 | Survey, Trawl1, Trawl2 | Survey, Trawl1, Trawl2 | Survey, Trawl1, Trawl2 | Survey, Trawl1, Trawl2, LL1, LL2 |
| Starting values (bounds) | $a_1$: 4 (1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 7 (0.1-20) | $a_1$: 4 (1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 7 (0.1-20) | $a_1$: 4 (1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 7 (0.1-20) | $a_1$: 4 (1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 7 (0.1-20) | $a_1$: 4 (1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 7 (0.1-20) |
| Double-normal plateau | Uniform | Uniform | Uniform | Uniform | Uniform |
| Sub-fisheries | LL1, LL2, Trap | LL1, LL2, Trap | LL1, LL2, Trap | LL1, LL2, Trap | Trap |
| Starting values (bounds) | $a_1$: 10 (1-20)<br>$a_2$: 6 (0.1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 3 (0.1-20)<br>$a_{max}$: 1 (1-1) | $a_1$: 10 (1-20)<br>$a_2$: 6 (0.1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 3 (0.1-20)<br>$a_{max}$: 1 (1-1) | $a_1$: 10 (1-20)<br>$a_2$: 6 (0.1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 3 (0.1-20)<br>$a_{max}$: 1 (1-1) | $a_1$: 10 (1-20)<br>$a_2$: 6 (0.1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 3 (0.1-20)<br>$a_{max}$: 1 (1-1) | $a_1$: 10 (1-20)<br>$a_2$: 6 (0.1-20)<br>$\sigma_L$: 1 (0.1-20)<br>$\sigma_R$: 3 (0.1-20)<br>$a_{max}$: 1 (1-1) |
| **N parameters** | 49 | 51 | 51 | 51 | 49 |
| **Data** | | | | | |
| Catch: | | | | | |
| Survey | 2001-2016 | 2001-2019 | 2001-2019 | 2001-2019 | 2001-2019 |
| Trawl1 | 1997-2004 | 1997-2004 | 1997-2004 | 1997-2004 | 1997-2004 |
| Trawl2 | 2005-2016 | 2005-2019 | 2005-2019 | 2005-2019 | 2005-2019 |
| LL1 | 2003-2016 | 2003-2019 | 2003-2019 | 2003-2019 | 2003-2019 |
| LL2 | 2004-2016 | 2004-2019 | 2004-2019 | 2004-2019 | 2004-2019 |
| Trap | 2006-2013 | 2006-2013 | 2006-2013 | 2006-2013 | 2006-2013 |
| IUU | 1996-2016 | 1996-2019 | 1996-2019 | 1996-2019 | 1996-2019 |
| SIOFA | | 2018-2019 | 2018-2019 | 2018-2019 | 2018-2019 |
| Gear loss | | | 2003-2019 | 2003-2019 | 2003-2019 |
| Observations: | | | | | |
| Survey (RSTS): | | | | | |
| Biomass index | 2001-2016 | 2001-2018 | 2001-2018 | 2001-2018 | 2001-2018 |
| Proportions-at-age | 2006-2016 | 2006-2018 | 2006-2018 | 2006-2018 | 2006-2018 |
| ESS | Estimated using Francis (2011a, 2011b) | Estimated using Francis (2011a, 2011b) | Estimated using Francis (2011a, 2011b) | Estimated using Francis (2011a, 2011b) | Estimated using Francis (2011a, 2011b) |
| Commercial sub-fisheries: | Trawl1, Trawl2, LL1, LL2, Trap | Trawl1, Trawl2, LL1, LL2, Trap | Trawl1, Trawl2, LL1, LL2, Trap | Trawl1, Trawl2, LL1, LL2, Trap | Trawl1, Trawl2, LL1, LL2, Trap |
| Proportions-at-age | 1997-2016 | 1998-2018 | 1998-2018 | 1998-2018 | 1998-2018 |
| ESS | Estimated using Francis (2011a, 2011b) Set to 1 for Trap | Estimated using Francis (2011a, 2011b) Set to 1 for Trap | Estimated using Francis (2011a, 2011b) Set to 1 for Trap | Estimated using Francis (2011a, 2011b) Set to 1 for Trap | Estimated using Francis (2011a, 2011b) Set to 1 for Trap |
| Tag-releases | LL1, LL2 | LL1, LL2 | LL1, LL2 | LL1, LL2 | LL1, LL2 |
| Years | 2012-2015 | 2012-2017 | 2012-2017 | 2012-2017 | 2012-2017 |
| Tag-recaptures | LL1, LL2 | LL1, LL2 | LL1, LL2 | LL1, LL2 | LL1, LL2 |
| Years | 2013-2016 | 2013-2017 | 2013-2017 | 2013-2017 | 2013-2017 |

## 8.5 Results

**Bridging analysis and MPD estimates**

Updating the model with catch to the end of 2019 and available observations to the end of 2018 in Model 1 reduced the estimated $B_0$ from 78 845 tonnes as estimated in the 2017 assessment to 77 776 tonnes (Table 8.7 and Figure 8.13).

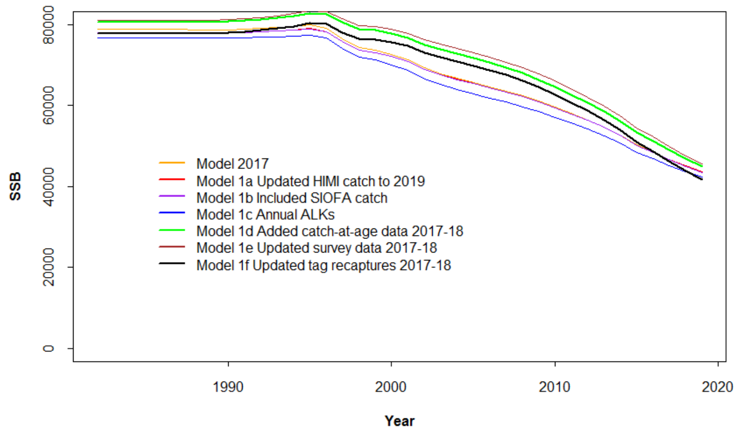
Due to their small quantities, including estimated fishing mortality from lost longline gear had little impact in Model 2. When updating the growth parameters in Model 3 the estimated $B_0$ was reduced to 75 279 tonnes, and when updating the length-weight relationship in Model 4 to 72 560 tonnes. Updating the model with the maturity parameters in Model 5 decreased the estimated $B_0$ to 71 162 tonnes, while simplifying the longline selectivity functions in Model 6 from double-normal-plateau to double-normal had only a minor impact on the $B_0$, with an estimate of 71 210 tonnes.

Compared to the 2017 assessment model, the estimated *SSB* status at the end of 2016 of 0.62 remained unchanged in Model 6. However, the estimated *SSB* status at the end of 2019 was 0.51 which is lower than the estimated stock status when the 2017 model was extrapolated to 2019 (Figure 8.13). This result was due to the stronger decline of the estimated stock trajectory driven by the change in the maturity function and the addition of the 2017 and 2018 observations, which lead to the year class strength estimates for earlier years to be more accentuated and those for more recent years to be consistently below the average (Figure 8.14). The tag dispersion was consistently estimated at around 1.19 (see 8.8 Appendix).

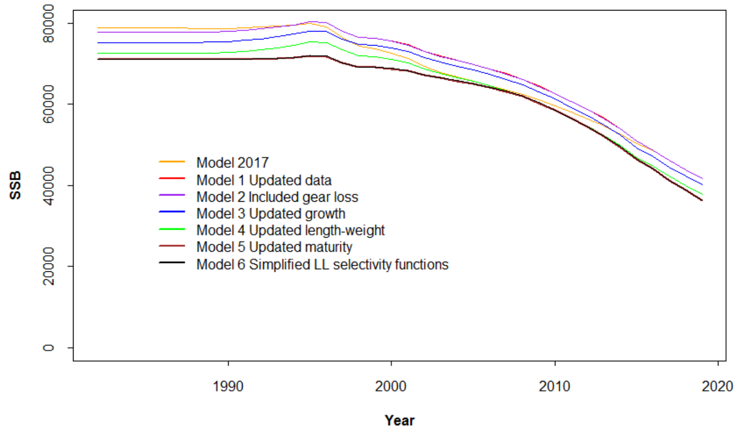
**Table 8.7:** MPD estimates of unfished spawning stock biomass $B_0$ in tonnes, SSB status at the end of 2019, $R_0$ (mean recruitment in millions that gives rise to $B_0$), survey catchability q, and the number of estimated parameters (N Parameters). * MPD stock projection with 3525 tonnes annual catch for 2017-2019 using the 2017 assessment model.

| Model | Description | $B_0$ | *SSB* status | | $R_0$ | Survey | N |
|---|---|---|---|---|---|---|---|
| | | | 2016 | 2019 | | *q* | Parameters |
| 0 | Assessment 2017 | 78 845 | 0.62 | 0.55* | 6.12 | 0.84 | 49 |
| 1 | Update data: | | | | | | |
| | a) Add HIMI catch to 2019 | 78 103 | 0.62 | 0.56 | 6.07 | 0.84 | 49 |
| | b) Add 2018 SIOFA catch | 78 102 | 0.62 | 0.56 | 6.06 | 0.84 | 49 |
| | c) Annual ALKs for commercial catch-at-age | 76 815 | 0.61 | 0.55 | 5.97 | 0.86 | 49 |
| | d) Add commercial catch-at-age 2017-2018 | 80 674 | 0.64 | 0.56 | 6.26 | 0.91 | 51 |
| | e) Add survey data 2017-2018 | 81 083 | 0.64 | 0.56 | 6.30 | 0.92 | 51 |
| | f) Add tag-recapture data 2017-2018 | 77 776 | 0.63 | 0.54 | 6.04 | 1.02 | 51 |
| 2 | Include mortality from gear loss | 77 797 | 0.63 | 0.54 | 6.04 | 1.02 | 51 |
| 3 | Update growth estimates | 75 279 | 0.62 | 0.53 | 5.76 | 1.01 | 51 |
| 4 | Update length-weight relationship | 72 560 | 0.62 | 0.52 | 5.83 | 1.02 | 51 |
| 5 | Update maturity estimates | 71 162 | 0.62 | 0.51 | 5.83 | 1.02 | 51 |
| 6 | Simplify longline selectivity | 71 210 | 0.62 | 0.51 | 5.83 | 1.02 | 49 |

a)




b)




c)

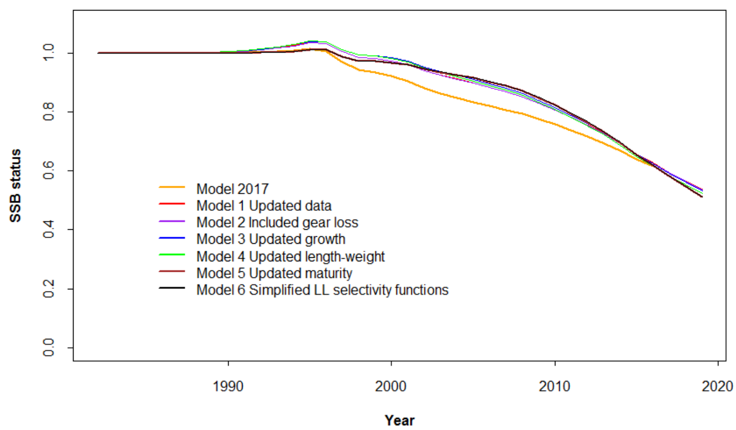



**Figure 8.13:** Estimated trajectories for (a) spawning biomass (*SSB*) for the 2017 assessment model and Model 1 when sequentially adding updated data for catch, survey, commercial catch-at-age, and tag-recaptures, (b) spawning biomass (*SSB*) and (c) spawning stock status (*SSB* status) for the 2017 assessment model and Models 1 to 6.

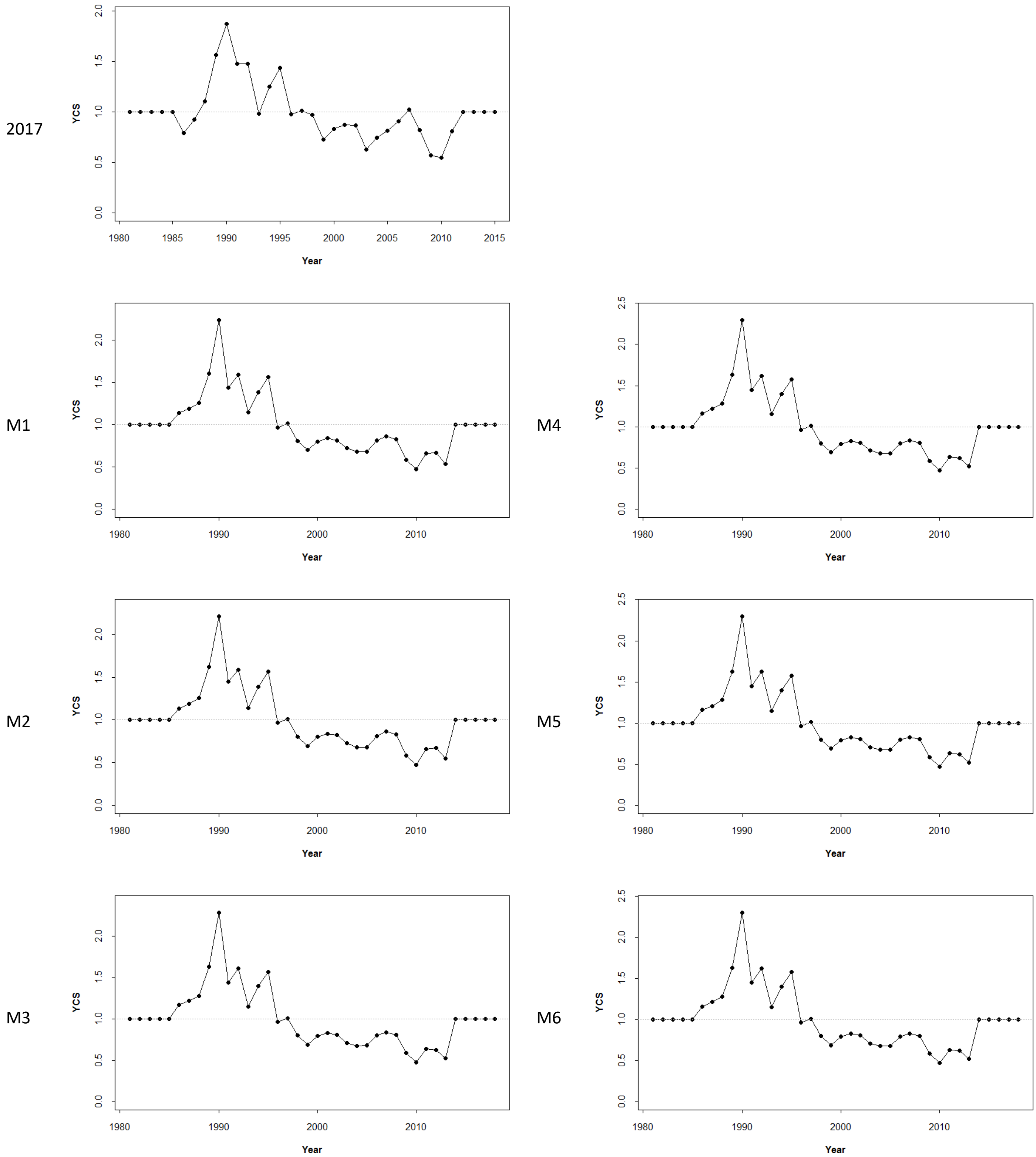



**Figure 8.14:** MPD estimates of *YCS* for the 2017 assessment model and Models 1 to 6.

**Table 8.8:** Contributions to the objective function for all models steps.

| Component | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| Survey Index | -9.8 | -9.8 | -9.6 | -9.7 | -9.7 | -9.7 |
| Survey Age Prop | 220 | 220.1 | 221.6 | 221.8 | 221.6 | 221.6 |
| LL1 Age Prop | 297.6 | 296.7 | 298.9 | 299.2 | 299.4 | 299.4 |
| LL2 Age Prop | 238.3 | 240.3 | 238.3 | 238.2 | 238.3 | 238.9 |
| Trawl1 Age Prop | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| Trawl2 Age Prop | 60.8 | 60.8 | 60.8 | 60.9 | 60.9 | 60.9 |
| Trap Age Prop | 90 | 77.9 | 89.9 | 89.8 | 89.8 | 89.8 |
| Tags 2012 | 81.6 | 81.6 | 82.6 | 83.0 | 83.0 | 83.0 |
| Tags 2013 | 75.2 | 75.2 | 75.2 | 75.7 | 75.7 | 75.7 |
| Tags 2014 | 60.6 | 60.6 | 61.1 | 61.3 | 61.3 | 61.3 |
| Tags 2015 | 61.1 | 61.2 | 61.8 | 62.1 | 62.2 | 62.2 |
| Tags 2016 | 52.0 | 52.1 | 53.1 | 53.5 | 53.5 | 53.5 |
| Tags 2017 | 17.9 | 17.9 | 18.3 | 18.5 | 18.5 | 18.5 |
| MeanYCS_1 | 1.9 | 1.9 | 1.9 | 1.9 | 1.8 | 1.8 |
| Prior for B0 | 11.3 | 11.3 | 11.2 | 11.2 | 11.2 | 11.2 |
| Other priors | -0.4 | -0.5 | -0.1 | 0.0 | 0.1 | 0.1 |
| Penalties | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total** | **1263** | **1252** | **1270** | **1272** | **1273** | **1273** |

Model fits

The contributions to the total objective function differed little between all model steps (Table 8.8). Model 6 with best available data, parameters estimates and model processes was considered to be the most appropriate model and model fits were generally acceptable (Figure 8.15-8.18 and 8.8 Appendix).

The model represented the trend in survey biomass and tag-recapture total numbers and numbers-by-length well. Generally good fits were obtained for the proportions-at-age datasets of the survey and the longline sub-fisheries (Figure 8.18, with final ESS values given in 8.8 Appendix. The data from the two trawl sub-fisheries were more variable, particularly in the most recent years when catches were very small. Despite the split into two trawl periods, there still remained a trend in the residuals during the period 1997-2004 (8.8 Appendix). The observed median age dropped substantially in 2017 and 2018 for the survey and trawl, with a high proportion of very young fish observed in the catch. Data in future years will be needed to confirm whether this is due to a recruitment pulse entering the fishery. Fits to the trap sub-fishery were reasonable, despite the fact that the ESS of this sub-fishery was set to 1.

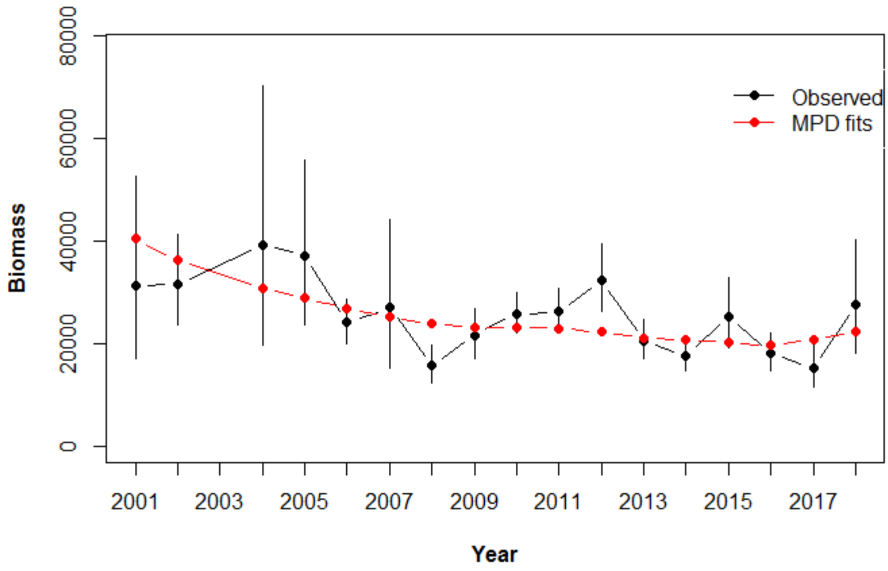



**Figure 8.15:** Observed (black line with 95% CI) and predicted (red line) survey biomass for Model 6.

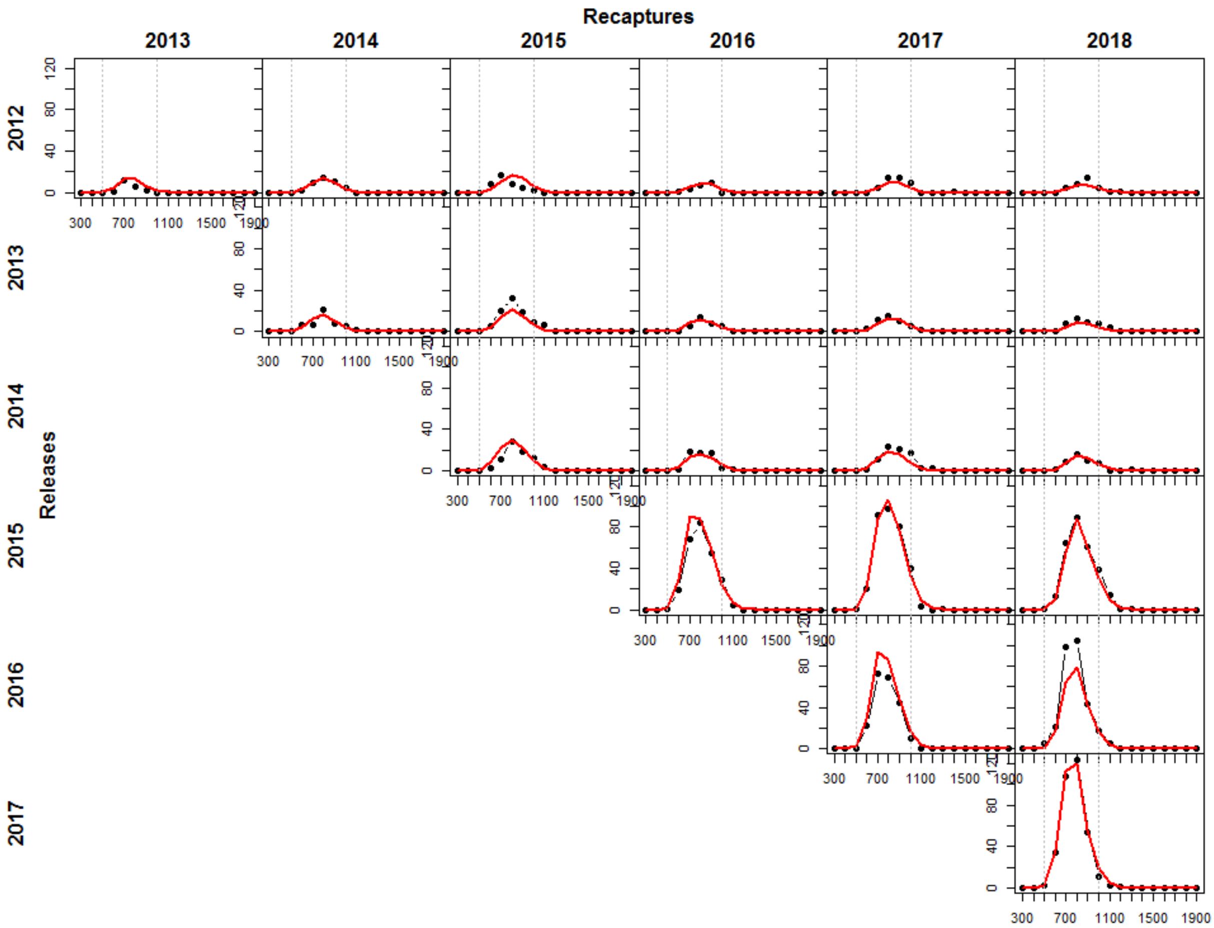
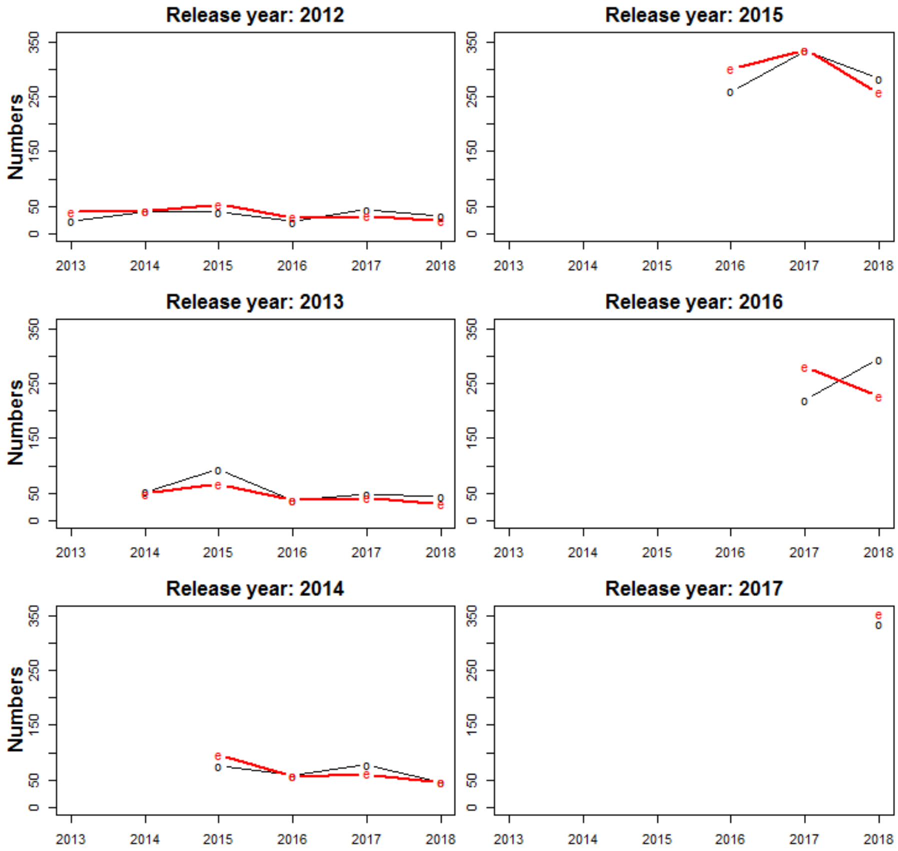



**Figure 8.16:** Numbers of observed (black) and predicted (red) tag recaptures by 100 mm length bins for tag-releases in 2012-2017 and tag-recaptures in 2013-2018 for Model 6.

a)




b)

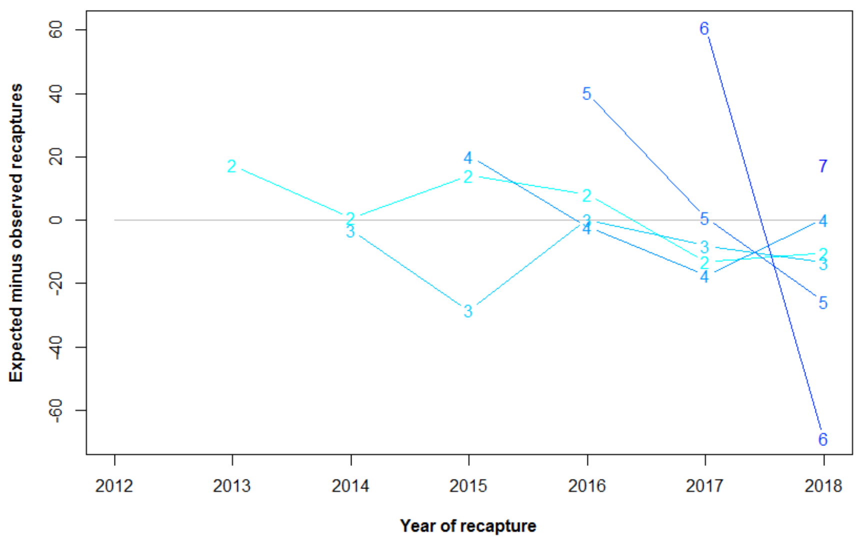



**Figure 8.17:** (a) Numbers of expected (red) and observed (black) tag recaptures, and (b) differences between expected and observed tag-recaptures for tag-releases in 2012-2017 and tag-recaptures in 2013-2018 for Model 6. Tag-release years are denoted by their last digit, i.e. 2 for 2012, 3 for 2013 etc.

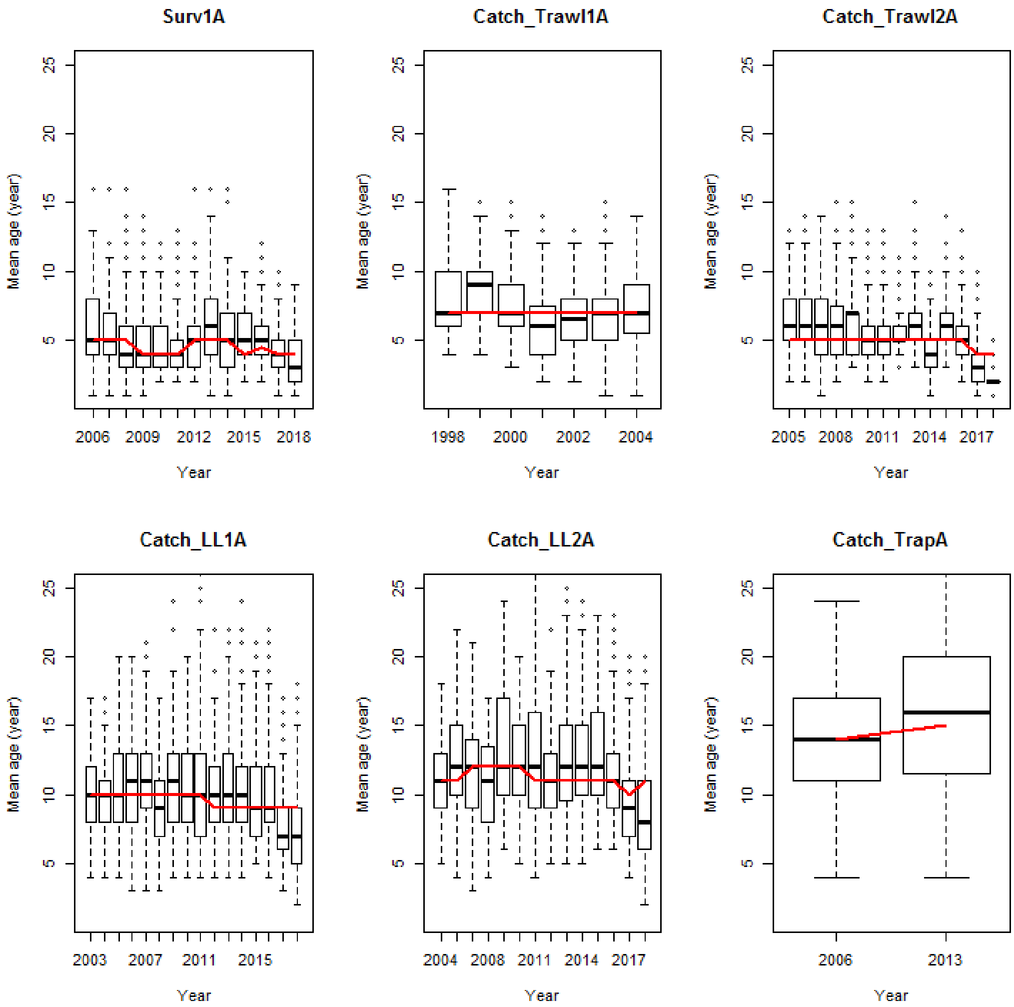


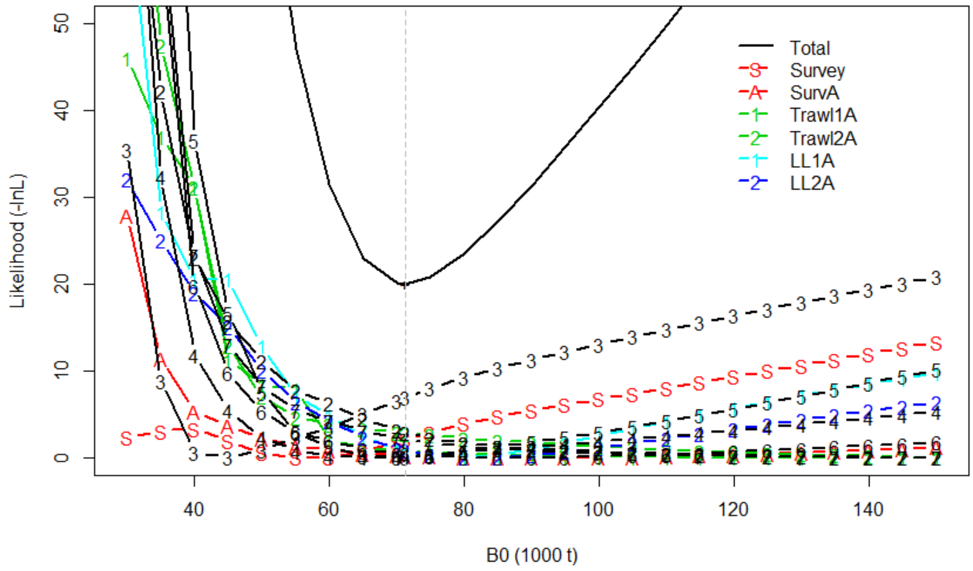

**Figure 8.18:** Boxplots of observed age by fishery and predicted median age (red line) for Model 6.

### Likelihood profiles

The likelihood profile for Model 6 is shown in Figure 8.19. While tag-releases from 2014 - 2016 were in agreement and indicated that a $B_0$ of around 60 000 tonnes was most likely, tag-releases from 2012, 2013 and 2017 were in diametrical disagreement indicating that either a much larger or much smaller $B_0$ was most likely. The survey abundance index indicated that a $B_0$ around 50 000 tonnes was most likely.

The estimate for survey catchability *q* increased substantially between the 2017 and 2019 models from 0.8 to 1.02. However, the likelihood profiles for survey *q* in Model 6 was flat with little information to discriminate between values from 0.8 to 1.2 and more determined by the survey proportion-at-age than the survey index (8.8 Appendix).

a)




b)

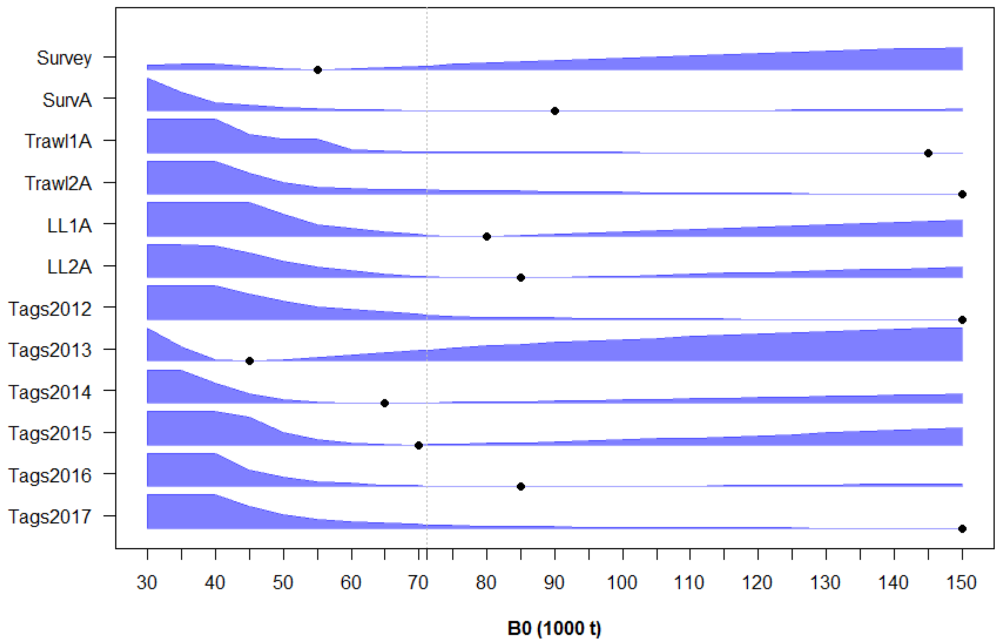



**Figure 8.19**: Likelihood profiles (-2 log-likelihood) across a range of $B_0$ values for (a) all data sets together and (b) separate data sets (dots indicate the location of the minimum value) for Model 6. To create these profiles, $B_0$ values were fixed while only the remaining parameters were estimated. Values for each data set were rescaled to have a minimum of 0, while the total objective function was rescaled to 20. The dotted grey line indicates the MPD estimate. Tag-release years are denoted by their last digit, i.e. 2 for 2012, 3 for 2013 etc.

**MCMC estimates**

Model 6 leads to a smaller estimate of the virgin spawning stock biomass $B_0$ than that obtained in 2017, with an MCMC estimate of 70 519 tonnes (95% CI: 65 634 - 76 626 tonnes). The estimated *SSB* status at the end of 2019 was 0.51 (95% CI: 0.49-0.53) (Table 8.9).

The estimated *YCS* showed large uncertainty for the earlier years 1986-1995, with an indication of a decline and increasingly higher confidence over time (Figure 8.20).

The estimated selectivity functions differed distinctly between the survey and the trawl, longline and trap sub-fisheries (Figure 8.21). The trawl surveys and the commercial trawl sub-fisheries observed predominantly young fish, while the longline and trap sub-fisheries concentrated on older fish, with LL2 in waters deeper than 1500 m catching older fish compared to LL1 in waters shallower than 1500 m. Trap was estimated to catch mainly fish older than 15 years.

**Table 8.9:** MCMC results (median and 95% confidence intervals) for $B_0$, SSB status and survey q.

| **Model** | ***B₀*** | ***SSB* Status** | ***Survey q*** |
|---|---|---|---|
| 2017 Assessment | 77 286 (71 492 - 84 210) | 0.61 (0.58 - 0.64) | 0.80 (0.71 - 0.91) |
| 2019 Assessment | 70 519 (65 634 - 76 626) | 0.51 (0.49 - 0.53) | 0.97 (0.85 - 1.12) |

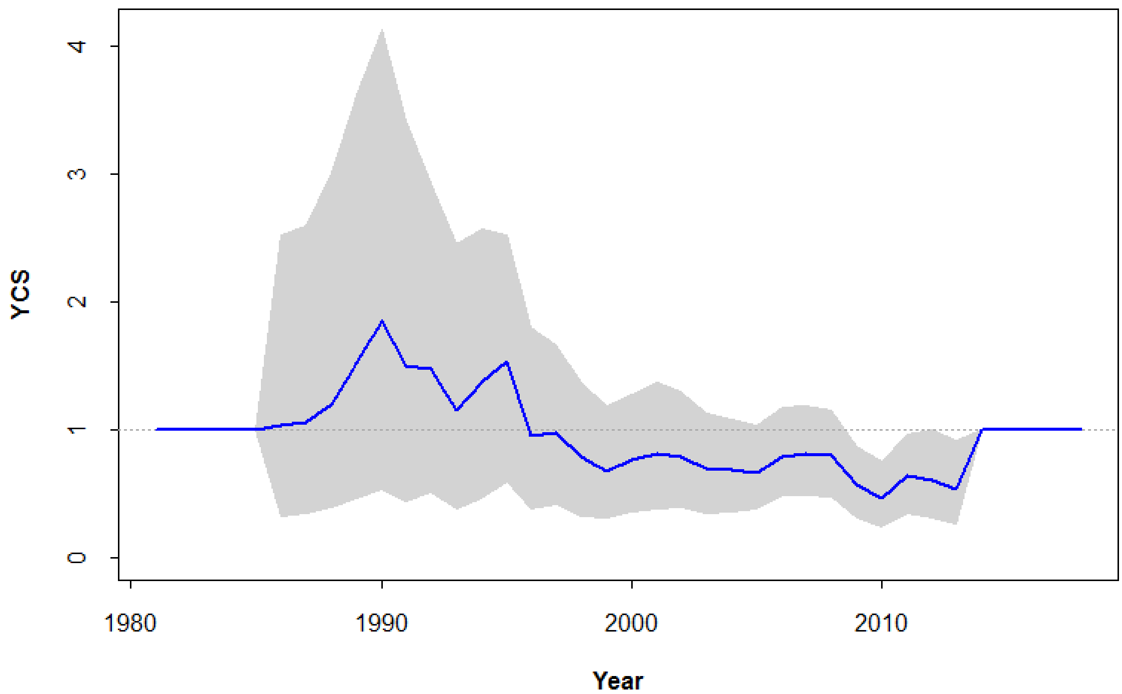



**Figure 8.20:** Estimated YCS for Model 6 showing 95% confidence bounds obtained from the MCMC sample.

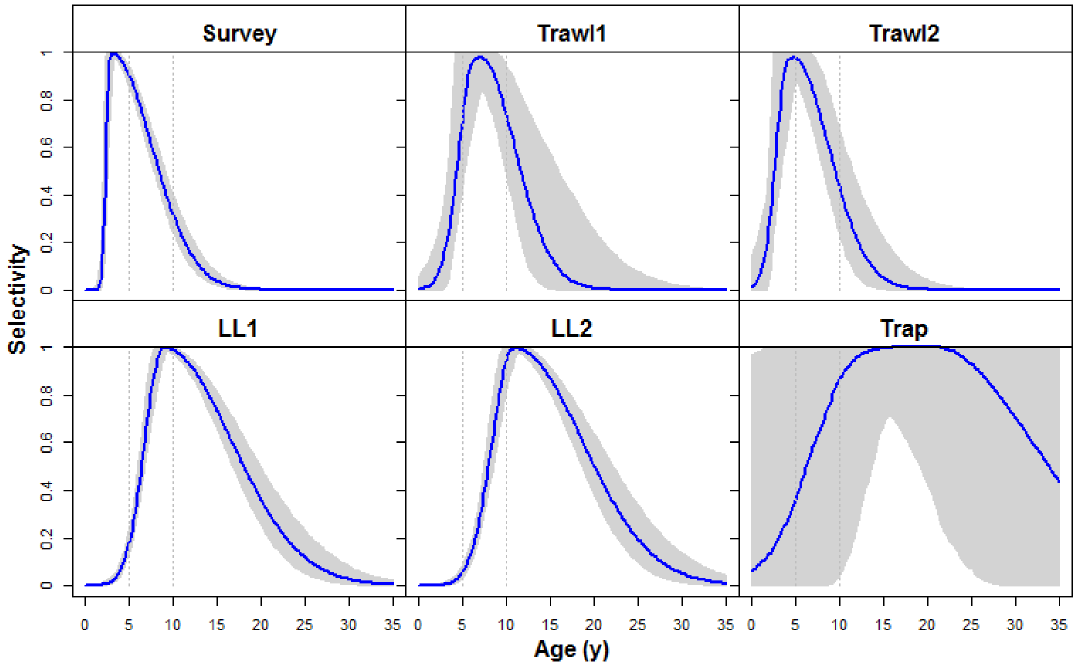



**Figure 8.21:** Estimated double-normal-plateau and double-normal fishing selectivity functions for the survey and commercial sub-fisheries in Model 6, showing 95% confidence bounds obtained from the MCMC samples. Vertical reference lines are shown at ages 5 and 10.

The posterior distribution and trace plots of the MCMCs for $B_0$, survey $q$, and all estimated *YCS* showed acceptable mixing behaviour (Figures 8.22 and 8.23, and 8.8 Appendix) and passed the Heidelberger and Welch (1983) stationary and half-width tests. There was some evidence of correlations in selectivity parameters of the survey, possibly due to the model bounds at the minimum age, however the resulting selectivity estimates were tight (Figure 8.21). While the trace plots for trap selectivity looked poor, this was likely to be without substantial consequences, since data from the trap fishery have little effect on biomass and *YCS* estimates.

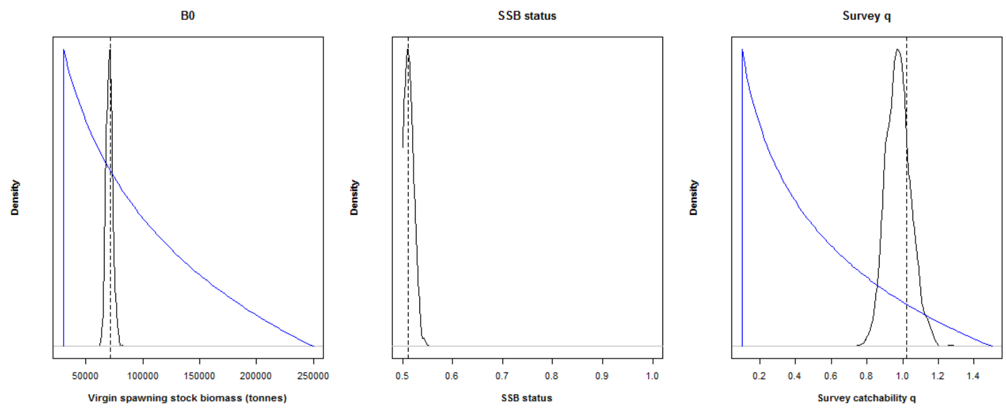



**Figure 8.22:** MCMC posterior distribution of $B_0$, SSB status in 2019, and survey catchability *q* (black), and prior distributions (blue) for Model 6. Vertical dashed lines indicate the MPD estimates.

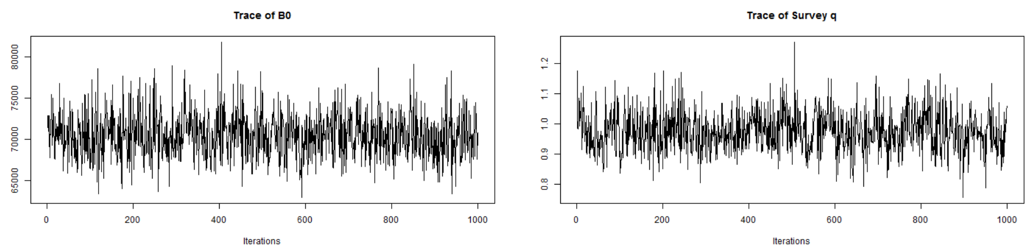



**Figure 8.23:** MCMC posterior trace plots for $B_0$ and survey catchability q for Model 6.

## Retrospective analysis

A retrospective analysis of Model 6 indicated that its predictions for spawning stock biomass and year class strength were largely consistent when data were restricted stepwise to 2015, although more recent data resulted in the estimated SSB and YCS to decrease more strongly over time (Figure 8.24).

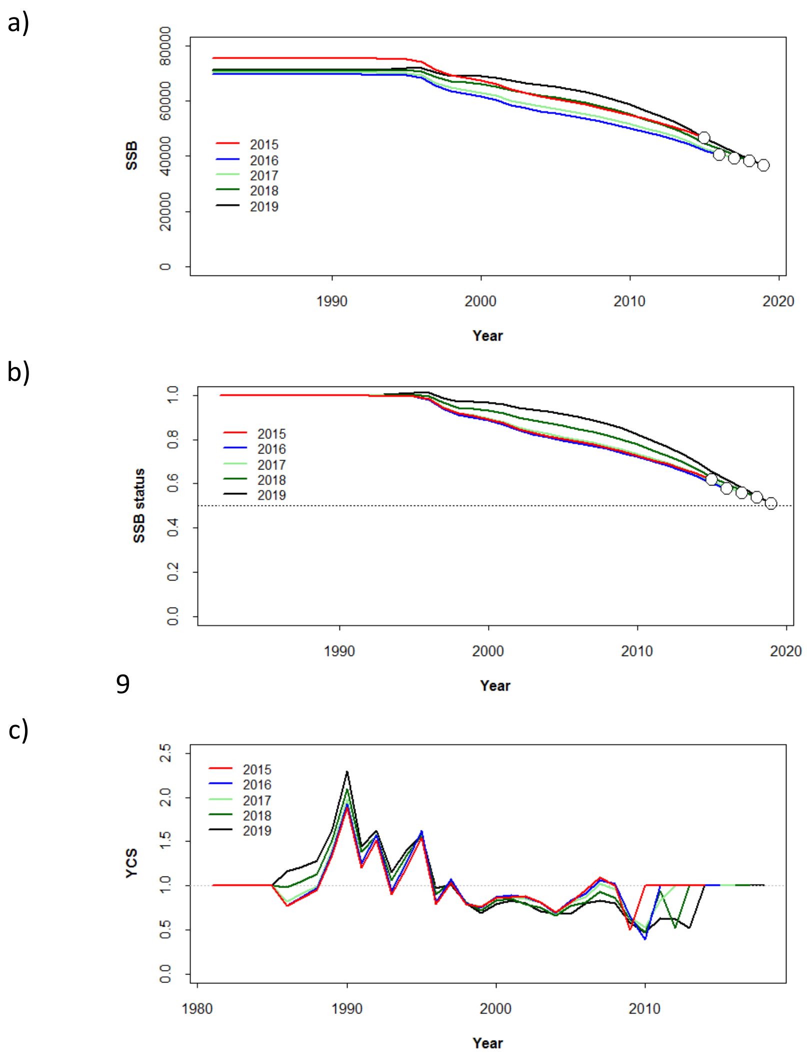



**Figure 8.24:** Retrospective analysis of Model 6, with estimated trajectories for (a) spawning biomass (*SSB*), (b) SSB status, and (c) year class strength (*YCS*) for all data (red) or limiting data up stepwise to 2015.

**Model sensitivity runs**

A number of scenarios were run to evaluate the sensitivity of the stock assessment model to some model parameters and assumptions (Table 8.10).

The inclusion of more or less tag-release and recapture data was evaluated in two sensitivity runs. Including all longline tag-releases and recaptures from 2008 or 2014 onwards resulted in spawning biomass estimates that were higher or close, respectively, to those from Model 6. The likelihood profiles indicated strong discrepancies in the data for individual tagging release events, i.e. tag-releases from 2008-2009 and 2013 indicated a smaller $B_0$, while tag-releases from 2010-2012 and 2017 indicated a larger $B_0$ (Figure 8.25).

As would be expected, changing the assumption of initial tag loss from 0.1 to either 0.05 or 0.2 increased or decreased the estimate of $B_0$.

Assuming an alternative value for natural mortality $M$ = 0.13 as e.g. used in the assessments of the Patagonian Toothfish fishery in South Georgia (Earl et al. 2015), substantially increased the estimate for $B_0$, while estimating $M$ in the model resulted in a slightly smaller estimate of $M$ = 0.145 and a higher estimate of $B_0$. This result indicated that the estimate of $M$ = 0.155 by Candy et al. (2011) was not inconsistent with the other information in the assessment model.

Assuming a logistic selectivity function for trap, i.e. assuming that the entire stock component of old fish is observed by trap, had little impact on the assessment results.

Using abundance numbers-at-age instead of separating the survey observations into a survey biomass index and proportions-at-age, similarly to the approach in the assessment models prior to 2017, resulted in a higher estimate of $B_0$. This was driven by the survey numbers, while the fits to the tag-recapture data and catch-at-age observations were worse. However, unlike the 2017 assessment (Ziegler 2017a), the trends in *YCS* remained largely the same (not shown).

The model results were not sensitive to the choice of early *YCS* to be estimated in the model and whether *YCS* in 2014 was estimated (Figure 8.26).

**Table 8.10:** MPD results of Model 6 and sensitivity analyses, with estimates of unfished spawning stock biomass $B_0$ in tonnes, *SSB* status at the end of 2019, $R_0$ (mean recruitment in millions that gives rise to $B_0$), survey catchability *q*, and the number of estimated parameters (*N* Parameters).

| Sensitivity run | $B_0$ | *SSB* status | $R_0$ | *Survey q* | *N* Parameters |
|---|---|---|---|---|---|
| Reference: Model 6 | 71210 | 0.51 | 5.83 | 1.02 | 49 |
| a) Include longline tagging data from 2008+ | 73 005 | 0.50 | 5.98 | 1.08 | 49 |
| b) Include longline tagging data from 2014+ | 71 926 | 0.51 | 5.89 | 1.01 | 49 |
| c) Initial tag loss = 0.05 | 73 711 | 0.53 | 6.03 | 0.98 | 49 |
| d) Initial tag loss = 0.2 | 66 179 | 0.48 | 5.42 | 1.12 | 49 |
| e) $M$ = 0.13 | 91 301 | **0.53** | 4.35 | 1.15 | 49 |
| f) Estimated $M$ = 0.145 | 78 784 | **0.52** | 5.19 | 1.07 | 50 |
| g) Logistic selectivity for Trap | 71 206 | 0.51 | 5.83 | 1.02 | 47 |
| h) Survey abundance-at-age | 82 536 | 0.56 | 6.76 | 1.18 | 49 |
| i) Estimated *YCS*: 1981-2013 | 70 884 | 0.51 | 4.17 | 1.02 | 54 |
| j) Estimated *YCS*: 1986-2014 | 70 904 | 0.51 | 5.81 | 1.03 | 50 |

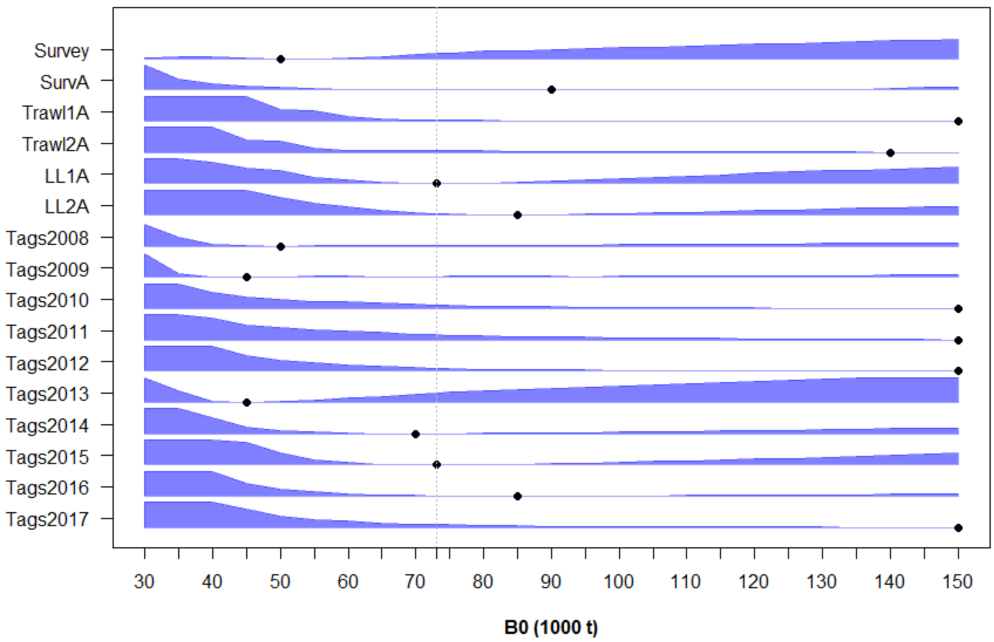



**Figure 8.25:** Likelihood profiles (-2 log-likelihood) across a range of $B_0$ values for separate data sets (dots indicate the location of the minimum value) for sensitivity run that included longline tagging data from 2008 onwards. To create these profiles, $B_0$ values were fixed while only the remaining parameters were estimated. Values for each data set were rescaled to have a minimum of 0. The dotted grey line indicates the MPD estimate.

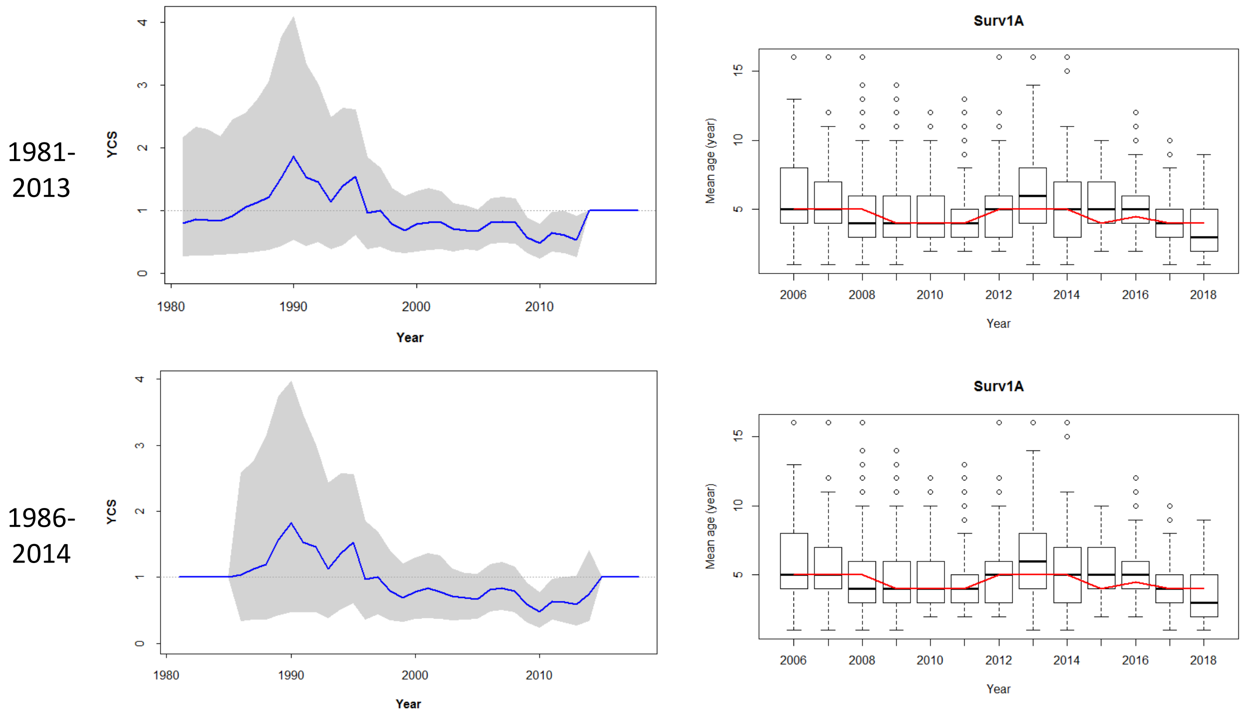



**Figure 8.26:** Estimated *YCS* showing 95% confidence bounds obtained from the MCMC sample (left) and boxplots of observed survey age and predicted median age (red line) for sensitivity runs where *YCS* was estimated for 1981-2013 and 1986-2014.

## Calculations of catch limits

The median CV estimated for the *YCS* period from 1986-2013 in Model 6 were used to generate the random recruitment from 2014-2018 and the 35-year projection period from 2019-2054 ($\sigma_R$ = 0.47). The maximum catches that satisfy the CCAMLR harvest control rules were estimated based on the assumption of future constant annual catches taken entirely by an annual survey of 20 tonnes and by longline (50% LL1 and 50% LL2).

Following the CCAMLR decision rules, the yield for Model 6 was estimated to be 3 030 tonnes (Table 8.11 and Figure 8.27). However, over the course of the projection period, the median *SSB* status reached a minimum of 40% before increasing to the target level at the end of the 35-year projection period.

This drop was largely driven by below-average *YCS* since 1998 and the change from trawl to longline fishing. The latter meant that some year classes have been subjected to fishing twice, at younger age by trawl and at older age again by longline. When progressing through the projection years, these year classes have a negative impact on the future *SSB* before the fishery would eventually benefit from the increase in yield-per-recruit through longline fishing.

**Table 8.11:** Estimates of catch limits in tonnes based on MCMC sampling that satisfy the CCAMLR harvest control rules, with (i) a median escapement of the spawning biomass at the end of the 35-year projection period of at least 50% of the median pre-exploitation level ('Target'), and (ii) a less than 10% risk of the spawning biomass dropping below 20% of its median pre-exploitation level at any time over the 35-year projection period ('Depletion').

| Model | Catch limit | Target | Depletion |
|---|---|---|---|
| 2017 Assessment | 3525 | | |
| 2019 Assessment (Model 6) | 3030 | 0.501 | 0.00 |

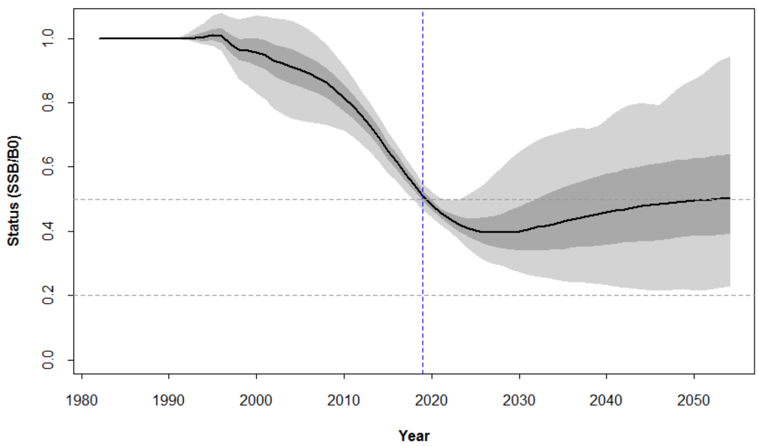



**Figure 8.27:** Projected SSB status relative to $B_0$ for the assessment Model 6 and a constant future catch of 3030 tonnes using MCMC samples. The YCS period from 1986-2013 was used to generate random lognormal recruitment from 2014-2054. Shown are median (black line), 100% confidence bounds (light grey) and 80% confidence bounds (dark grey). Horizontal dotted lines show the 50% and 20% status levels used in the CCAMLR decision rules, the vertical blue line indicates the current year.

The choice of period of estimated YCS which is used in the projections has a substantial influence on the median *SSB* status at the end of the 35-year projection period, but only little impact on the median *SSB* status at the time of the next assessment in 2021 (Tables 8.12). The projected *SSB* status in 2021 was 0.45 - 0.46 independent of whether the future *YCS* patterns would reflect the historical *YCS* period 1986-2013, 1990-2013, 1993-2013 or 1996-2013.

**Table 8.12:** Median probabilities at the time of the next assessment or at end of the 35-year projection period assuming different *YCS* reference periods used for the projections.

| | **YCS** | | | |
|---|---|---|---|---|
| | **1986-2013** | **1990-2013** | **1993-2013** | **1996-2013** |
| At time of next assessment 2021 | 0.46 | 0.46 | 0.46 | 0.45 |
| At end of 35-y projection period | 0.50 | 0.44 | 0.33 | 0.24 |

## 8.6 Discussion

This paper presents an updated assessment for Patagonian Toothfish (*Dissostichus eleginoides*) at Heard Island and McDonald Islands in Division 58.5.2 with catch until the end of 2019 and observations until the end of 2018. Starting with the 2017 assessment model that was used to provide management advice, this paper presents a bridging analysis and proposes a new assessment model for 2019. The new model is based on the best available data, estimates of model parameters and model processes.

Compared to the 2017 assessment that was accepted by WG-FSA-17 to be used for management advice, this assessment takes into account (1) catches until 2019 and new fishery observations up to the end of 2018 including new ageing data from the RSTS and commercial fishery from 2017-2018, (2) inclusion of mortality from longline gear loss, (3) updated growth parameters, (4) updated length-weight relationship parameters, (5) updated maturity-at-age parameters, and (6) a simplification of the longline selectivity functions. All model runs were conducted with the CASAL version 2.30-2012-03-21 rev. 4648 that was agreed on by WG-SAM-14.

The updated assessment model leads to a smaller estimate of the virgin spawning stock biomass $B_0$ than that obtained in 2017, with an MCMC estimate of 70 519 tonnes (95% CI: 65 634 - 76 626 tonnes). The estimated *SSB* status at the end of 2019 was 0.51 (95% CI: 0.49-0.53). The smaller biomass and a steeper decrease in SSB over the period of the fishery meant that the catch limit that satisfies the CCAMLR decision rules decreased from 3525 tonnes to 3030 tonnes.

The stock assessment model estimated that *YCS* was above average in the late 1980s and below average since 1998. This trend was consistent across the different data sets and also when the survey data were included as abundance numbers-at-age into the model. The driver for this *YCS* trend and whether it is likely to continue into the future is unclear, i.e. whether below-average *YCS* should be assumed in the future for the expected recruitment pattern.

The fishery has also switched from trawl in the earlier years to predominantly longline in more recent years, meaning that some age cohorts have been subjected to a high cumulative fishing mortality, initially at younger age by trawl and again at older age by longline. This switch together with the predicted *YCS* pattern strongly affects the shape of the stock projections. When the CCAMLR decision rules are applied, the current assessment predicts that the spawning stock status would drop below the target level, reaching a minimum of 40% before increasing to the target level at the end of the 35-year projection period.

The long-term trend in *SSB* and *SSB* status will be strongly influenced by the future *YCS* pattern. However, the level of the predicted drop in *SSB* status by 2021, the time of the next stock assessment, is largely independent of the *YCS* period chosen as reference for the projections. With a comprehensive monitoring program of the fishery until then which include annual trawl surveys and extensive fish ageing to consolidate and estimate recent trends in *YCS*, the 2021 assessment will inform any decision whether further catch reductions will be necessary.

There is also an need to conduct an evaluation of the CCAMLR harvest strategy, i.e. investigate issues such as (1) the behaviour of the decision rules under different exploitation scenarios, (2) how to account for autocorrelation and/or potential regime shifts in the estimated historical *YCS*, (3) how to account for uncertain catch histories in the estimation of $B_0$, and (4) strategies that account for the feedback mechanism in fisheries with regular stock assessment and management advice.

As the result of this assessment, we recommend a reduction of the catch limit from currently 3525 tonnes to 3030 tonnes for the Patagonian Toothfish fishery in Division 58.5.2.

## 8.7 Acknowledgements

We would like to thank Dirk Welsford, Paul Burch, Tim Lamb, Troy Robertson, Gabrielle Nowara, Steven Brown, Bryn Farmer, Tom Barnes, Emma Woodcock, Jeremy Verdouw, Joe Hutchins, and observers on board of fishing vessels for their support in providing data and supporting this work. Thanks also to the members of the Sub-Antarctic Resource Assessment Group for helpful comments on the science. Components of this work were made possible through grants from the Australian Fisheries Research and Development Corporation (FRDC), the Australian Fishery Management Authority (AFMA), and the Australian Toothfish fishing industry.

## 8.8. Appendix - Model specifications and diagnostics

**Table 8A.1:** Length-age frequency of otoliths samples from all surveys combined over the years from 2006-2018.

| Age class (year) | Length bin (mm) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **251-350** | **351-450** | **451-550** | **551-650** | **651-750** | **751-850** | **851-950** | **951-1050** | **1051-1150** | **1151-1250** | **1251-1350** | **1351-1450** | **1451-1550** |
| 1 | 75 | 52 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 61 | 344 | 95 | 10 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 20 | 487 | 414 | 77 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 7 | 263 | 522 | 226 | 25 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 101 | 383 | 356 | 77 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 26 | 195 | 376 | 144 | 13 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 5 | 60 | 333 | 227 | 37 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 5 | 23 | 156 | 222 | 59 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 1 | 7 | 65 | 147 | 58 | 12 | 4 | 1 | 0 | 0 | 0 | 0 |
| 10 | 0 | 3 | 3 | 22 | 72 | 79 | 26 | 6 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 11 | 47 | 47 | 22 | 7 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 6 | 24 | 45 | 18 | 8 | 1 | 1 | 0 | 0 | 0 |
| 13 | 0 | 0 | 1 | 1 | 4 | 12 | 19 | 11 | 2 | 2 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 6 | 8 | 9 | 6 | 3 | 0 | 1 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 4 | 7 | 5 | 11 | 4 | 0 | 1 | 0 | 0 |
| 16 | 0 | 0 | 0 | 1 | 1 | 6 | 5 | 3 | 2 | 2 | 0 | 1 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 3 | 3 | 0 | 2 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 | 1 | 2 | 0 | 0 |
| 20 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 32 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 34 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 163 | 1287 | 1709 | 1641 | 1006 | 386 | 126 | 60 | 23 | 13 | 7 | 3 | 0 |

**Table 8A.2:** Length-age frequency of otoliths samples from all commercial sub-fisheries combined over the years from 1997-2018.

| Age class (year) | Length bin (mm) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 251-350 | 351-450 | 451-550 | 551-650 | 651-750 | 751-850 | 851-950 | 951-1050 | 1051-1150 | 1151-1250 | 1251-1350 | 1351-1450 | 1451-1550 |
| 1 | 49 | 21 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 37 | 138 | 58 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 9 | 163 | 203 | 45 | 8 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 113 | 376 | 188 | 29 | 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 30 | 377 | 345 | 86 | 18 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 10 | 193 | 436 | 217 | 31 | 5 | 2 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 2 | 72 | 443 | 384 | 103 | 23 | 6 | 3 | 0 | 0 | 0 | 0 |
| 8 | 0 | 1 | 22 | 232 | 421 | 183 | 50 | 12 | 2 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 10 | 99 | 338 | 273 | 82 | 27 | 3 | 1 | 0 | 0 | 0 |
| 10 | 0 | 1 | 11 | 39 | 253 | 302 | 149 | 45 | 15 | 5 | 0 | 0 | 0 |
| 11 | 0 | 0 | 2 | 14 | 114 | 275 | 221 | 83 | 17 | 10 | 1 | 0 | 0 |
| 12 | 0 | 0 | 0 | 4 | 56 | 179 | 226 | 131 | 47 | 13 | 5 | 0 | 0 |
| 13 | 0 | 0 | 2 | 4 | 28 | 122 | 203 | 131 | 62 | 23 | 9 | 3 | 1 |
| 14 | 0 | 0 | 0 | 4 | 14 | 59 | 143 | 128 | 106 | 37 | 19 | 3 | 0 |
| 15 | 0 | 0 | 0 | 1 | 9 | 41 | 80 | 130 | 108 | 71 | 31 | 8 | 0 |
| 16 | 0 | 0 | 0 | 0 | 2 | 15 | 72 | 104 | 109 | 60 | 37 | 11 | 3 |
| 17 | 0 | 0 | 0 | 0 | 3 | 10 | 47 | 87 | 109 | 91 | 49 | 29 | 4 |
| 18 | 0 | 0 | 0 | 0 | 0 | 7 | 15 | 57 | 93 | 84 | 65 | 28 | 9 |
| 19 | 0 | 0 | 0 | 0 | 0 | 3 | 17 | 43 | 60 | 82 | 65 | 33 | 15 |
| 20 | 0 | 0 | 0 | 0 | 1 | 1 | 10 | 24 | 44 | 83 | 56 | 33 | 14 |
| 21 | 0 | 0 | 0 | 1 | 0 | 2 | 5 | 10 | 46 | 47 | 70 | 39 | 20 |
| 22 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 13 | 25 | 46 | 64 | 45 | 19 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 5 | 12 | 28 | 26 | 30 | 18 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 4 | 13 | 30 | 31 | 28 | 16 |
| 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 10 | 12 | 19 | 18 | 13 |
| 26 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 5 | 17 | 17 | 20 | 13 |
| 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 5 | 4 | 10 | 9 | 4 |
| 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 5 | 6 | 9 | 4 | 4 |
| 29 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 6 | 8 | 5 | 1 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 2 | 5 | 4 |
| 31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 | 4 | 5 | 1 |
| 32 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 6 | 4 | 6 |
| 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 6 | 2 | 2 |
| 34 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 3 | 4 | 2 | 1 |
| 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 15 | 29 | 33 | 12 |
| Total | 95 | 479 | 1328 | 1869 | 1963 | 1633 | 1362 | 1058 | 915 | 787 | 642 | 397 | 180 |

**Table 8A.3:** Ageing error matrix for an average readability score of 3.

| True Age | Read Age | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 |
| 1 | 0.697 | 0.252 | 0.042 | 0.008 | 0.001 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.204 | 0.548 | 0.204 | 0.035 | 0.007 | 0.001 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0.036 | 0.200 | 0.519 | 0.200 | 0.036 | 0.007 | 0.001 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0.008 | 0.038 | 0.200 | 0.505 | 0.200 | 0.038 | 0.008 | 0.001 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.001 | 0.008 | 0.041 | 0.202 | 0.494 | 0.202 | 0.041 | 0.008 | 0.001 | 0.001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0.002 | 0.002 | 0.009 | 0.043 | 0.203 | 0.482 | 0.203 | 0.043 | 0.009 | 0.002 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0.002 | 0.002 | 0.010 | 0.045 | 0.205 | 0.472 | 0.205 | 0.045 | 0.010 | 0.002 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0.002 | 0.002 | 0.011 | 0.048 | 0.206 | 0.461 | 0.206 | 0.048 | 0.011 | 0.002 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0.002 | 0.003 | 0.012 | 0.050 | 0.207 | 0.451 | 0.207 | 0.050 | 0.012 | 0.003 | 0.002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0.003 | 0.003 | 0.013 | 0.053 | 0.208 | 0.441 | 0.208 | 0.053 | 0.013 | 0.003 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0.003 | 0.003 | 0.014 | 0.056 | 0.209 | 0.430 | 0.209 | 0.056 | 0.014 | 0.003 | 0.003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0.004 | 0.004 | 0.015 | 0.058 | 0.209 | 0.420 | 0.209 | 0.058 | 0.015 | 0.004 | 0.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.004 | 0.004 | 0.016 | 0.061 | 0.210 | 0.410 | 0.210 | 0.061 | 0.016 | 0.004 | 0.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.005 | 0.005 | 0.017 | 0.064 | 0.210 | 0.400 | 0.210 | 0.064 | 0.017 | 0.005 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.005 | 0.006 | 0.018 | 0.067 | 0.209 | 0.389 | 0.209 | 0.067 | 0.018 | 0.006 | 0.005 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.006 | 0.006 | 0.020 | 0.070 | 0.209 | 0.379 | 0.209 | 0.070 | 0.020 | 0.006 | 0.006 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0.007 | 0.021 | 0.072 | 0.208 | 0.370 | 0.208 | 0.072 | 0.021 | 0.007 | 0.007 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0.008 | 0.022 | 0.075 | 0.207 | 0.360 | 0.207 | 0.075 | 0.022 | 0.008 | 0.007 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.008 | 0.009 | 0.024 | 0.078 | 0.206 | 0.350 | 0.206 | 0.078 | 0.024 | 0.009 | 0.008 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.009 | 0.010 | 0.025 | 0.081 | 0.205 | 0.341 | 0.205 | 0.081 | 0.025 | 0.010 | 0.009 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.010 | 0.011 | 0.026 | 0.083 | 0.203 | 0.331 | 0.203 | 0.083 | 0.026 | 0.011 | 0.010 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.012 | 0.012 | 0.028 | 0.086 | 0.201 | 0.322 | 0.201 | 0.086 | 0.028 | 0.012 | 0.012 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.013 | 0.014 | 0.029 | 0.089 | 0.199 | 0.313 | 0.199 | 0.089 | 0.029 | 0.014 | 0.013 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.014 | 0.015 | 0.031 | 0.091 | 0.197 | 0.304 | 0.197 | 0.091 | 0.031 | 0.015 | 0.014 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.016 | 0.017 | 0.032 | 0.094 | 0.194 | 0.295 | 0.194 | 0.094 | 0.032 | 0.017 | 0.016 | 0 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.018 | 0.018 | 0.033 | 0.096 | 0.191 | 0.286 | 0.191 | 0.096 | 0.033 | 0.018 | 0.018 | 0 | 0 | 0 | 0 |
| 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.019 | 0.020 | 0.035 | 0.098 | 0.189 | 0.278 | 0.189 | 0.098 | 0.035 | 0.020 | 0.019 | 0 | 0 | 0 |
| 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.021 | 0.022 | 0.036 | 0.100 | 0.185 | 0.270 | 0.185 | 0.100 | 0.036 | 0.022 | 0.021 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.023 | 0.024 | 0.037 | 0.102 | 0.182 | 0.261 | 0.182 | 0.102 | 0.037 | 0.024 | 0.023 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.025 | 0.027 | 0.038 | 0.104 | 0.179 | 0.253 | 0.179 | 0.104 | 0.038 | 0.027 | 0.025 |
| 31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.027 | 0.029 | 0.040 | 0.106 | 0.175 | 0.245 | 0.175 | 0.106 | 0.040 | 0.056 |
| 32 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.030 | 0.031 | 0.041 | 0.108 | 0.172 | 0.238 | 0.172 | 0.108 | 0.102 |
| 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.032 | 0.034 | 0.042 | 0.109 | 0.168 | 0.230 | 0.168 | 0.217 |
| 34 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.035 | 0.037 | 0.043 | 0.110 | 0.164 | 0.223 | 0.389 |
| 35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0.013 | 0.020 | 0.037 | 0.061 | 0.863 |

**Table 8A.4:** Estimated weights for the effective sample sizes (ESS) of the survey proportions-at-age and each commercial sub-fishery, and estimated tag-dispersion $\phi$.

| Model | Description | Weights for ESS | | | | | Tag-dispersion |
|---|---|---|---|---|---|---|---|
| | | Survey | Trawl1 | Trawl2 | LL1 | LL2 | $\phi$ |
| 1 | Updated data | 0.108 | 0.015 | 0.011 | 0.053 | 0.045 | 1.191 |
| 2 | Include mortality from gear loss | 0.108 | 0.015 | 0.009 | 0.052 | 0.046 | 1.190 |
| 3 | Updated growth | 0.111 | 0.015 | 0.011 | 0.053 | 0.045 | 1.190 |
| 4 | Updated length-weight | 0.111 | 0.015 | 0.011 | 0.053 | 0.045 | 1.185 |
| 5 | Updated maturity | 0.111 | 0.015 | 0.011 | 0.053 | 0.045 | 1.185 |
| 6 | Simplified longline selectivity | 0.111 | 0.015 | 0.011 | 0.053 | 0.045 | 1.185 |

**Table 8A.5:** Final effective sample sizes (ESS) for survey proportions-at-age and each commercial sub-fishery in Model 6. ESS of Trap was set to 1.

| Year | Survey | Trawl1 | Trawl2 | LL1 | LL2 | Trap |
|---|---|---|---|---|---|---|
| 1998 | | 4 | | | | |
| 1999 | | 9 | | | | |
| 2000 | | 12 | | | | |
| 2001 | | 13 | | | | |
| 2002 | | 12 | | | | |
| 2003 | | 10 | | 36 | | |
| 2004 | | 5 | | 17 | 15 | |
| 2005 | | 4 | | 62 | 52 | |
| 2006 | 13 | | 12 | 58 | | 1 |
| 2007 | 60 | | 6 | 31 | 26 | |
| 2008 | 71 | | 1 | 5 | 3 | |
| 2009 | 70 | | 1 | 4 | 2 | |
| 2010 | 95 | | 1 | 6 | 5 | |
| 2011 | 57 | | 3 | 16 | 14 | |
| 2012 | 60 | | 1 | 5 | 4 | |
| 2013 | 29 | | 13 | 66 | 56 | 1 |
| 2014 | 54 | | 13 | 65 | 55 | |
| 2015 | 36 | | 6 | 29 | 25 | |
| 2016 | 34 | | 5 | 28 | 24 | |
| 2017 | 22 | | 5 | 27 | 23 | |
| 2018 | 26 | | 6 | 29 | 25 | |

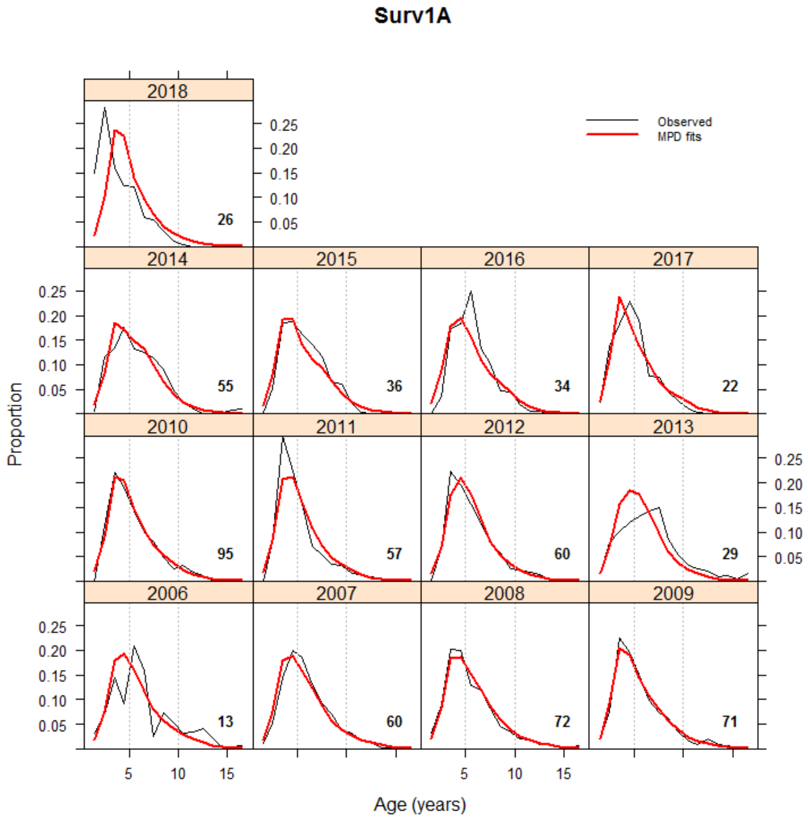



**Figure 8A.1:** Observed (black) and predicted (red) proportions-at-age for the Survey in Model 6. Numbers indicate the effective sample size.

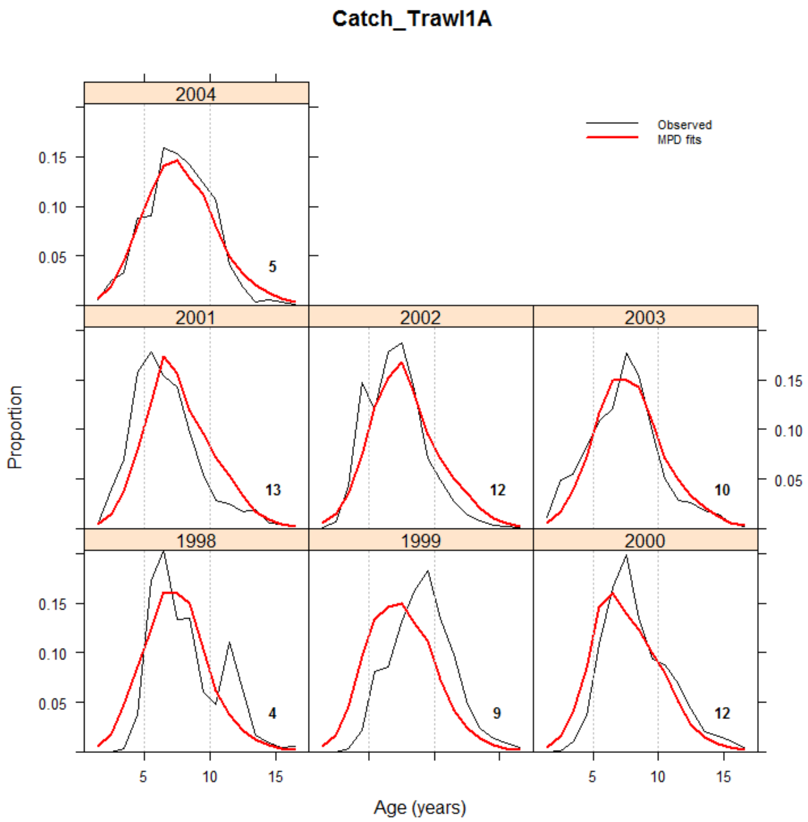



**Figure 8A.2:** Observed (black) and predicted (red) proportions-at-age for Trawl1 in Model 6. Numbers indicate the effective sample size.

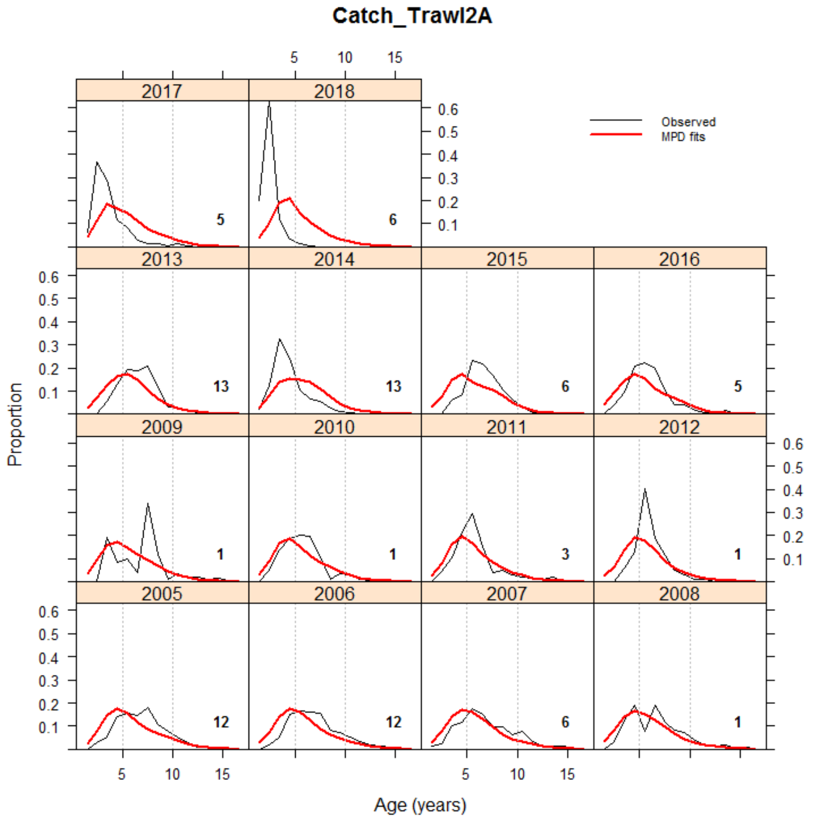



**Figure 8A.3** Observed (black) and predicted (red) proportions-at-age for Trawl2 in Model 6. Numbers indicate the effective sample size.

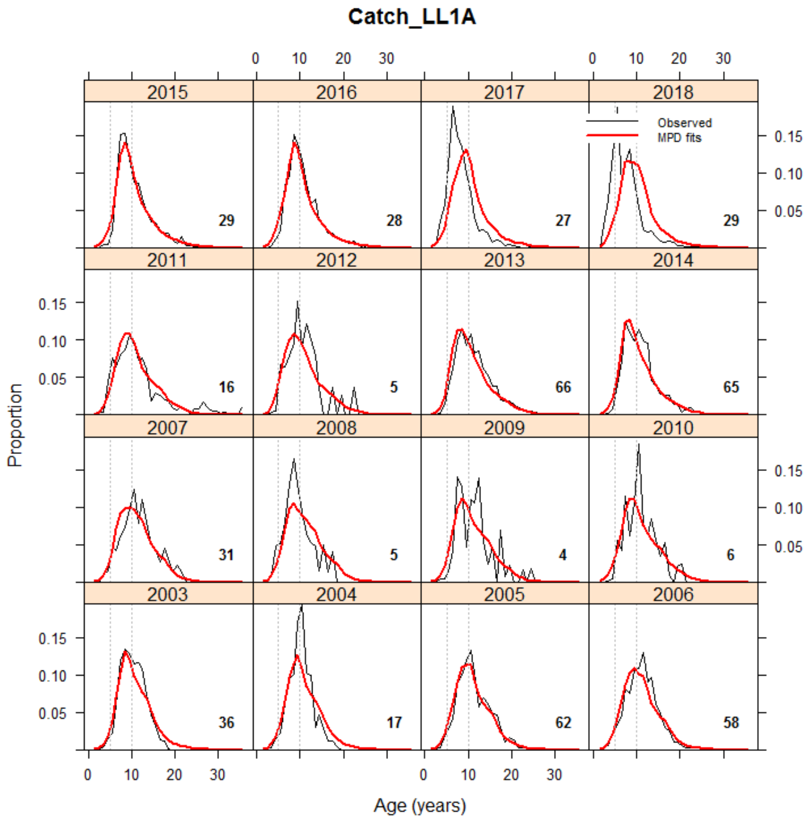



**Figure 8A.4:** Observed (black) and predicted (red) proportions-at-age for LL1 in Model 6. Numbers indicate the effective sample size.

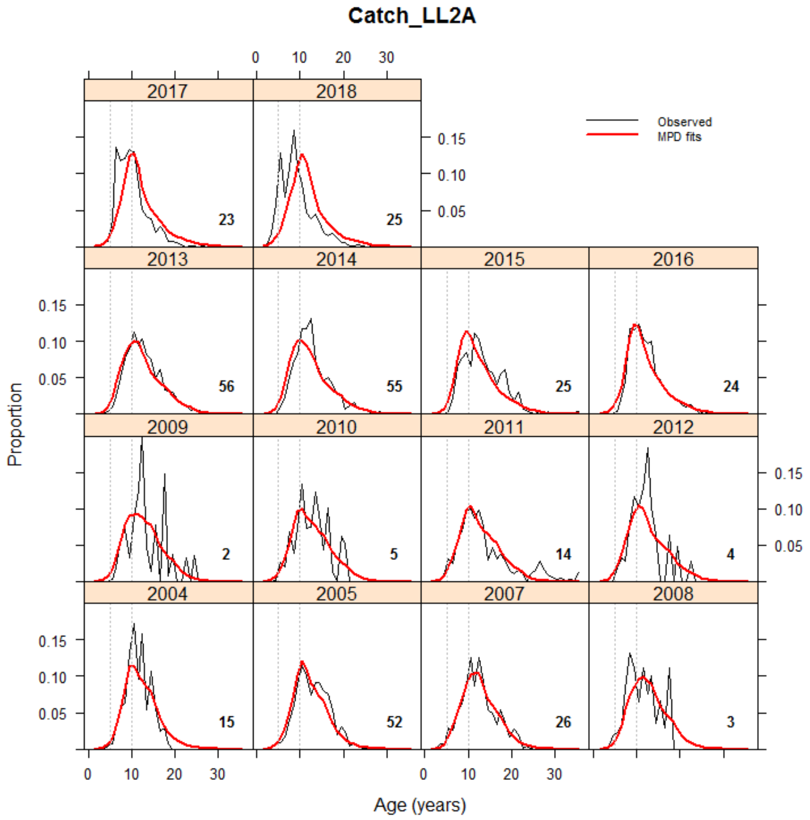



**Figure 8A.5:** Observed (black) and predicted (red) proportions-at-age for LL2 in Model 6. Numbers indicate the effective sample size.

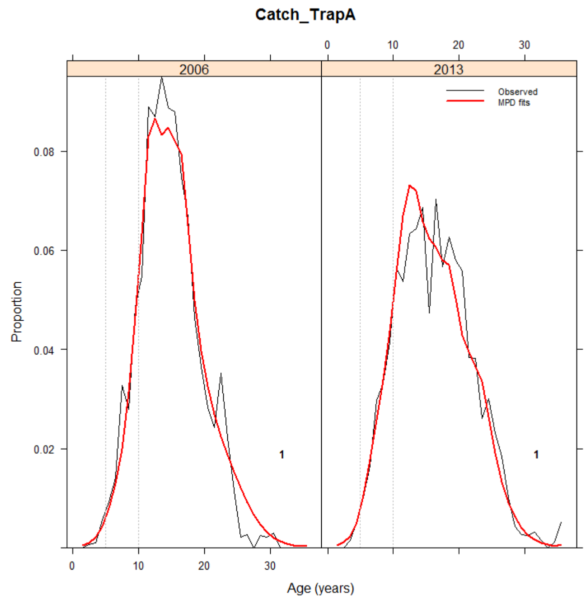



**Figure 8A.6:** Observed (black) and predicted (red) proportions-at-age for Trap in Model 6. Numbers indicate the effective sample size. Note that years are not consecutive.

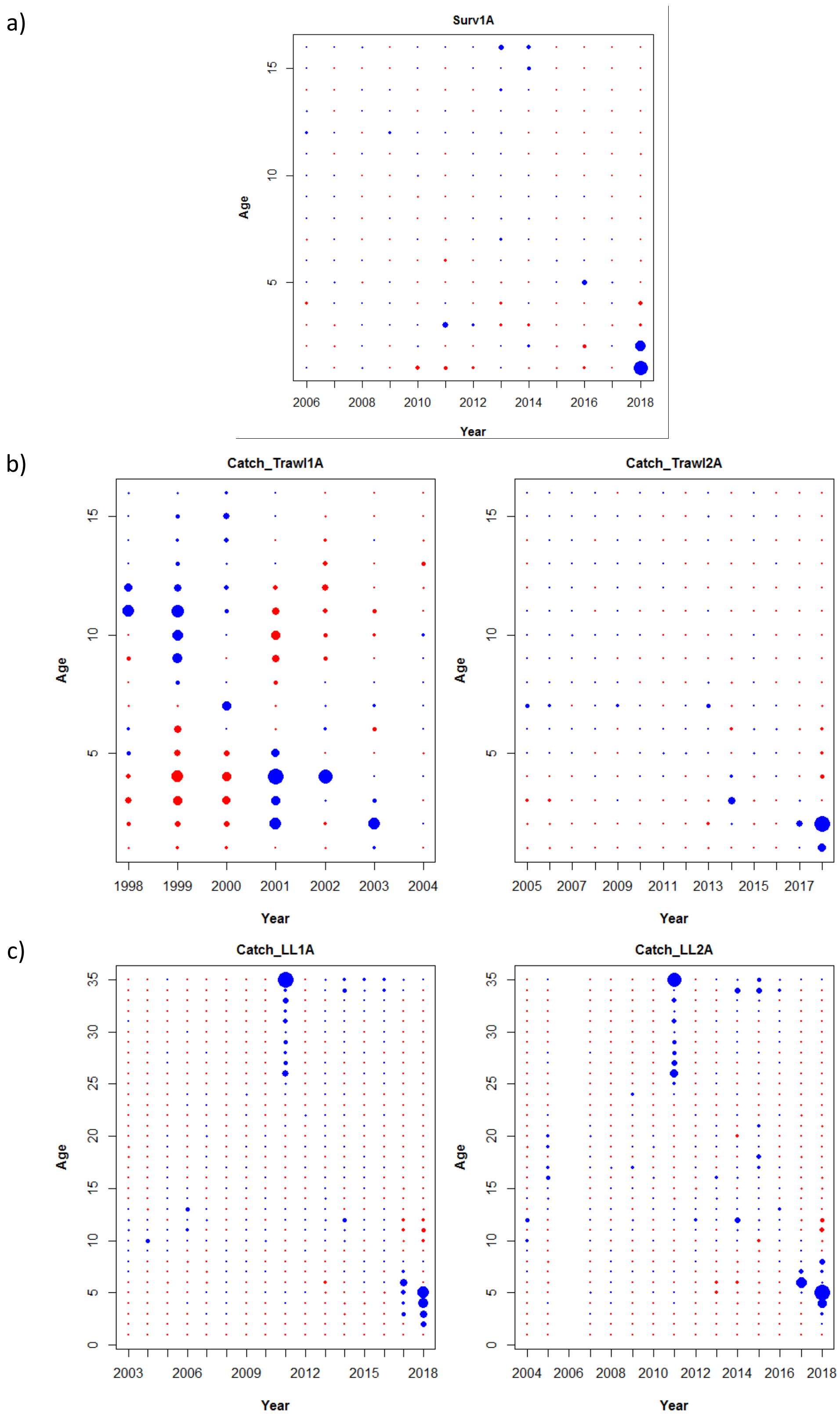
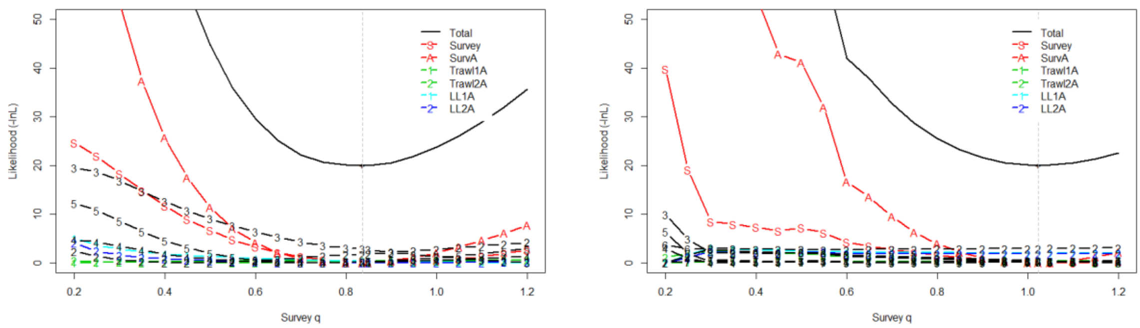



**Figure 8A.7:** Pearson's residuals of MPD fits by age and year for the survey and commercial sub-fisheries in Model 6.

a)




b)

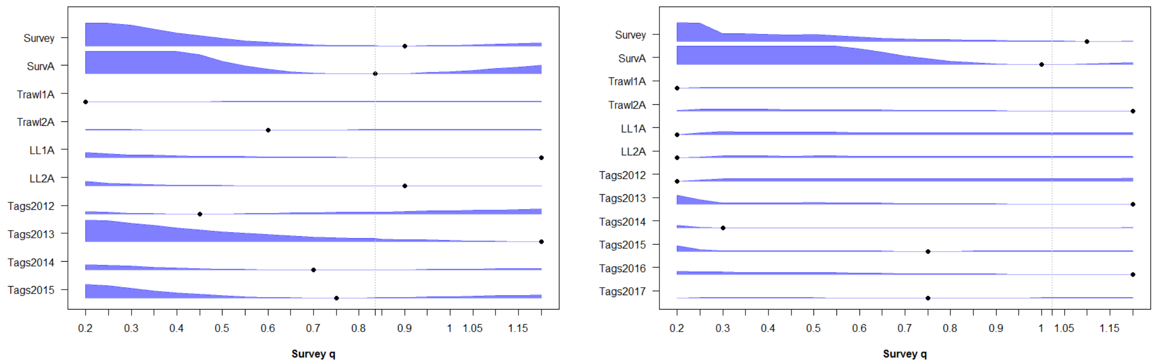



**Figure 8A.8:** Likelihood profiles (-2 log-likelihood) across a range of survey catchability q values for (a) all data sets together and (b) separate data sets (dots indicate the location of the minimum value) for the 2017 assessment model (left) and Model 6 (right). To create these profiles, q values were fixed while only the remaining parameters were estimated. Values for each data set were rescaled to have a minimum of 0, while the total objective function was rescaled to 20. The dotted grey line indicates the MPD estimate. Tag-release years are denoted by their last digit, i.e. 2 for 2012, 3 for 2013 etc.

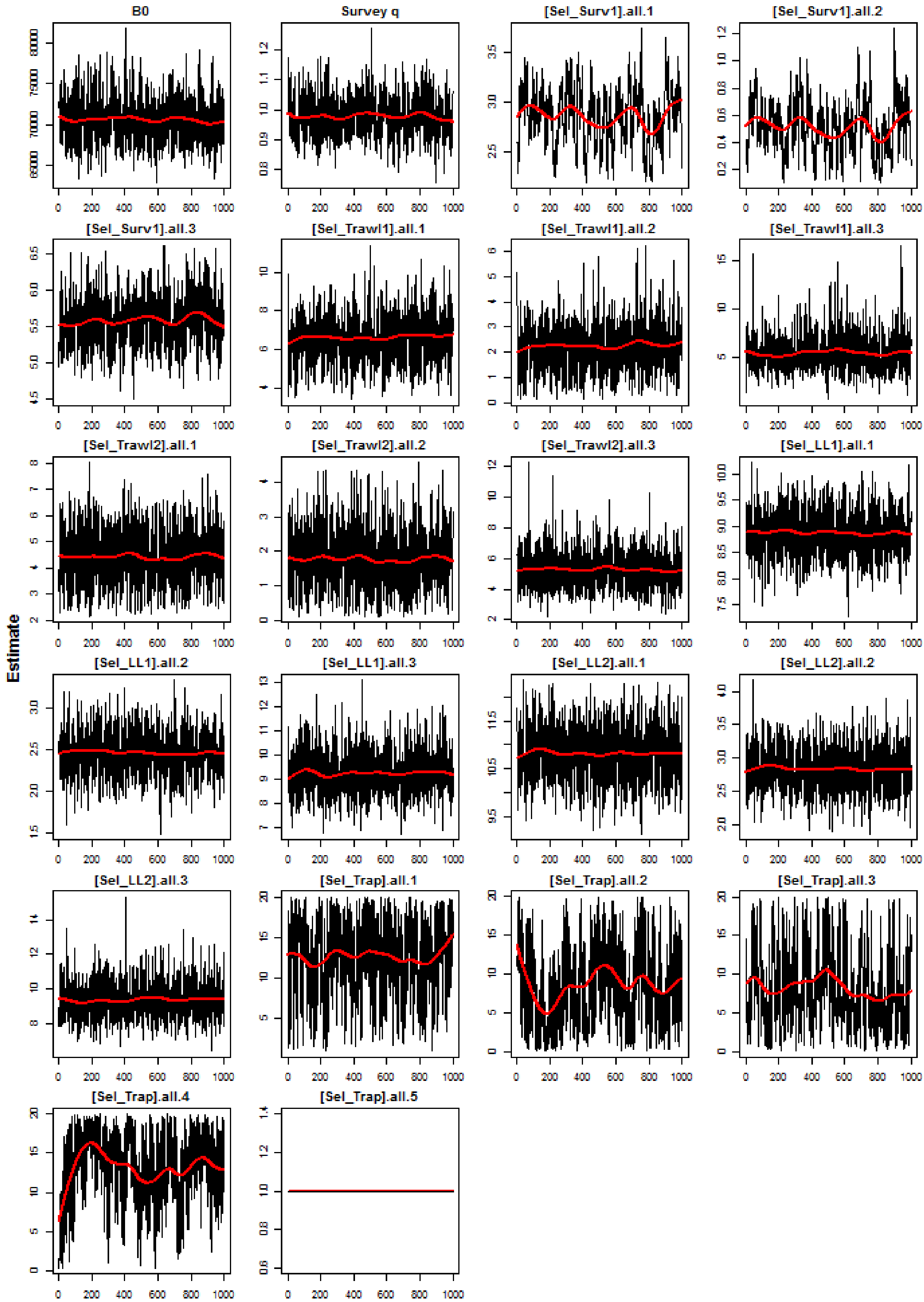



**Figure 8A.9:** MCMC posterior trace plots for $B_0$, survey catchability $q$, and all selectivity parameters in Model 6.

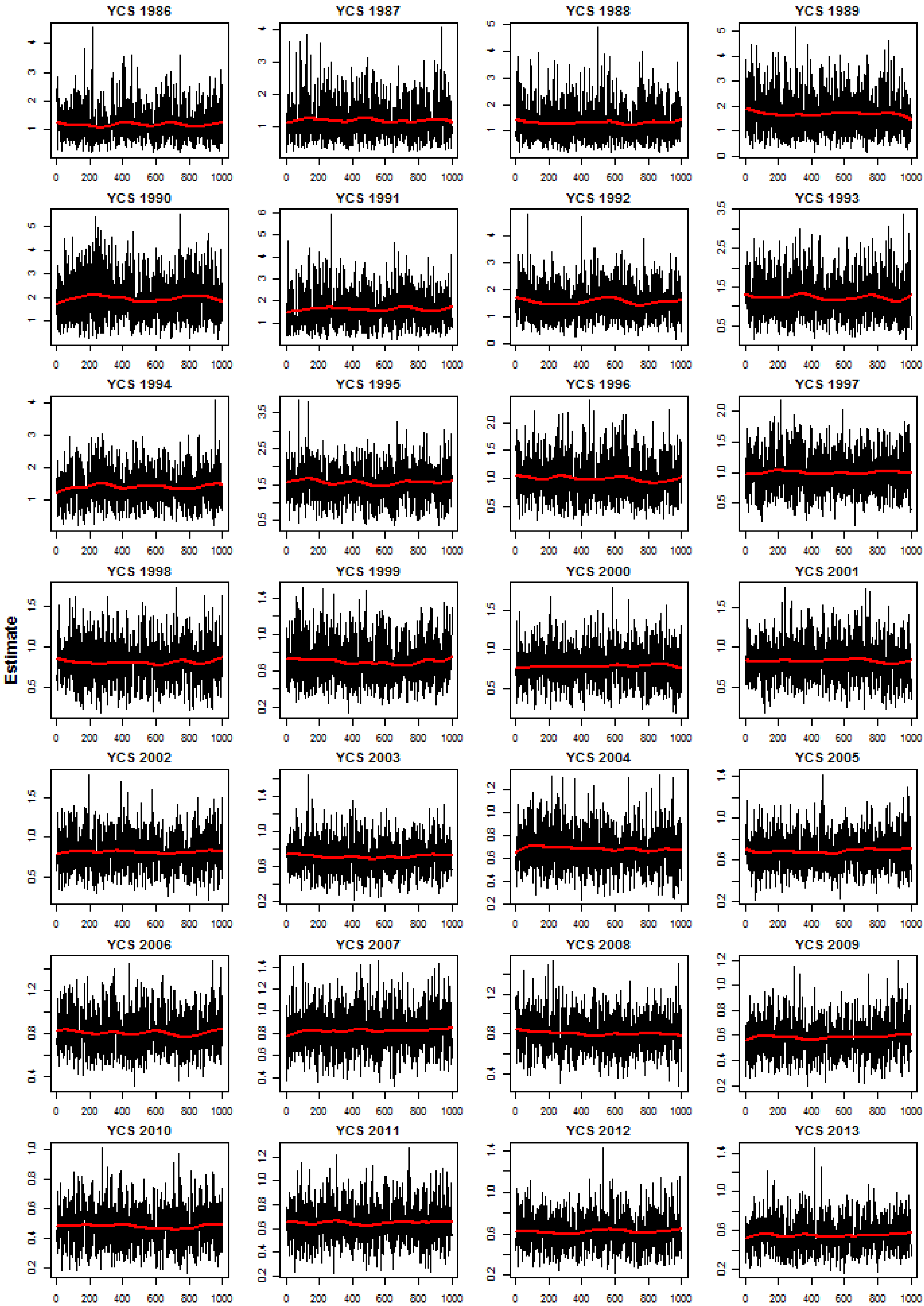



**Figure 8A.10:** MCMC posterior trace plots for all *YCS* parameters in Model 6.

# Chapter 9: 2020 Update of the Patagonian Toothfish fishery at Heard Island and McDonald Islands (HIMI)

Philippe Ziegler

**This Chapter is based on:**

Delegation of Australia (2020a) Update on the Heard Island and McDonald Islands Patagonian Toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2. CCAMLR Document SC-CAMLR-39/BG/36, Hobart, Australia

## Abstract

WG-FSA-19 recommended an update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery be presented to WG-FSA-20 to evaluate whether recruitment and the stock trajectory were consistent with those estimated by the stock assessments for Patagonian Toothfish (*Dissostichus eleginoides*) fishery in CCAMLR Division 58.5.2.

Here, we present an update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery. These data indicate that the stock trajectory is consistent with that predicted by the 2019 stock assessment model. Increases in the survey biomass and young fish in the survey catch composition also indicate the potential for a recruitment pulse in recent years.


## 9.1 Introduction

In 2019, the stock assessments for Patagonian Toothfish (*Dissostichus eleginoides*) fishery at Heard Island and McDonald Islands (HIMI) in CCAMLR Division 58.5.2 (Ziegler 2019a) indicted that the stock was expected to decline below 50% $B_0$ as a result of weak year classes in recent years and the effect of the historical switch from trawl fishing on younger fish to longline fishing on the same cohorts when older.

The assumption of average recruitment in the future would allow the stock to rebuild to 50% $B_0$ at the end of the 35-year projection period. However, the estimated year class strength (YCS) has been below average since 1998. Scenarios that assumed future recruitment patterns similar to the average YCS estimated for the period after 1990 would result in the stock failing to rebuild to 50% $B_0$ over the 35-year projection period.

The estimated stock status at the time of the next assessment in 2021, irrespective of the assumption of future YCS, was expected to be about 46% of $B_0$.

While the Working Group noted that fluctuations around the target of 50% $B_0$ would be expected for stocks near or at the target levels (WG-FSA-19 para. 3.19), it expressed concern that the stock may continue to decline if below-average YCS continued and were not accounted for in future assessments.

WG-FSA-19 recommended an update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery be presented to WG-FSA-20 to evaluate whether recruitment and the stock trajectory were consistent with those estimated by this assessment (para. 3.90).

Here, we present an update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery. These data indicate that the stock trajectory is consistent with that predicted by the 2019 stock assessment model. Increases in the survey biomass and young fish in the survey catch composition also indicate the potential for a recruitment pulse in 2016 and 2017.

## 9.2 Recruitment index from Stratified Random Trawl Survey (RSTS)

The random stratified trawl surveys (RSTS) in 2019 (Novara et al. 2019) and 2020 (SC-39/BG/xx) in Division 58.5.2 indicate increasing biomass of juvenile fish (Figure 9.1). A strong year class strength was apparent in the survey catch composition of both 2018 and 2019 (Figure 9.2, data up to 2019).

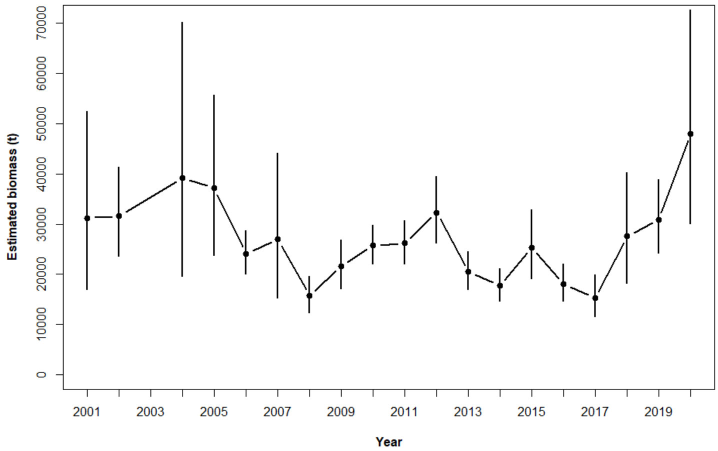



**Figure 9.1:** Estimated Toothfish biomass (with 95% CI) in the random stratified trawl survey (RSTS) in Division 58.5.2.

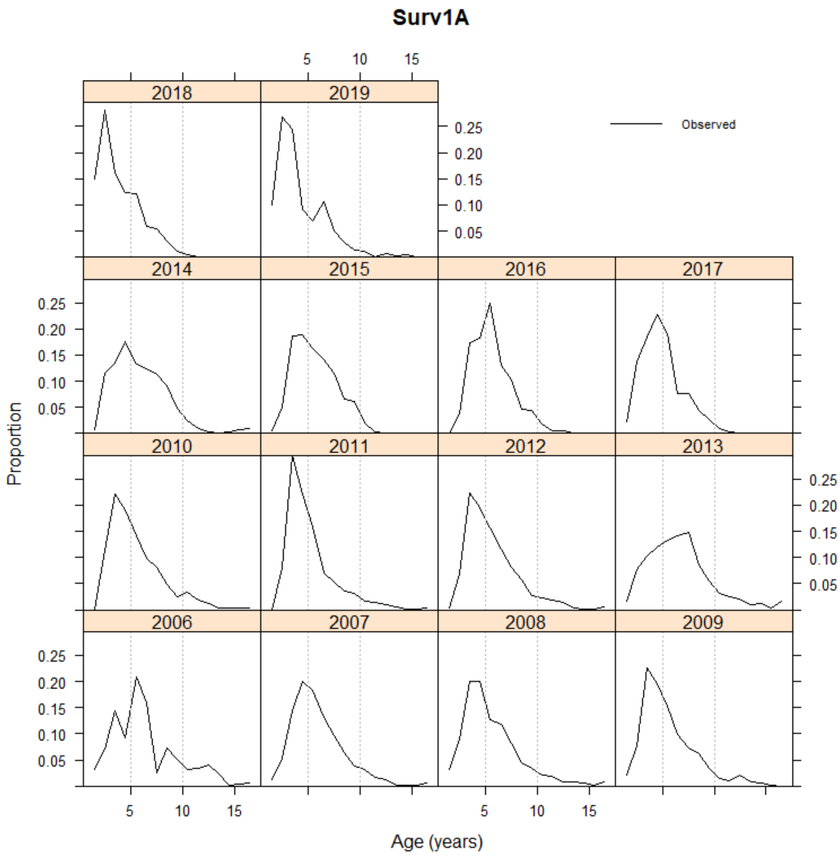



**Figure 9.2:** Observed proportions-at-age in the random stratified trawl survey (RSTS) in Division 58.5.2. Note that fish ages from the RSTS in 2020 have not been available yet.

## 9.3 Distribution of fishing effort

Fishing effort has continuously expanded since the start of longline fishing in 2003 to recent years (Figure 9.3). In 2019, the spatial distribution of fishing effort slightly contracted compared to 2017 and 2018, with fewer deep areas in the south covered.

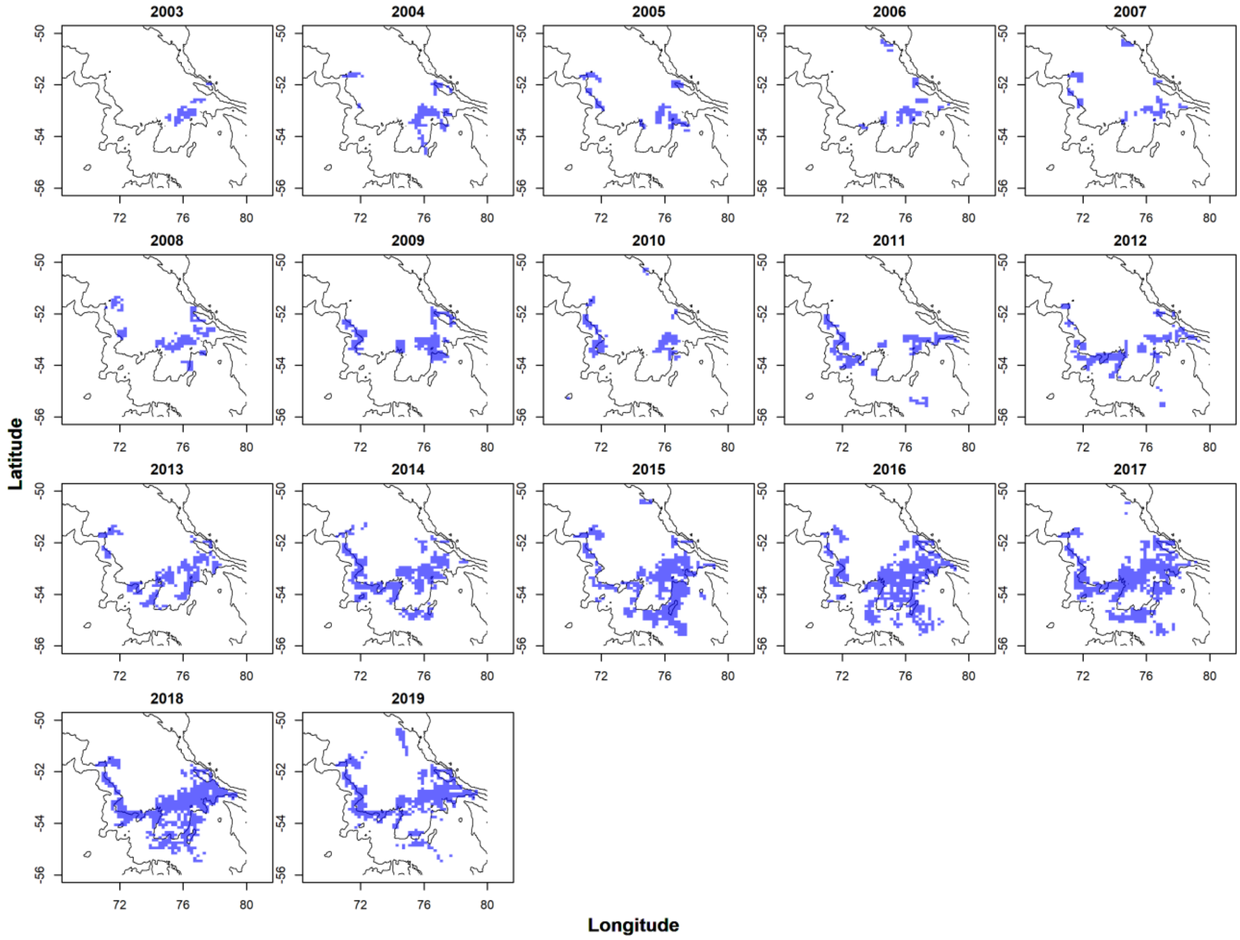



**Figure 9.3:** Annual spatial distribution of longline fishing effort for Patagonian Toothfish in Division 58.5.2 from 2003 to 2019. Blue cells correspond to locations where at least one longline haul event occurred.

## 9.4 Tagging data

Annual tag-release and recapture numbers from longline have increased since 2008, and particularly since 2015 due to a higher catch limit and an increase in tagging rates from 2 fish per 3 tonnes to 2 fish per tonne (Table 9.1). In total, over 41 000 fish have been tagged and released and over 3550 have been recaptured since 2008.

**Table 9.1:** Numbers of longline tag-releases and tag-recaptures from 2008 to 2019. Within-season recaptures are marked in grey.

| Releases | | Recaptures | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Numbers** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **Total** |
| 2008 | 891 | 25 | 14 | 3 | 8 | 23 | 19 | 24 | 9 | 5 | 5 | 1 | 136 |
| 2009 | 1249 | 7 | 49 | 44 | 9 | 21 | 39 | 46 | 13 | 22 | 4 | 8 | 262 |
| 2010 | 1216 | - | 2 | 41 | 5 | 12 | 52 | 36 | 9 | 14 | 10 | 13 | 194 |
| 2011 | 1197 | - | - | 0 | 20 | 19 | 35 | 39 | 27 | 28 | 28 | 22 | 218 |
| 2012 | 1434 | - | - | - | 1 | 22 | 40 | 39 | 21 | 44 | 33 | 22 | 222 |
| 2013 | 1471 | - | - | - | - | 4 | 52 | 94 | 37 | 48 | 43 | 19 | 297 |
| 2014 | 1808 | - | - | - | - | - | 9 | 76 | 58 | 78 | 45 | 44 | 310 |
| 2015 | 7713 | - | - | - | - | - | - | 80 | 261 | 336 | 284 | 248 | 1209 |
| 2016 | 5321 | - | - | - | - | - | - | - | 31 | 221 | 296 | 254 | 802 |
| 2017 | 6740 | - | - | - | - | - | - | - | - | 54 | 337 | 406 | 797 |
| 2018 | 5645 | - | - | - | - | - | - | - | - | - | 46 | 444 | 490 |
| 2019 | 6339 | - | - | - | - | - | - | - | - | - | - | 101 | 101 |
| Total | 41 024 | 32 | 65 | 88 | 43 | 101 | 246 | 434 | 466 | 850 | 1131 | 1583 | 5039 |

Vulnerable population number $N_y$ in year $y$ was estimated using a Chapman estimator following Burch et al. (2015) as:

$$N_y = \frac{(\tilde{T}_{i,y} + 1)(C_y + 1)}{(R_{i,y} + 1)} - 1$$

where $\tilde{T}_{i,y}$ is the number of fish tagged in year $i$ and available to the fishery in year $y$, $C_y$ is the catch numbers in year $y$, and $R_{i,y}$ is the number of fish tagged in year $i$ and recaptured in year $y$. To estimate vulnerable biomass $B_y$, $N_y$ were multiplied with the average weight of a fish.

The number of fish $\tilde{T}_{i,y}$ tagged in year $y$-1 and available to the fishery in year $y$ was estimated from the number of fish tagged $T_y$ in year $y$-1, the tag-release mortality $r$, recaptures $R_{y-1}$ in year $y$-1, natural mortality $M$ and annual tag-loss rates $t$ estimated for that tagging cohort as:

$$\tilde{T}_{y-1,y} = (T_{y-1}(1 - r) - R_{y-1})e^{-M-t}$$

As specified in Ziegler (2019a), tag release mortality *r* was assumed to be 0.1, natural mortality $M$ = 0.155, and tag-loss rates $t$ = 0.006 since 2012.

In addition to annual biomass estimates from individual tag-release cohorts, we also calculated overall annual biomass estimates from individual annual estimates by weighting with the inverse of their estimate variances, and annual estimates using a multivariate hypergeometric distribution.

For the hypergeometric distribution, let $\tilde{T}_1, \tilde{T}_2, \ldots \tilde{T}_n$ be the the number of tags remaining in the population from *n* previous tagging events, and $R_1, R_2, \ldots R_n$ be the corresponding number of recaptures in the current year from those events. Further, let $\tilde{T}_{n+1}$ be the number untagged individuals in the population, and $R_{n+1}$the number of untagged individuals in the catch. Let $N = \sum_{i=1}^{n+1} \tilde{T}_i$ be the total abundance, and $C = \sum_{i=1}^{n+1} R_i$ be the number caught in the current year. Then the total recaptures (tagged and untagged) $R_1, R_2, \ldots, R_{n+1}$ follow a multivariate hypergeometric distribution:

$(R_1, R_2, \ldots R_{n+1})$ ~ Hypergeometric($N$, $(\tilde{T}_1, \tilde{T}_2, \ldots \tilde{T}_{n+1})$, $n$)

where:

$$-\log p(R_1, R_2, \ldots., R_{n+1}) = log\binom{N}{C} - \sum_{i=1}^{n+1} log\binom{\tilde{T}_i}{R_i}$$

Estimated biomass from individual tag-release cohorts have fluctuated over the years, but somewhat stabilised in recent years (Figure 9.4). Weighted annual Chapman estimates and biomass estimates when assuming a hypergeometric distribution were similar. Both indicated a slow decrease over the last few years. Consistent with expectations, vulnerable biomass was estimated slightly lower in 2019 than in 2018, driven by relatively large recapture numbers from the 2017 and 2018 tag-release cohorts. Biomass estimates from a Chapman estimator using catch weight instead of catch numbers were also similar (Burch et al. 2015, not shown).

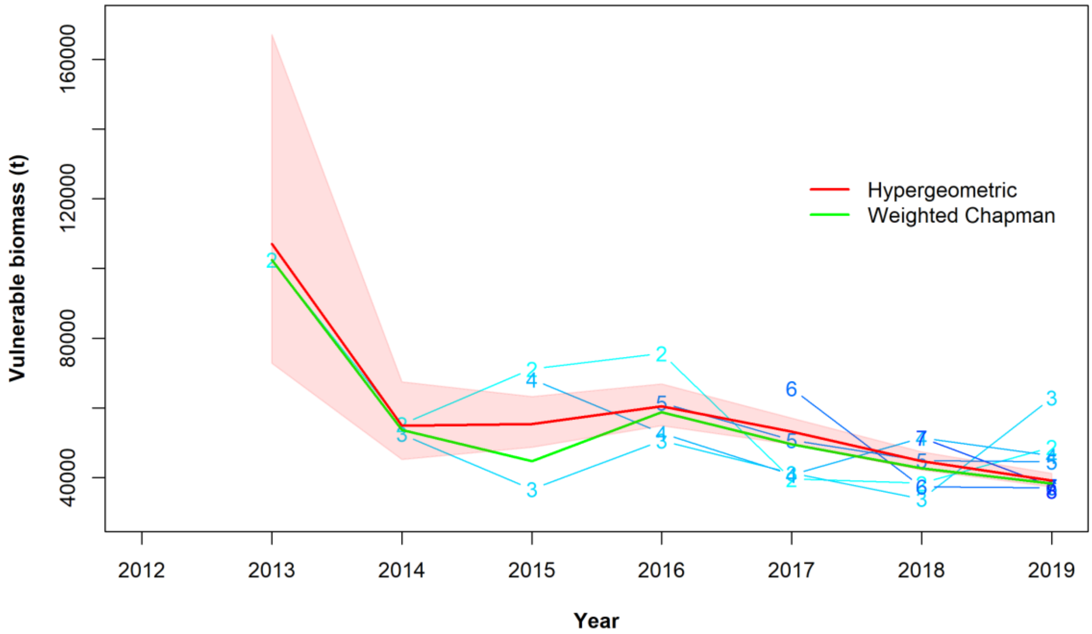



**Figure 9.4:** Chapman tag-recapture biomass estimates for Patagonian Toothfish in Division 58.5.2 for tag partitions released between 2012 and 2018 (blue, identified by numbers 2 to 8), the overall biomass estimate weighted by the variance of annual biomass estimates (green), and multivariate hypergeometric estimates (red) with 95% confidence intervals.

## 9.5 Discussion

The update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery, indicates that the stock trajectory is consistent with the prediction by the 2019 stock assessment model (Ziegler 2019). Increases in the survey biomass and young fish in the survey catch composition also indicate the potential for a recruitment pulse in 2016 and 2017.

# Chapter 10: Seabird bycatch analysis in the Toothfish longline fishery at Heard Island and McDonald Islands (HIMI)

Philippe Ziegler, Tim Lamb, Simon Wotherspoon and Jim Dell

**This Chapter is based on:**

Ziegler P., Lamb T., Wotherspoon S. and Dell J. (2019) Report on fishing effort and seabird interactions during the season extension trials in the longline fishery for Patagonian Toothfish (Dissostichus eleginoides) in Statistical Division 58.5.2. CCAMLR Document WG-FSA-2019/31, Hobart, Australia

## Abstract

Minimising seabird interactions with longline operations is a key objective of the management of fisheries in CCAMLR (see e.g. Conservation Measure CM 25-02 and 41-08). Longline fishing in the fishery for Patagonian Toothfish (*Dissostichus eleginoides*) in Statistical Division 58.5.2 started as a winter fishery (1 May - 14 September) to minimise seabird interactions, and has employed a wide range of seabird mitigation measures since the initial fishing season in 2003. Over the years, CCAMLR has agreed to add season extensions from 15-30 April and 15 September - 31 October to the core season. In 2015, CCAMLR XXXIV (para. 5.68) endorsed new pre-season (1-14 April) and post-season (15-30 November) season extension trials, in addition to an existing post-season (1-14 November) extension trial.

We recommend that the three season extension trial periods be added to the existing season extensions for the fishery, as the risk in the period of the three season extension trials is comparable to that in the existing season extension period. The risk of seabird mortality during these trial extensions has been analysed relative to that in the core season and existing season extensions. The rate of seabird mortality in the core fishing season and the existing post season extension from 15 September - 31 October, was less than 0.0001 birds per 1000 hooks (or less than 0.1 birds per million hooks). The rates of seabird mortality for the pre-season and two post season extension trials were comparable to that during the existing pre-season extension from 15-30 April.

Given the specification and application of effective seabird bycatch mitigation by fishing vessels in this fishery, we also recommend that the requirement for any vessel to demonstrate full compliance with Conservation Measure 25-02 in the previous season be removed in CM 41-08 (para. 3).

## 10.1 Introduction

The ultimate aim in managing seabird bycatch in the Convention Area is to allow fishing at any time of day without seasonal closure of fishing grounds (SC-CAMLR-XIX, para 4.41(iv)). Any relaxation of closed seasons should proceed in a step-wise fashion with the results of this being carefully monitored and reported (SC-CAMLR-XIX, para 4.42).

Longline fishing in the fishery for Patagonian Toothfish (*Dissostichus eleginoides*) in Statistical Division 58.5.2 started as a winter fishery (1 May - 14 September) to minimise seabird interactions, and has employed a wide range of seabird mitigation measures since the initial fishing season in 2003. Over the years, CCAMLR has agreed to add season extensions from 15-30 April and from 15 September - 31 October to the core season. In 2015, CCAMLR XXXIV (para. 5.68) endorsed new pre-season (1-14 April) and post-season (15-30 November) season extension trials, in addition to an existing post-season (1-14 November) extension trial (WG-FSA-15/48).

Australia has reported annually on the results of all the trials (WG-FSA-16/28 Rev. 1, WG-FSA-17/20, WG-FSA-18/57). During the 2018 season sufficient hooks were set and retrieved during the pre-season (1-14 April) and the post-season (1-14 November and 15-30 November) extension trial periods to satisfy the criteria for completing all trials, as proposed in WG-FSA-15/48 and agreed in SC-CAMLR-XXXIV/04. This is the final report presenting a summary and analysis of all the data collected within the season extension trials.

## 10.2 Methods

**Data collection**

Data on hooks set and fishing periods were collated from Australian data holdings.

Data on seabird interactions with longline fisheries were sourced from the CCAMLR Secretariat's C2 (vessel submitted) and the E-longline (observer submitted) databases. These data were collated with Australian data holdings to provide a single dataset. Australia evaluated each interaction record to determine whether it met the criteria for submission in the CCAMLR E-longline and C2 forms. Only interactions that resulted from a bird being caught by fishing gear (including seabird mitigation measures, such as streamer lines and seabird exclusion devices) were included. An interaction was recorded where the bird was released alive, but required human intervention to unhook or release the seabird from an entanglement. Where a seabird was killed, the interaction was recorded as a mortality. Seabirds killed by striking the vessel, and seabirds that lightly contacted the fishing gear or were able to free themselves from the fishing gear without intervention were not recorded as an interaction.

**Analysis**

Seabird mortality in each of the three season extension trials, as well as in each existing season extensions (15-30 April and 15 September - 31 October) and the core season (1 May - 14 September), was modelled using Bayesian zero inflated Poisson models (BZIP). Alternative models such as Poisson or binary regression models and bootstrap were trialled, but did not perform well due to the high number of zero seabird counts.

In the BZIP, zero inflation was modelled by a Bernoulli process. The estimation utilises a Markov Chain Monte Carlo method to take samples from the probability distributions arising from the BZIP. The shape of the posterior distribution represents the most probable rate of seabird mortality given the available data. The Bernoulli process is equivalent to a coin toss where the outcome is binary (either a one or a zero). A zero outcome from the Bernoulli means a zero count in the model, while the alternate result means that the outcome is determined by the Poisson process.

The prior information to be included on the influence of the two processes is difficult to select because we must judge the number of additional zeros over and above the zeros we expect from the Poisson process. Given these data we have the expectation that the Poisson mean will be so low that there will be many Poisson zeros anyway. We considered three alternative priors:

- An uninformative prior that essentially provides no influence on which process the addition zeros are drawn;
- A prior that slightly favours the observed zeros being drawn from the Poisson process (low Poisson mean);
- A prior that slightly favours the observed zeros being drawn from the Bernoulli process.

The core season was treated as a control to evaluate whether the season extensions varied substantially from the core season.

## 10.3 Results

**Data summary**

During the 2018 season, sufficient numbers of hooks were set and retrieved in the 1-14 April pre-season extension trial to satisfy the criterion to complete the trial (cumulative total of 500,000 hooks set during daylight), as proposed in WG-FSA-15/48 (Table 10.1 and 10.2). The two post-season extension trials had previously satisfied their respective criteria (cumulative total of 500,000 hooks set during the trial).

**Table 10.1**. Numbers of hooks set by year and month in the fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. Time periods closed to longline fishing are shaded in grey.

| Year | 1-14 Apr<br>Trial | 15-30 Apr<br>Extension | May | Jun | July<br>Core | Aug | 1-14 Sep | 15 Sep-31 Oct<br>Extension | 1-14 Nov<br>Trial | 15-30 Nov<br>Trial | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003 | | | 307,010 | 332,635 | | | | | | | 639,645 |
| 2004 | | | 551,748 | 325,850 | 145,068 | 438,348 | 133,291 | | | | 1,594,305 |
| 2005 | | | 320,000 | 503,000 | 127,301 | 625,752 | 16,000 | | | | 1,592,053 |
| 2006 | | | 475,000 | 448,400 | 77,900 | 475,000 | 193,800 | | | | 1,670,100 |
| 2007 | | 40,850 | 437000 | 318,250 | 278,000 | 556,000 | 58,000 | | | | 1,688,100 |
| 2008 | | | 125,100 | 921,520 | 158,100 | 1,002,450 | 397,200 | 264,100 | | | 2,868,470 |
| 2009 | | 302,500 | 947,500 | 764,250 | 248,000 | 936,550 | 260,250 | 210,000 | | | 3,669,050 |
| 2010 | | 201,750 | 894,250 | 772,000 | 787,500 | 566,250 | 169,500 | | | | 3,391,250 |
| 2011 | | 254,250 | 455,250 | 490,750 | 932,500 | 1,167,750 | 293,000 | 830,750 | | | 4,424,250 |
| 2012 | | 86,000 | 990,000 | 1,076,000 | 844,500 | 587,000 | 205,500 | 664,500 | | | 4,453,500 |
| 2013 | | 249,750 | 1,198,350 | 1,330,400 | 1,105,050 | 1,725550 | 464,400 | 656,250 | | | 6,729,750 |
| 2014 | | 504,750 | 1,386,100 | 1,150,850 | 1,214,350 | 1,724136 | 540,307 | 2,228,013 | 223,200 | | 8,971,706 |
| 2015 | | 781,406 | 2,278,143 | 2,178,401 | 2,161,128 | 1,976054 | 976,875 | 4,893,672 | 891,625 | | 16,137,304 |
| 2016 | 648,900 | 390,600 | 1,519,846 | 1,880,480 | 2,208,785 | 1,269378 | 600,879 | 3,935,502 | 1,246,169 | 997,488 | 14,698,027 |
| 2017 | 873,688 | 1,055,480 | 2,316,108 | 1,609,167 | 2,439,712 | 1,953457 | 804,082 | 3,548,144 | 1,363,908 | 1,136,687 | 17,100,433 |
| 2018 | 874,222 | 1,061,362 | 2,029,694 | 1,591,373 | 2,157,755 | 2,017333 | 564,792 | 4,005,324 | 975,176 | 1,155,150 | 16,432,181 |
| **Total** | **2,396,810** | **4,928,698** | **16,231,099** | **15,693,326** | **14,88,5649** | **17,021,008** | **5,677,876** | **21,236,255** | **4,700,078** | **3,289,325** | **106,060,124** |

**Table 10.2.** Numbers of hooks set in 2016, 2017 and 2018 pre-season and post-season extensions by daylight period, in the longline fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. *Daylight is specified to include nautical dawn and nautical dusk. Season extension trials are shaded in grey.

| Year | Period | Night | Nautical Dawn | Day | Nautical Dusk | Daylight* total | Total |
|---|---|---|---|---|---|---|---|
| 2016 | 1-14 Apr | 618,300 | 13,500 | 17,100 | | 30,600 | 648,900 |
| 2016 | 15-30 Apr | 390,600 | | | | 0 | 390,600 |
| 2016 | 15 Sep -31 Oct | 2,426,594 | 194,413 | 938,995 | 375,500 | 1,508,908 | 3,935,502 |
| 2016 | 1-14 Nov | 706,800 | 100,800 | 286,469 | 152,100 | 539,369 | 1,246,169 |
| 2016 | 15-30 Nov | 450,496 | 98,199 | 323,594 | 125,199 | 546,992 | 997,488 |
| 2017 | 1-14 Apr | 592,505 | 40,999 | 205,984 | 34,200 | 281,183 | 873,688 |
| 2017 | 15-30 Apr | 786,396 | 33,400 | 127,288 | 108,396 | 269,084 | 1,055,480 |
| 2017 | 15 Sep -31 Oct | 2,082,204 | 175,396 | 761,752 | 528,792 | 1,465,940 | 3,548,144 |
| 2017 | 1-14 Nov | 733,272 | 156,284 | 251,018 | 223,334 | 630,636 | 1,363,908 |
| 2017 | 15-30 Nov | 373,146 | 156,878 | 411,663 | 195,000 | 763,541 | 1,136,687 |
| 2018 | 1-14 Apr | 560,016 | 36,900 | 228,006 | 49,300 | 314,206 | 874,222 |
| 2018 | 15-30 Apr | 882,632 | | 160,722 | 18,008 | 178,730 | 1,061,362 |
| 2018 | 15 Sep -31 Oct | 2,063,456 | 218,008 | 1,405,615 | 318,245 | 1,941,868 | 4,005,324 |
| 2018 | 1-14 Nov | 415,188 | 123,300 | 352,088 | 84,600 | 559,988 | 975,176 |
| 2018 | 15-30 Nov | 582,750 | 87,300 | 304,650 | 180,450 | 572,400 | 1,155,150 |

Overall, 20 seabirds have been killed in the longline fishery since 2003 (Table 10.3). Between zero and two seabird mortalities occurred in all years except 2016 when seven seabirds were killed and very high seabird abundances around fishing vessels in November were reported. The overall mortalities consisted of one grey-headed albatross (*Diomedea chrysostoma*), five giant petrels (*Macronectes spp.*), three Cape petrel *(Daption capense*), seven white-chinned petrel (*Procellaria aequinoctialis*), two grey petrel (*Procellaria cinerea*), and two penguins (*Spheniscidae*). A total of 17 seabirds were killed during setting, eight during dawn/day/dusk setting and nine during night setting, while three birds were killed during night hauling.

During the extension trial period from 1-14 April, a total of two seabirds were killed between 2016 and 2018, one white-chinned petrel (*P. aequinoctialis*) was caught in each 2016 and 2017 during a night set and a dawn set, respectively.

During the existing extension period from 15-30 April, a total of four seabirds were killed between 2015 and 2018, one northern giant petrel (*M. halli*) in 2015 during a night set, one grey-headed albatross (*Diomedea chrysostoma* ) in 2016 during a night set, and one grey petrel (*P. cinerea*) during night sets in each 2017 and 2018.

During the core season from 1 May - 14 September, six seabirds have been killed since 2003: A giant petrel (*Macronectes spp.*) in 2008 during a dawn set, one Cape petrel (*Daption capense)* in 2009 during a day set, two Cape petrels (*Daption capense*) in 2010 during night hauls, one penguin (*Spheniscidae)* in 2014 during a night haul, and one northern giant petrel (*M. halli*) in 2015 during a dawn set.

During the existing extension period from 15 September - 31 October, there have been a total of two seabird mortalities between 2011 and 2018. Two giant petrels (*M. halli, Macronectes spp.*) were reported dead in the 2012 season during day sets.

During the extension trial period from 1-14 November, a total of four seabirds were killed between 2016 and 2018. Two white-chinned petrels (*P. aequinoctialis*) died on the same night set and one macaroni penguin (*Eudyptes chrysolophus*) during a night set in 2016, and one white-chinned petrel (*P. aequinoctialis*) died during a night set in 2018.

During the extension trial period from 15-30 November, a total of two seabirds were killed during between 2016 and 2018: two white-chinned petrels (*P. aequinoctialis*) were killed on the same dawn set in 2016.

**Table 10.3.** Seabird interactions by month and year, in the longline fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. Interactions resulting in mortality are indicated in brackets. Time periods closed to longline fishing are shaded in grey.

| Year | 1-14 Apr | 15-30 Apr | May | Jun | Jul | Aug | 1-14 Sep | 15 Sep - 31 Oct | 1-14 Nov | 15-30 Nov | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Trial | Extension | Core | | | | | Extension | Trial | Trial | |
| **2003** | | | 1 (0) | 2 (0) | | | | | | | **3 (0)** |
| **2004** | | | | | | | | | | | |
| **2005** | | | | | | | | | | | |
| **2006** | | | 1 (0) | | | | | | | | **1 (0)** |
| **2007** | | | | | | | | | | | |
| **2008** | | | | | | 2 (1) | | | | | **2 (1)** |
| **2009** | | | 3 (1) | | | | | | | | **3 (1)** |
| **2010** | | | 2 (0) | 3 (2) | | | | | | | **5 (2)** |
| **2011** | | | 1 (0) | 1 (0) | | | | | | | **2 (0)** |
| **2012** | | | 1 (0) | | | | | 2 (2) | | | **3 (2)** |
| **2013** | | | | | | 1 (0) | | | | | **1 (0)** |
| **2014** | | | | 1 (0) | | 1 (1) | | | | | **2 (1)** |
| **2015** | | 1 (1) | 1 (0) | | 1 (0) | | 1 (1) | | | | **4 (2)** |
| **2016** | 1 (1) | 1 (1) | | | | | | | 3 (3) | 2 (2) | **7 (7)** |
| **2017** | 1 (1) | 1 (1) | | | | | | | | | **2 (2)** |
| **2018** | | 1 (1) | | | | | | | 1(1) | | **2 (2)** |
| **Total** | **2 (2)** | **4 (4)** | **8 (1)** | **5 (2)** | **1 (0)** | **4 (2)** | **1 (1)** | **2 (2)** | **4 (4)** | **2 (2)** | **37 (20)** |

**Analysis**

Seabird mortality was lowest in the core season and the existing post-season extension from 15 September - 31 October, with less than 0.0001 seabirds killed per 1000 hooks (or less than 0.1 birds per million hooks, Table 10.4). The seabird mortality rate was about an order of magnitude higher during the existing pre-season extension (15-30 April) and season extension trial periods (1-14 April, 1-14 November, and 15-30 November).

When applying the BZIP model, we found consistency in the estimates of seabird mortality rates when using the three different priors and the results of the model with the uninformative prior are presented below.

The posterior distributions from the BZIP of seabird mortality rates per 1000 hooks for each period of the fishing season are shown in Figure 10.1. Seabird mortality rates in the core season and the existing post-season extension from 15 September - 31 October were predicted to be small at less than 0.0001 seabird mortalities per 1000 hooks, while mortality rates in the three trials were around 10 to 15 times higher than during the core season, but comparable to the existing season extension from 15-30 April.

**Table 10.4.** Mortality rate per 1000 hooks of seabirds that have been killed in the core season, the existing pre-season and post-season extensions and the season extension trials in the fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2.

| Period | 1-14 Apr Trial | 15-30 Apr Extension | 1 May-14 Sep Core | 15 Sep-31 Oct Extension | 1-14 Nov Trial | 15-30 Nov Trial |
|---|---|---|---|---|---|---|
| Mortality rate per 1000 hooks | 0.000834 | 0.000812 | 0.000086 | 0.000094 | 0.000851 | 0.000608 |

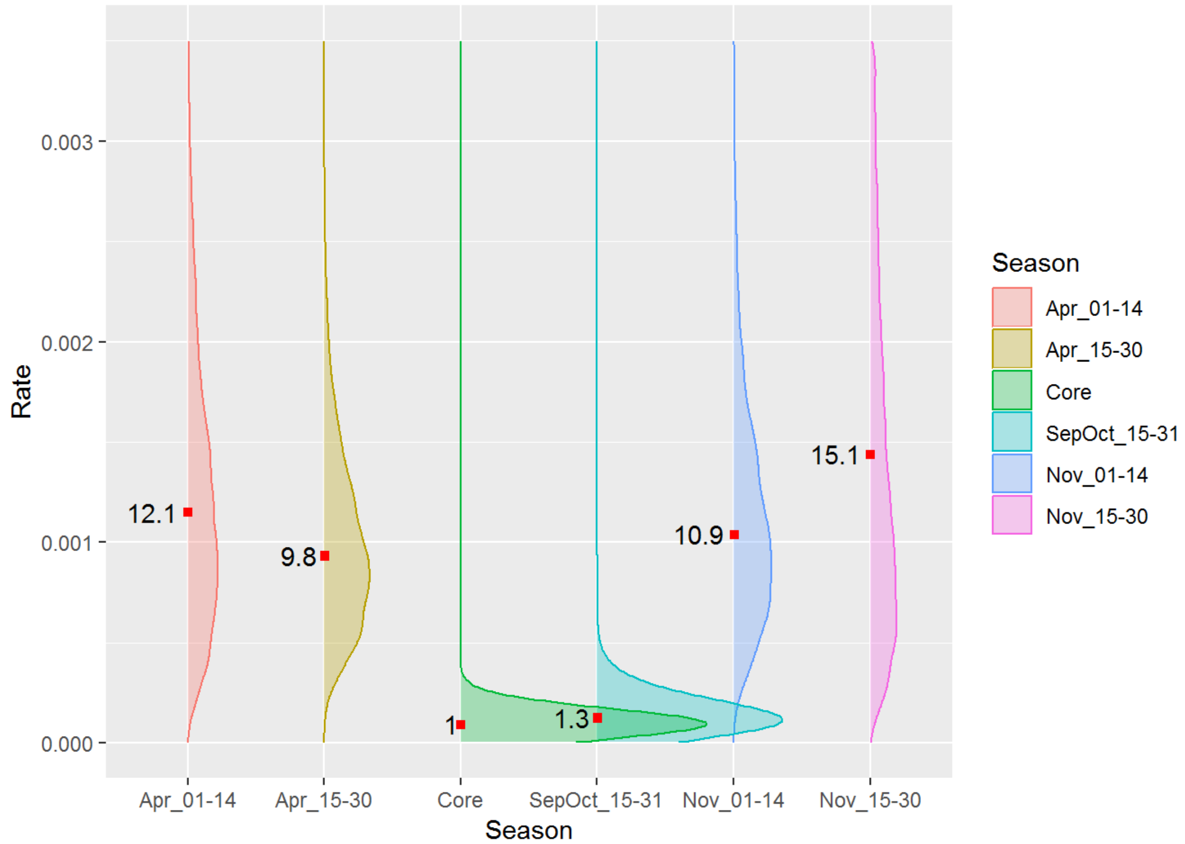



**Figure 10.1**: Posterior distributions of seabird mortality rates per 1000 hooks in the fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. Season extensions and core season appear in chronological order from left to right (Trial 1-14 Apr, Extension 15-30 Apr, Core season 1 May-14 Sep, Extension 15 Sep-31 Oct, Trial 1-14 Nov, and Trial 15-30 Nov). The red points and numbers illustrate the ratio of the posterior medians relative to the core season.

## 10.4 Conclusions

Low levels of seabird interactions have been recorded during longline operations in the fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. Only 20 seabird mortalities have occurred over the course of 15 years since longlining started in 2003. This outcome is due to the application of effective seabird bycatch mitigation by fishing vessels that comply with or exceed the requirements outlined in CM 25-02 and 41-08.

The trials for the pre-season and the two post-season extensions have now been completed. All season extension trials have satisfied their respective criteria of a cumulative total of 500,000 hooks set during each of the two the trial periods (1-14 November and 15-30 November), or set during daylight during the trial period (1-14 April).

The seabird mortality rate during longline operations in the fishery remains low. Seabird mortality rates in the core season and the existing post-season extension from 15 September - 31 October were predicted to be less than 0.0001 birds per 1000 hooks (or less than 0.1 birds per 1 million hooks). While mortality rates in the three pre-season and post season extension trials were 10 to 15 times higher, they were comparable to that during the existing pre-season extension from 15-30 April.

We recommend that the three season extension trial periods be added to the existing season extensions, given that the seabird mortality rates were low and the risk in the period of the three season extension trials was comparable to that in an existing season extension period.

There is no need for an additional management response at this stage. We recommend that there be no change to the specifications of the longline fishing season and the catch limit of seabirds per vessel during the season extensions.

Given the specification and application of effective seabird bycatch mitigation by longline fishing vessels in this fishery, we recommend that the requirement for any vessel to demonstrate full compliance with CM 25-02 in the previous season be removed in CM 41-08 (para. 3).

To give effect to the above recommendations, and we recommend CM 41-08 para. 3 be changed to:

> 'For the purpose of the trawl and pot fisheries for *Dissostichus eleginoides* in Statistical Division 58.5.2, the ~~2017/18~~2019/20 and ~~2018/19~~2020/21 seasons are defined as the period from 1 December to 30 November in each season, or until the catch limit is reached, whichever is sooner. For the purpose of the longline fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2, the ~~2017/18~~2019/20 and ~~2018/19~~2020/21 seasons are defined as the period from 1 May to 14 September in each season, or until the catch limit is reached, whichever is sooner. The season for longline fishing operations may be extended from 1 April to 30 April and 15 September to 30 November~~ for any vessel which has demonstrated full compliance with Conservation Measure 25-02 in the previous season[1]~~. Access to ~~T~~these extensions to the season will also be subject to a total catch limit of three (3) seabirds per vessel. If three (3) seabirds are caught during the season extension, fishing throughout the season extensions shall cease immediately for that vessel for the remainder of that fishing season.'

# Chapter 11: Skate bycatch assessment in the Icefish and Toothfish fisheries at Heard Island and McDonald Islands (HIMI)

Jaimie Cleeland, Gabrielle Nowara, Tim Lamb, Simon Wotherspoon and Philippe Ziegler

**This Chapter is based on a paper presented to SARAG in August 2021.**

## Abstract

Skates (Rajidae) represent the greatest biomass of incidental bycatch caught in the Patagonian Toothfish (*Dissostichus eleginoides*) and Mackerel Icefish (*Champsocephalus gunnari*) fishery operating within Australian EEZ waters around HIMI. By combining multiple data sources for *Bathyraja eatonii*, *B. irrasa* and *B. murrayi,* we aimed to test a selection of plausible life-history and fishing scenarios as input parameters into a population projection model using the Generalised Yield Model (GYM) to determine a range of precautionary yields for long-term population viability. Where input parameters could not be determined from available data, we followed a qualitative stepwise approach to obtain quantitative estimates from other species based on taxonomic, ecological and life-history similarities. In doing so, we provide a formal framework for performing bycatch assessments for data-poor species in the Southern Ocean.


## 11.1 Introduction

Skates (Rajidae) are commonly taken as incidental bycatch in demersal fishing operations throughout deep waters of the Southern Ocean (Kock et al. 2007). Due to their life history characteristics of slow growth and late maturation, their populations are particularly vulnerable to artificial increases in mortality which can lead to localised population declines (Elliott et al. 2020). An impact assessment is required to determine the risk of fisheries-driven population depletion. However, impact assessments for bycatch species require a basic suite of life-history parameters including information on age, growth and recruitment. For many bycatch species in the Southern Ocean, these parameters are not available.

Due to their deep-water, demersal existence little is known about the life history of the three species of skate, *Bathyraja eatonii, B. irrasa* and *B. murrayi*, most frequently taken as bycatch in the Heard Island and McDonald Islands (HIMI) Patagonian Toothfish (*Dissostichus eleginoides*) and Mackerel Icefish (*Champsocephalus gunnari*) fisheries. The fisheries, operating since 1997, initially engaged in demersal trawl operations pursuing both target species in relatively shallow waters (< 700 m) of the Kerguelen Plateau (Duhamel and Williams 2010). From 2003, demersal longlining became the predominant fishing method for Toothfish allowing the fishery to move into deeper slope waters up to 2000 m.

Prior to 2005, the HIMI region was subject to illegal, unreported and unregulated (IUU) demersal longline operations targeting Toothfish. However, since 2005 IUU operations in the HIMI region have been almost entirely eliminated due to actions supported by the Treaty on Cooperation in the Maritime Areas Adjacent to the French Southern and Antarctic Territories, Heard Island and McDonald Islands (Australia and France 2004). The historical influence of IUU fishing on skate populations in the HIMI region is unclear, however could be substantial due to the absence of bycatch mitigation measures.

Despite being widely distributed over the Kerguelen Plateau, the three skate species vary in abundance by depth strata. The smaller *B. murrayi* (up to 600 mm total length) is most commonly observed in the shallower waters of less than 1500 m depth where the Icefish fishery currently operates (Nowara et al. 2017). Similarly, the larger *B. eatonii* (up to 1400 mm total length) is seen frequently in Icefish trawls, as well as ranging into deeper waters where longline operations target Toothfish (270 – 1800 m). The largest species, *B. irrasa* (up to 1500 mm total length), is predominantly observed in the longline fishery on the slopes of the Kerguelen Plateau (150 – 2000 m). These skates represent the most abundant bycatch of any species in these fisheries (Nowara et al. 2017). Furthermore, a significant decline in mean total length for *B. eatonii* from 950 mm in 1998 to 835 mm in 2014 suggests that the Icefish and Toothfish trawl fisheries, where *B. eatonii* comprise 84% and 45% of skate bycatch, may have negatively influenced their populations. With a recent decline in hauls with zero bycatch, it is imperative that a quantitative bycatch assessment is performed for this species.

The HIMI fisheries, managed by the Australian Fisheries Management Authority (AFMA), operate within the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Division 58.5.2 and are guided by its current conservation measures (Australian Fisheries Management Authority 2002). In regards to skates, the CCAMLR Conservation Measure 33-02 states that bycatch shall not exceed 120 tonnes, and if bycatch in any one haul is equal to or greater than 2 tonnes, a move on rule is triggered and the vessel shall not fish within 5 nautical miles of that haul for 5 days. The current bycatch limit is based on the results from a bycatch assessment for *Bathyraja* spp. at HIMI performed using the Generalised Yield Model (GYM, Constable et al. 1998).

The GYM is a population projection model that allows for variable recruitment and incorporates uncertainty in input parameters of growth, natural mortality, maturity, recruitment and fishing (Constable and de la Mare 1996). For data-poor bycatch species like many in Southern Ocean fisheries, model input parameters can be difficult to define due to limited availability of information on life-history characteristics. To overcome this problem, the preliminary assessment grouped all *Bathyraja* species into a single population and used abundance measures from three research cruises in 1990-1993. Recruitment variability, growth and natural mortality were taken from substitute species, and age and length thresholds were used for maturity and fishing selectivity, respectively. The results of the assessment were adopted by CCAMLR in 1997 (CCAMLR 1997) and still form the basis for the current bycatch limit.

By combining multiple data sources for *B. eatonii, B. irrasa* and *B. murrayi* we aimed to test a selection of plausible life-history and fishing scenarios as input parameters into the GYM population projection model to determine a range of precautionary yields for long-term population viability. Where input parameters could not be determined from available data, we followed a qualitative stepwise approach to obtain quantitative estimates from other species based on taxonomic, ecological and life-history similarities. In doing so, we provide a formal framework for performing bycatch assessments for data-poor species in the Southern Ocean.

## 11.2 Methods

**Data collection**

The data used in this assessment was collected by independent scientific observers during random stratified trawl surveys (RSTS) and commercial trawl and longline operations between 1997 and 2020 at Heard Island and McDonald Islands (HIMI, approx. 73°E 53°S). The RSTS is an annual research survey conducted across nine survey strata in the shallow waters (<1000m) of the HIMI region (e.g. Nowara et al. 2019). The survey, taking place in March-April every year, aims to determine the distribution, abundance and population structure of Toothfish, Icefish and bycatch species.

Several gear types are used in the HIMI fishery. For longline operations, an autoline system with integrated weighted line is used to ensure fast sink rates to minimise seabird bycatch (AFMA 2013). Demersal trawl nets are limited to a minimum mesh size of 120 mm when targeting Toothfish, 90 mm when targeting Icefish to allow escapement of juvenile fish, and 50 mm for the RSTS to retain small organisms.

**Bycatch history**

In the longline fishery, there are two measures of total bycatch for each haul; the vessel counts and the scaled observer partial count.

The total number of skates caught during each haul is counted by the vessel captain (vessel counts). The total count is then multiplied by the average weight of skates sampled by the independent observer to give a total weight of skate bycatch for each haul.

Observers also count the number of skates caught but only for 40-50% of a haul (observer partial count). The observers usually record the number of skates at the order levle (Rajidae, 77.2 % of all counts), and sometimes at the genus (*Bathyraja* spp., 3.5 %) or species level (25.3 %). To determine the number of skates from each species caught on each haul, the HIMI region was divided into 1.0 x 0.5 degree blocks (as per Nowara et al. 2017) and the proportion of species sampled was calculated for each year in each block. Where the total number of skates was less than 55, the proportion was calculated including adjacent blocks. The total number of skates caught on each haul was split based on these year-block proportions and scaled up to 100% of the line.

A spatial Generalised Additive Model (GAM) with a gamma error distribution and a log link was fitted to the weights of sampled skates using the R package *mgcv* (Wood 2017) for each species. Each model contained a bivariate smooth of latitude and longitude and standardised for the effect of year. The resulting predicted weight for each block in each year was multiplied by the total number of skates calculated from the scaled observer partial counts to give the total bycatch weight of each haul. The two measures of total bycatch, vessel counts and scaled observer partial count were compared using a simple linear regression.

For hauls using trawl gear, all skates are brought onboard, identified to species, counted and weighed. If the number of skates is greater than 10 per haul, the mean weight is used to scale the total bycatch. Hauls where skates were counted but not identified to species level (3.4% of data), the total number of skates were split using the species block proportions similar to longline data. On the occasion where large catches or a rapid sequence of hauls prevented bycatch from being processed separately, bycatch from multiple hauls were pooled together (1.3% of hauls, similar to Nowara et al. 2017). For consistency in data analyses, the recorded bycatch was split evenly between the hauls that were pooled.

In both fisheries, skates assessed to be in good or average condition following the CCAMLR Skate Condition guidelines (https://www.ccamlr.org/en/document/publications/skate-discard-poster) are released. In the longline fishery, released skates are cut-off the snood at the roller to maximise post-release survival. Skates in poor condition or dead are retained onboard, the total weight recorded and then later discarded.

**Standardised bycatch rates**

Standardised bycatch rates in the HIMI region were modelled separately for the annual RSTS, trawls targeting Toothfish, trawls targeting Icefish and longline hauls targeting Toothfish, using a systematic modelling process. Observer partial counts from trawl and longline (~45%) hauls were first assessed for zero-inflation for each species and fishery. Data sets containing more than 25% zero counts were modelled using zero-inflated Generalised Additive Models (GAMs) with the R package *zigam* (https://github.com/AustralianAntarcticDataCentre/zigam), where the zero component was represented by a binary model with a logistic link.

Modelled covariates included the CCAMLR fishing season (December 1$^{st}$ - November 30$^{th}$), month and vessel as factors, a smoothed term of depth, a bivariate smooth of fishing location (longitude, latitude) and log transformed target catch (Icefish or Toothfish). Collinearity amongst numerical covariates was assessed using a Pearson correlation matrix.

To account for variability in fishing effort, swept area (km$^2$) for trawl and number of hooks for longline were included as an offset in the models. Initially, counts were assumed to be Poisson distributed and tested for over-dispersion using the ratio of residual deviance and degrees of freedom. In instances where the ratio was greater than two, a negative binomial distribution was assumed. Models were selected by adding an extra penalty to each term to allow non-significant terms to be automatically removed from the base model. To identify any spatial patterns in CPUE (bycatch per swept area in square kilometres (km$^2$) and bycatch per 1000 hooks), all hauls were averaged over a 0.1 x 0.1 degree raster grid over the entire period of the fisheries.

**Biological sampling**

To determine key biological input parameters for the stock assessment modelling, a range of onboard measures was undertaken. From 2003 to 2005, five skates per haul were identified to species level and sampled for total length and disk width (mm), weight (kg), sex and gonad stage. To obtain a more representative sample, ten skates per haul were sampled from 2006 onwards. Gonad staging for skates followed CCAMLR protocols (CCAMLR Secretariat 2019), with the males staged externally by inspection of the claspers and females staged following an internal examination of the ovary. Following examination individuals were grouped into one of three stages: 1 - immature, 2 - maturing or 3 - mature.

**Skate tagging**

A comprehensive skate tagging program began in 2001 with an average of 167 skates tagged per cruise (range: 1-1989). Skates measured and assessed to be in good condition following the CCAMLR Skate Condition guidelines were double tagged with a T-bar anchor tag in the middle of each wing and then released. All skates caught were examined for the presence of a tag before being cut-off longlines, released or processed. To concentrate future tagging effort the core utilization distributions (10%) of tag releases and recaptures were determined for each species using kernel density estimation and a proposed new tagging area identified.

**Population projection model**

The long-term population trajectory of skates caught in the HIMI fisheries was evaluated using the Generalised Yield Model (GYM), a flexible population projection model that allows for variable recruitment and incorporates uncertainty in input parameters of growth, natural mortality, maturity, recruitment and fishing (Constable and de da Mare 1996). The model determines yield as a proportion of an estimated pre-exploitation biomass (γ) which was used to estimate fishing mortality following the CCAMLR decision rules for skates (Constable et al. 1998) to satisfy both of the following conditions:

- the median escapement of the spawning stock at the end of a 20-year projection period be at least 75% of the pre-exploitation spawning biomass; and
- the probability of depletion below 20% of the median pre-exploitation spawning biomass be no greater than 10% over a 20-year projection period.

An initial base model was set up for each species (Table 11.1). Due to limited availability of information on life-history characteristics, a range of scenarios for model input parameters of age and growth, natural mortality, recruitment, fishing mortality were then tested for each species (Table 11.2). The model input parameters are described below.

**Table 11.1:** Input parameters for the base scenario of the skate (*Bathyraja* spp.) bycatch assessments using the Generalised Yield Model (GYM) at HIMI.

| Category | Parameter | *B. eatonii* | *B. irrasa* | *B. murrayi* | Reference |
|---|---|---|---|---|---|
| **Age structure** | Recruitment age | 1 | 1 | 1 | |
| | Plus class accumulation | 20 | 20 | 20 | |
| | Oldest age in initial structure | 30 | 30 | 30 | |
| **Natural mortality** | Mean annual *M* | 0.12-0.28 | 0.12-0.28 | 0.12-0.28 | |
| **von Bertalanffy growth** | $t_0$ | -0.61 | -2.1 | -1.87 | Bücker (2006), Gburski et al. (2007), Perez et al. (2011) |
| | $L_\infty$ | 1669 mm | 2039 mm | 558 mm | |
| | *k* | 0.064 | 0.04 | 0.21 | |
| **Weight at length (kg, mm)** | Weight-length parameter - *a* | 1.75 x $10^{-09}$ | 3.13 x $10^{-09}$ | 5.43 x $10^{-09}$ | Table 2, Figure 14. |
| | Weight-length parameter - *b* | 3.19 | 3.11 | 3.04 | |
| **Maturity** | $L_{m50}$ (set such that status of whole stock is being monitored) | 1020 mm | 1119 mm | 461 mm | Wong et al. (2021) Figure 15 |
| | Range: 0 to full maturity | 405 mm | 497 mm | 229 mm | |
| **Spawning season** | Set such that stock status is determined at end of each year | 1 Mar | 1 Mar | 1 Mar | Constable et al. (1998) |
| **Recruitment** | Age of estimating recruitment | 2 | 2 | 2 | Constable et al. (1998) |
| **Fishery parameters** | Length first selected | 170 mm | 240 mm | 120 mm | Figure 17 |
| | Length fully selected | 460 mm | 940 mm | 330 mm | |
| | Season | 1 Mar – 30 Nov | 1 Mar – 30 Nov | 1 Mar – 30 Nov | |
| | Reasonable upper bound for Annual F | 5 | 5 | 5 | |
| | Tolerance for finding F in each year | 0.000001 | 0.000001 | 0.000001 | |
| **Initial population structure** | Date of estimate (survey) | 1 Mar | 1 Mar | 1 Mar | Constable et al. (1998) |
| **Simulation specifications** | Number of runs in simulation | 1001 | 1001 | 1001 | Constable et al. (1998) |
| **Individual trial specifications** | Years to remove initial age structure | 1 | 1 | 1 | Constable et al. (1998) |
| | Year prior to projection | 1996 | 1996 | 1996 | |
| | Reference Start Date in year | 1-Dec | 1-Dec | 1-Dec | |
| | Increments in year | 365 | 365 | 365 | |
| | Years to project stock in simulation | 20 | 20 | 20 | |

**Table 11.2:** Scenarios of skate life-history and fishing parameters for input into the Generalised Yield Model (GYM). Shaded cells represent the base model parameter being adopted.

| Scenario | Age structure (min, max, plus class) | Growth | Mortality | Age of first recruitment | Recruitment ages | Fisheries selectivity | Bycatch (fishing mortality) | Projection years |
|---|---|---|---|---|---|---|---|---|
| **Base model** | All species: 0, 20, 30 | Ecologically similar species | 0.12-0.28 | 2 | 2-10 | Length distribution | Retained bycatch | 20 |
| **2** | *B. eatonii* & *B. irrasa*; 0, 15, 20 *B. murrayi*: 0, 10, 15 | | | | | | | |
| **3** | | Wong et al. (2021) | | | | | | |
| **4** | | Verdouw and Hutchins (2009) | | | | | | |
| **5** | | Slow | | | | | | |
| **6** | | Fast | | | | | | |
| **7** | | | 0.05-0.15 | | | | | |
| **8** | | | 0.20-0.30 | | | | | |
| **9** | | | | 3 | | | | |
| **10** | | | | 4 | | | | |
| **11** | | | | 5 | | | | |
| **12** | | | | | 2-5 | | | |
| **13** | | | | | | Higher | | |
| **14** | | | | | | | + 50% released bycatch | |
| **15** | | | | | | | + 100% released bycatch | |
| **16** | | | | | | | | 30 |

**Projection model parameters**

*Age structure*

For the base model, the population age structure for each species was based on a likely age range for high-latitude, deep-water skates from the literature. A further scenario of population age structure based on Wong et al. (2021) and an unpublished vertebra centre ageing study completed at the Australian Antarctic Division by Verdouw and Hutchins (2009) were also tested.

*Natural mortality*

Three scenarios of annual natural mortality (M) were tested; moderate (0.12-0.28), high (0.20-0.30) and low (0.05-0.15). The parameter bounds were based on estimates of mortality for high latitude, deep-water skates found in the literature.

*Growth (age-at-length)*

Vertebral ageing data from Wong et al. (2021) was used to determine growth functions for each species. The von Bertalanffy growth parameters of $L_\infty$ (the theoretical asymptotic length), $k$ (the rate of constant growth) and $t_0$ (the theoretical time at zero length) (von Bertalanaffy 1938) from ecologically similar species were used to define the growth input parameter in the base assessment model. Furthermore, a von Bertalanffy growth function was fitted to the age-at-length data for each species from Verdouw and Hutchins (2009), and calculated as:

$$L_t = L_\infty(1 - e^{-k(t-t_0)})$$

where $L_t$ is length as a function of time $t$. Due to uncertainty associated with ageing methodology and evidence of systemic age underestimation across elasmobranch studies (James 2020, Harry 2018), scenarios of faster and slower growth were tested by increasing and decreasing the $k$ parameter in the base model by 0.01 for each species. Furthermore, scenarios of growth from an ecologically similar species, based on latitudinal distribution, depth distribution, total length and maximum age, were also tested.

*Weight-at-length*

The coefficients of the weight-at-length relationship, $a$ and $b$ were estimated by fitting the relationship:

$$W = aL^b$$

where $W$ is the weight (kg), $L$ is the length (mm) of individual male and female skates.

*Maturity*

The length at which 50% of the population are mature ($L_{M50}$ ± 95% CI) and the length range over which skates mature, was taken from Wong et al. (2021) who fitted a three-parameter logistic model:

$$y = \frac{a}{1 + (\frac{L_t}{L_{M50}})^b}$$

where $y$ is the percentage of mature animals, $a$ is the asymptotic value, and $b$ is the shape parameter.

*Recruitment*

Estimates of annual recruitment were obtained from the abundance of different age classes from the RSTS between 1999 and 2020. The mean density of skates per length class from hauls were transformed into age classes by applying the von Bertalanffy growth function from the corresponding assessment scenario using the age_slicing function from the R package ALKr (Loff et al. 2019).

Scenarios of age at first recruitment from 2 to 5 years old were tested to account for uncertainty in age related maturity. Furthermore, a single scenario constraining the age frequency in recruitment to years 2 to 5 was tested.

*Fisheries information*

For the GYM, a single length-based fisheries selectivity was used for each species based on length distribution of bycatch across all fisheries and gear types. A knife-edge distribution of the proportion of lengths representing the slope of length-based selectivity between 0-1 was used to determine the median and range of lengths over which skates were recruited into the fishery. For comparison, a scenario of higher length-based selectivity (+100 mm) was tested for each species.

The annual combined weight of retained bycatch for all fisheries and gear types was used to estimate fisheries mortality ($F$) in each year. To account for mortality of released skates, scenarios of retained bycatch weight plus 50% and 100% of released bycatch weight determined from the scaled bycatch history were also tested for each species.

**Precautionary yield estimation**

To estimate 95% confidence intervals in the annual total biomass for each strata from the RSTS (1999-2020), a stratified non-parametric bootstrap algorithm was implemented in R (R Core Team 2020). The total biomass estimates of skate bycatch in the survey area were calculated by summing over all stratum biomass estimates, based on the mean densities calculated from the bootstrapped hauls in a stratum. The estimation of $\gamma$ was applied to the average biomass estimate (2010-2020) to determine the total precautionary yield in tonnes for each scenario.

## 11.3 Results

### Bycatch history

Estimated total skate bycatch increase considerable over the duration of fisheries operating at HIMI (1997-2020, Figure 11.1). An increase in bycatch of *B. eatonii* in the Icefish fishery and *B. irrasa* has contributed predominantly to this overall trend.

Similarly, the retained bycatch has increased since the start of the fishery, but has never triggered the bycatch limit of 120 t. Despite a slight increase of retained bycatch in the Toothfish longline fishery, this trend was largely driven by an increase in the Icefish trawl fishery (Table 11.3). In 2019, both estimated total (459 t) and retained (81 t) skate bycatch represented the highest catches ever recorded.

The proportion of retained bycatch of the overall total bycatch was high in the Icefish trawl fishery (63% on average between 2010-2020) and has remained above 50% since 2015, whereas the proportion of retained bycatch in the Toothfish longline fishery was low (8% on average between 2010-2020) and shown a considerable decline since 2012 (Figure 11.2).

Discrepancies exist between the total bycatch determined from the scaled observer partial counts and vessel counts in the longline fishery (Table 11.3). For all vessels operating in the longline fishery the vessel counts represent between 66 - 90% of the scaled observer partial counts (Figure 11.3).

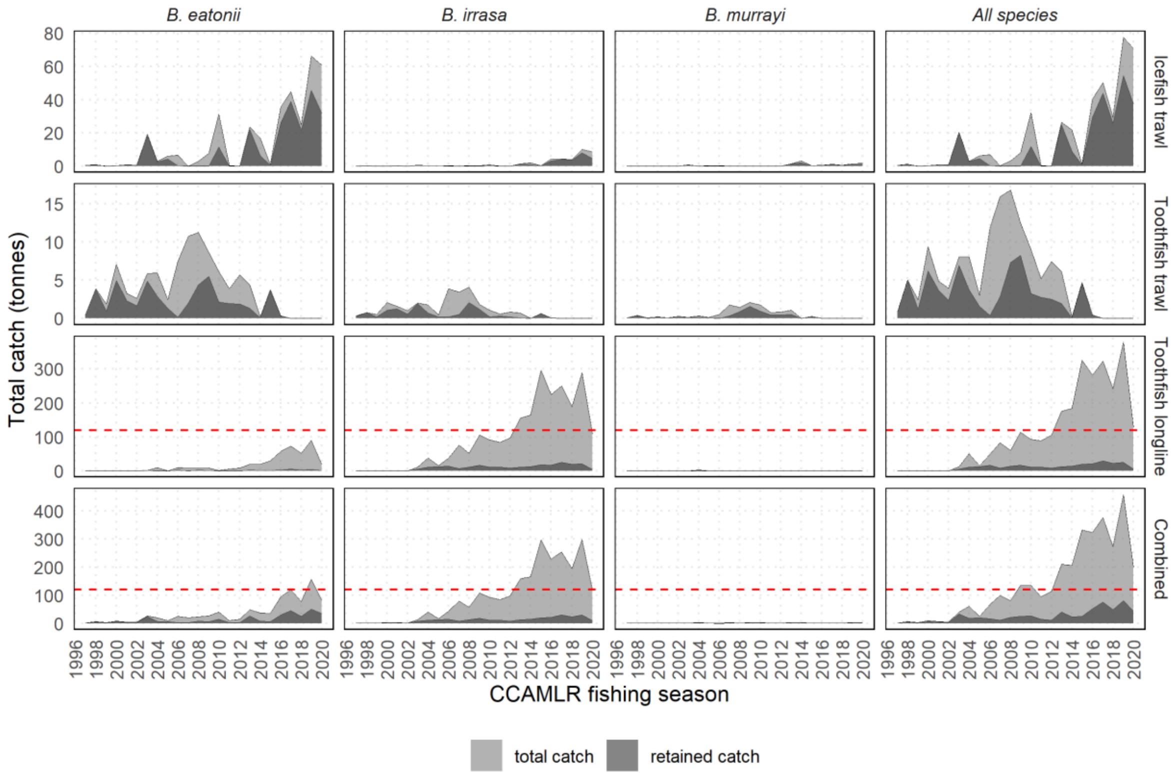



**Figure 11.1:** Estimated total and retained bycatch (tonnes) of skate (*Bathyraja* spp.) between 1997 and 2020 in the random stratified trawl survey (RSTS), Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) trawl and longline fisheries at HIMI. The estimated total bycatch for the Toothfish longline fishery is based on scaled observer partial counts. The red dashed line represents the total bycatch limit (for all skates combined).

**Table 11.3:** Estimated total and retained bycatch (tonnes) of skate (*Bathyraja* spp.) between 1997 and 2020 in the random stratified trawl survey (RSTS), Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) trawl and longline fisheries at HIMI. For the Toothfish longline fishery, the estimated total bycatch is based on scaled observer partial counts, whereas the 'Vessel bycatch' is the vessel-reported total bycatch.

| CCAMLR Season | RSTS | | Icefish trawl | | Toothfish trawl | | Toothfish longline | | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Retained bycatch (t) | Total bycatch (t) | Retained bycatch (t) | Total bycatch (t) | Retained bycatch (t) | Total bycatch (t) | Retained bycatch (t) | Total bycatch (t)* | Vessel bycatch (t) | Retained bycatch (t) | Total bycatch (t) |
| **1997** | | | 1 | 1 | 1 | 1 | | | | 1 | 1 |
| **1998** | | 1 | 1 | 1 | 5 | 5 | | | | 6 | 7 |
| **1999** | | | | | 1 | 2 | | | | 1 | 3 |
| **2000** | | | | | 6 | 9 | | | | 6 | 10 |
| **2001** | | | 1 | 1 | 4 | 5 | | | | 5 | 6 |
| **2002** | | | 1 | 1 | 2 | 4 | | | | 3 | 5 |
| **2003** | | | 20 | 20 | 7 | 8 | 6 | 12 | 12 | 33 | 41 |
| **2004** | | | 3 | 3 | 4 | 8 | 11 | 50 | 50 | 18 | 61 |
| **2005** | | 1 | 5 | 6 | 2 | 3 | 13 | 15 | 36 | 19 | 25 |
| **2006** | | 1 | | 7 | | 12 | 16 | 49 | 29 | 17 | 68 |
| **2007** | | 1 | | | 3 | 16 | 8 | 83 | 42 | 11 | 100 |
| **2008** | | | | 3 | 7 | 17 | 14 | 60 | 40 | 21 | 80 |
| **2009** | | 1 | | 8 | 8 | 13 | 17 | 114 | 52 | 25 | 136 |
| **2010** | | 2 | 12 | 32 | 3 | 9 | 12 | 93 | 41 | 27 | 136 |
| **2011** | | 1 | | | 3 | 5 | 11 | 89 | 40 | 14 | 95 |
| **2012** | | 1 | | | 3 | 7 | 8 | 105 | 70 | 11 | 114 |
| **2013** | | 1 | 25 | 26 | 2 | 6 | 13 | 176 | 73 | 40 | 210 |
| **2014** | | 1 | 9 | 22 | | | 14 | 184 | 108 | 24 | 207 |
| **2015** | | 1 | 1 | 1 | 5 | 5 | 20 | 326 | 176 | 25 | 333 |
| **2016** | 1 | 2 | 30 | 40 | | | 20 | 282 | 129 | 51 | 325 |
| **2017** | 1 | 2 | 44 | 50 | | | 30 | 323 | 135 | 75 | 376 |
| **2018** | 1 | 3 | 26 | 29 | | | 22 | 242 | 106 | 49 | 274 |
| **2019** | 1 | 2 | 54 | 78 | | | 26 | 379 | 168 | 81 | 459 |
| **2020** | 1 | 3 | 37 | 71 | | | 6 | 127 | 102 | 44 | 201 |

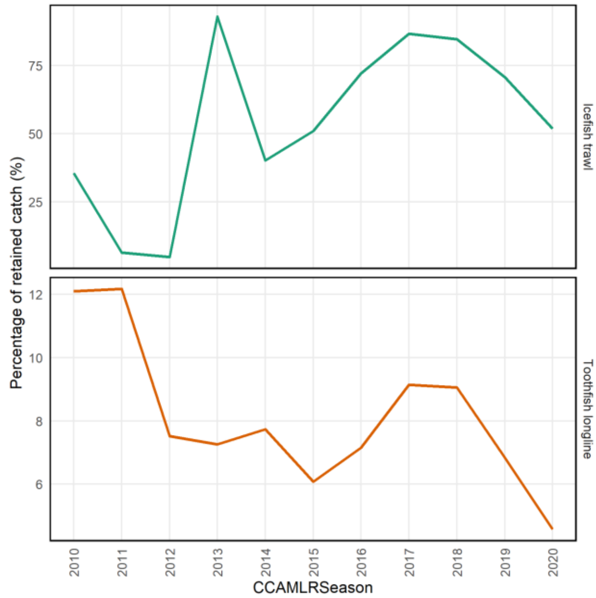



**Figure 11.2:** Annual proportions of retained bycatch relative to estimated total bycatch of skate (*Bathyraja* spp.) between 2010 and 2020 in the Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) longline fishery at HIMI.

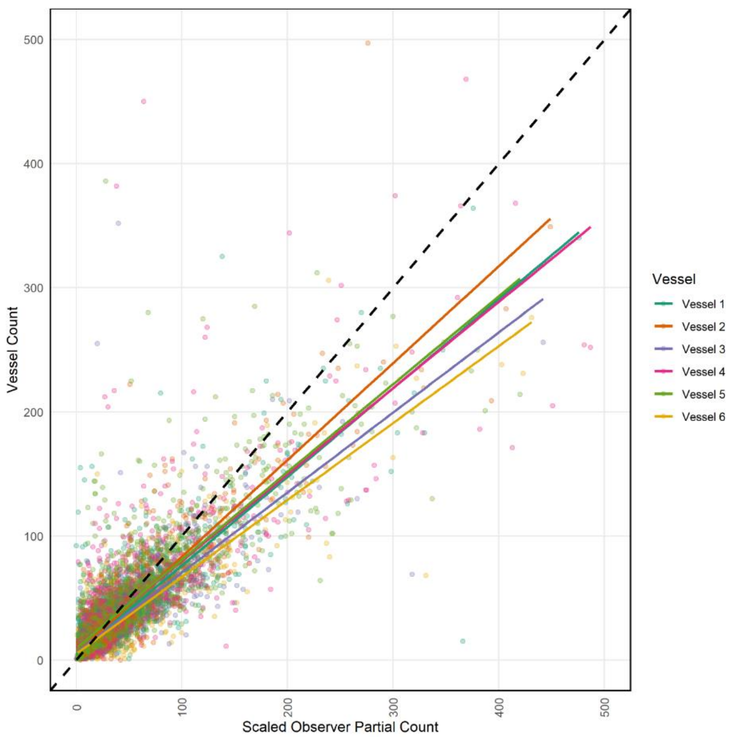



**Figure 11.3:** Linear regression between the scaled observer partial counts and vessel counts of skate (*Bathyraja* spp.) bycatch by vessel in the Patagonian Toothfish (*Dissostichus eleginoides*) longline fishery at HIMI. Vessels which have operated in the fishery for a short-time only were not included. The black dashed line indicates parity.

**Standardised bycatch rates**

The estimated bycatch per unit effort for each species varied by fishery and depth strata. *Bathyraja eatonii* represents the most abundant bycatch species in the Icefish trawl fishery where it was caught in depths below 600 m (Figure 11.4). Furthermore, average densities of up to 167 per km$^2$ have been observed in depths between 200-300 m to the north-east of Heard Island (Figure 11.5). Similarly, the CPUE for *B. eatonii* in the Toothfish longline fishery was highest in the shallow waters east of Heard Island (Figure 11.6).

For both the Icefish (1997-2020) and Toothfish trawl (1997-2015) fisheries and the RSTS (2006-2020), a general increase in CPUE over time for *B. eatonii* has been observed (Figure 11.7, Table 11.4). In the Toothfish longline fishery, *B. eatonii* was caught in high numbers in shallower waters and low numbers in the deeper waters where the fishery is most active. No observable trend over time has been detected for *B. eatonii* caught in the Toothfish longline fishery (Figure11. 8).

*Bathyraja irrasa* was predominantly caught in the Toothfish longline fishery in deeper waters (1200 - 1500 m) along the slope in average densities of up to 7 per 1000 hooks (Figure 11.6). This species was infrequently caught in shallow waters where trawl fisheries and the RSTS occur (Figure 11.4). However, in recent years there has been a small increase in bycatch rates in the RSTS and Icefish trawl fishery (Figure 11.7). For the Toothfish longline fishery, a consistent decline in standardised bycatch rates of *B. irrasa* was observed between 2010 and 2018 (Figure 11.8, Table 11.4).

*Bathyraja murrayi* was most commonly caught in the Toothfish trawl fishery in shallow waters below 600 m (Figure 4) in average densities of up 89 per km$^2$. This species was only very rarely seen in the Toothfish longline fishery (Figure 11.6). The standardised bycatch rates has shown a recent (2012-2020) increase in the Icefish trawl fishery (Figure 11.7, Table 11.4).

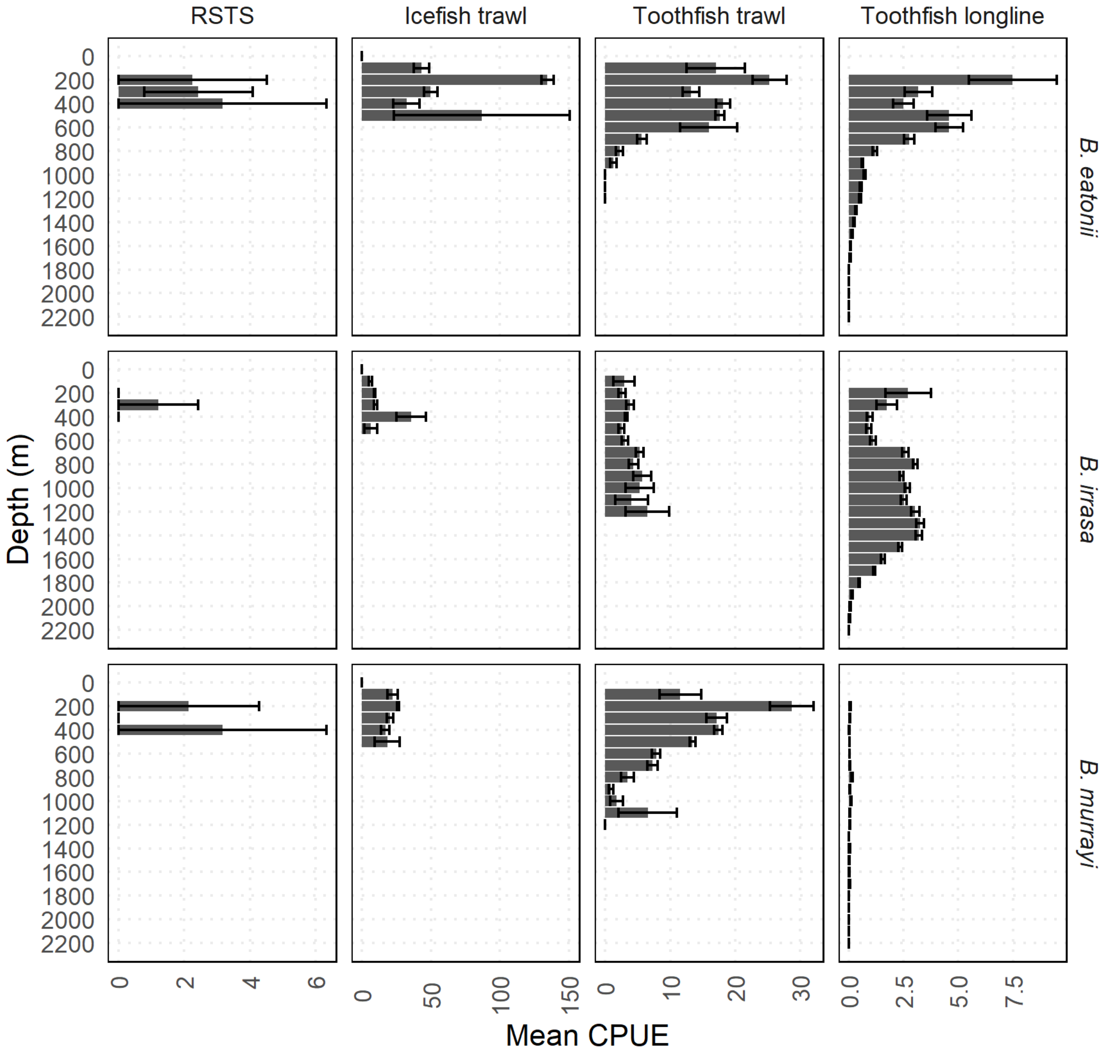



**Figure 11.4:** Mean bycatch per unit effort (CPUE) for skate (*Bathyraja* spp.) per depth strata between 1997 and 2020 for the annual random stratified trawl survey (RSTS), Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) trawl and longline fisheries at HIMI.

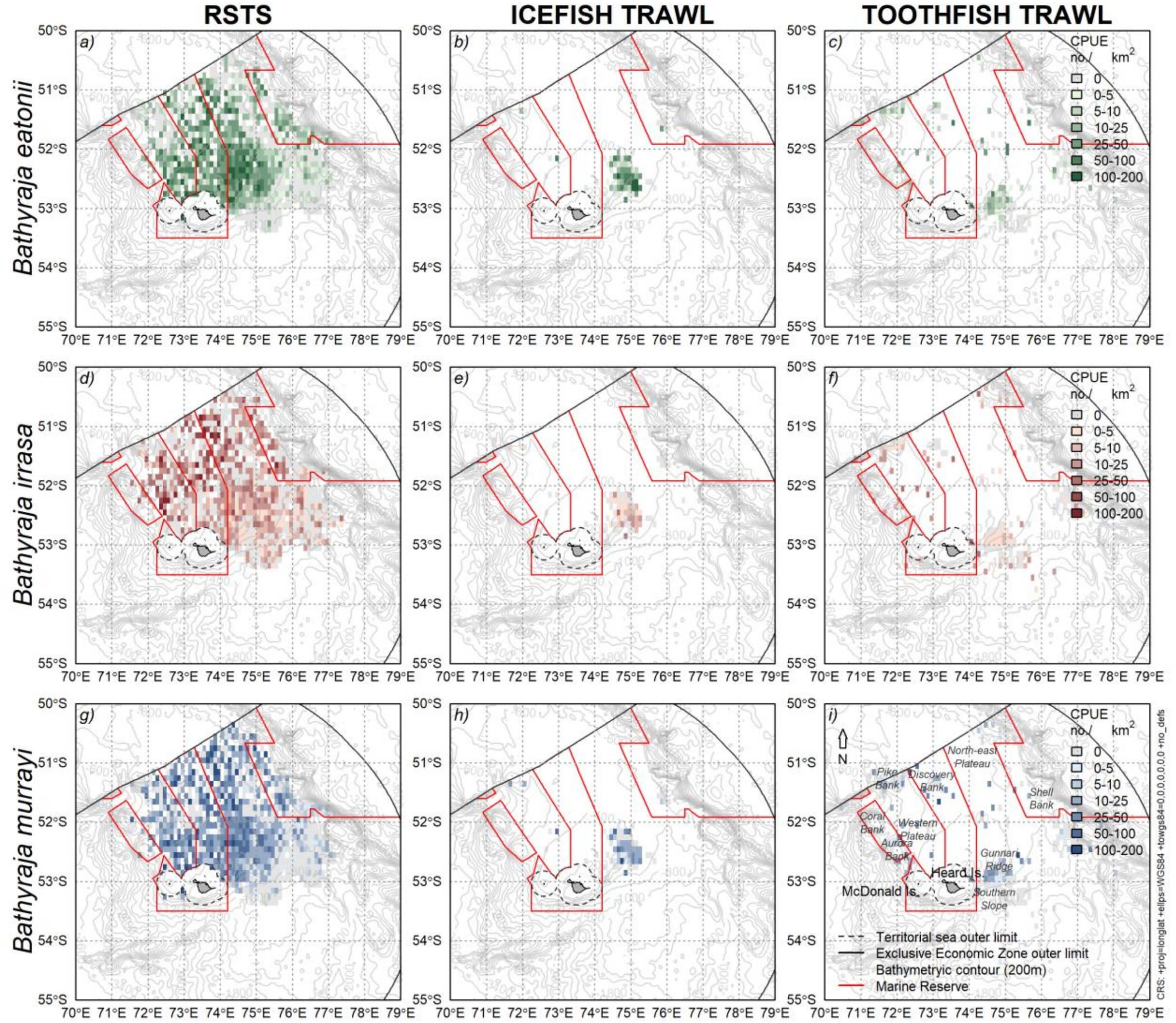



**Figure 11.5:** Spatial distribution of bycatch per unit effort (CPUE, 0.1 degree resolution) for skate (*Bathyraja* spp.) between 1997 and 2020 for the annual random stratified trawl survey (RSTS), Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) trawl fishery at HIMI.

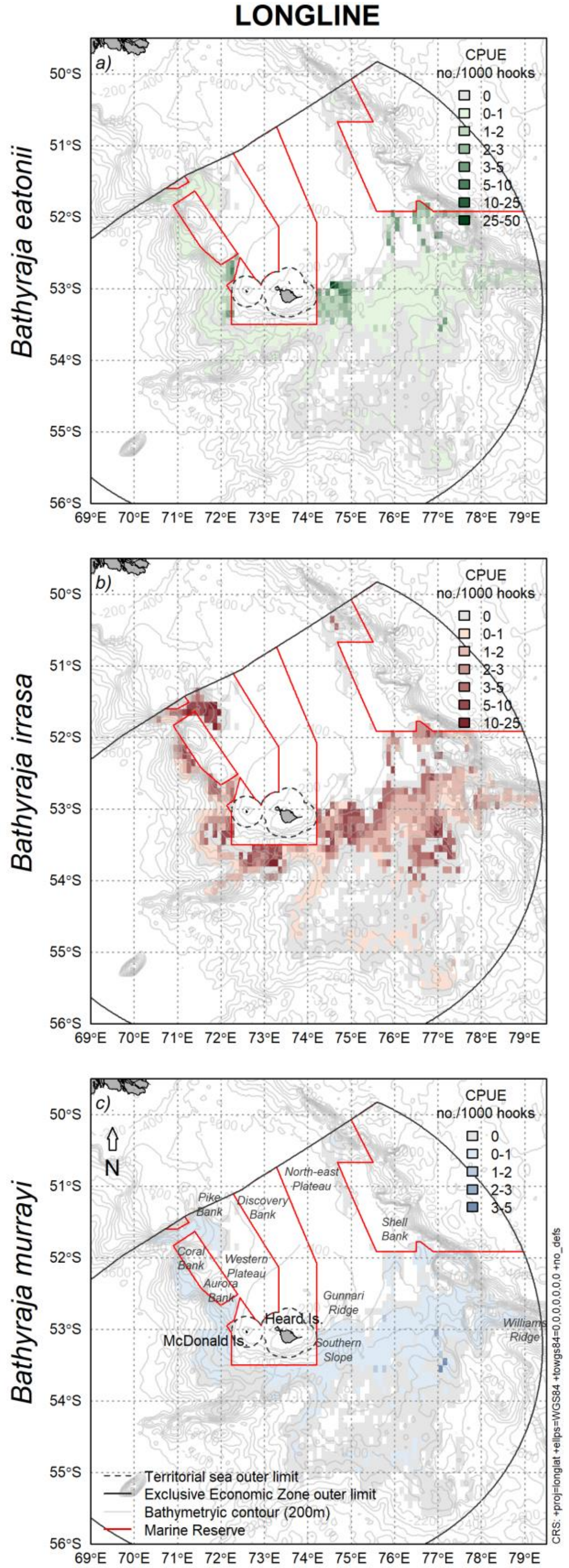



**Figure 11.6:** Spatial distribution of bycatch per unit effort (CPUE, 0.1 degree resolution) for skate (*Bathyraja* spp.) between 2006 and 2020 for the Patagonian Toothfish (*Dissostichus eleginoides*) longline fishery at HIMI.

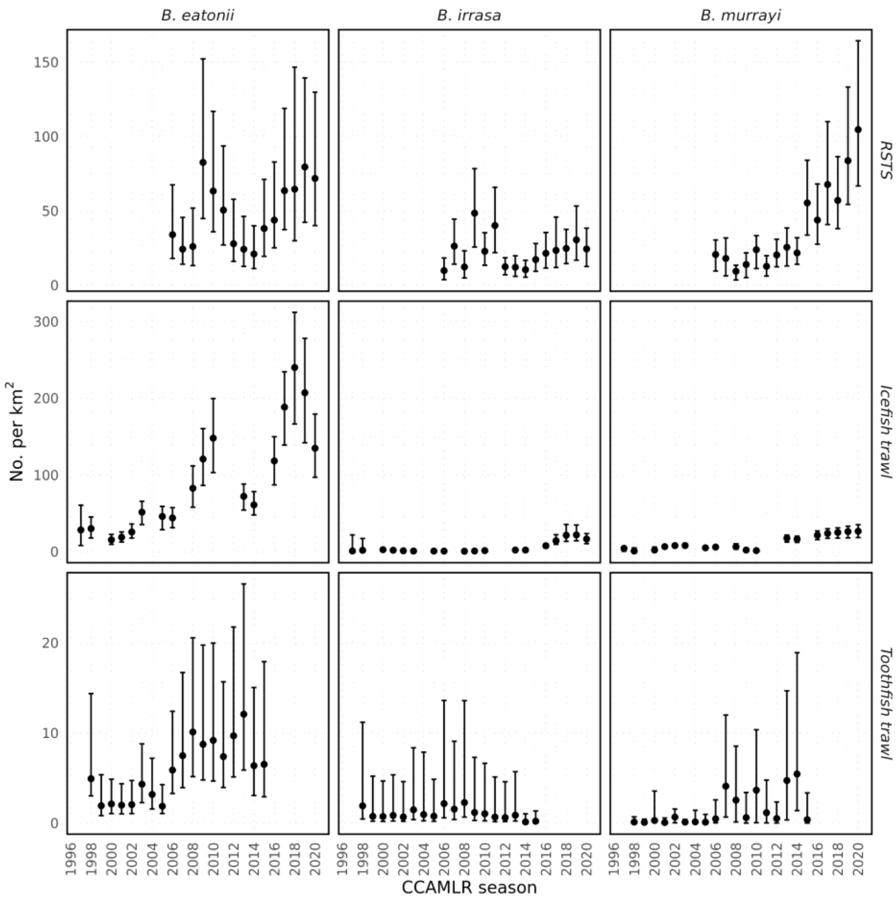



**Figure 11.7:** Annual standardised bycatch rates using a Generalised Additive Model (GAM) for skate (*Bathyraja* spp.) between 1997 and 2020 in the random stratified trawl survey (RSTS), Mackerel Icefish (*Champsocephalus gunnari*) trawl fishery and the Patagonian Toothfish (*Dissostichus eleginoides*) trawl fishery at HIMI.

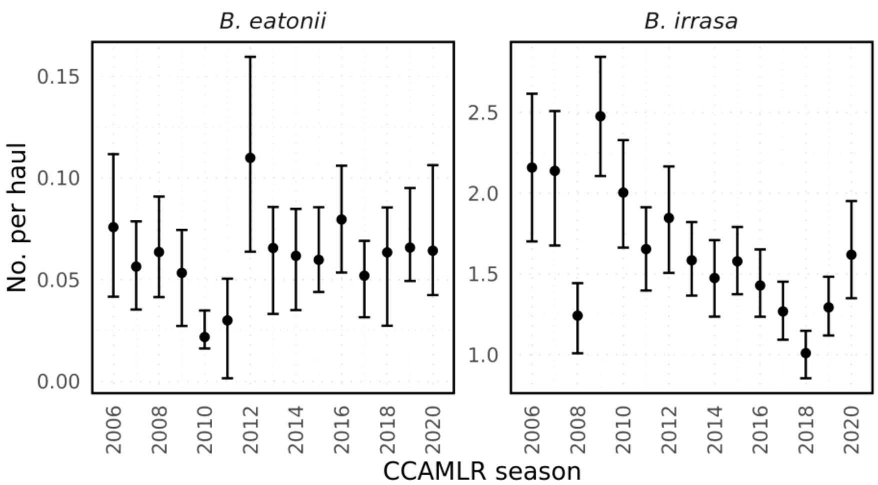



**Figure 11.8:** Annual standardised bycatch rates using a Generalised Additive Model (GAM) for skate (*Bathyraja* spp.) between 2006 and 2020 in the Patagonian Toothfish (*Dissostichus eleginoides*) longline fishery at HIMI.

**Table 11.4:** Details of the Generalised Additive Models (GAM) used to standardised bycatch rates for skate (*Bathyraja* spp.) between 1997 and 2020 for the annual random stratified trawl survey (RSTS), and the Mackerel Icefish (*Champsocephalus gunnari*) and Patagonian Toothfish (*Dissostichus eleginoides*) fisheries at HIMI.

| Species | Fishery | Model | Component | AIC | n | adjusted $r^2$ | Deviance explained (%) | Covariates | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | CCAMLR Season | Longitude, latitude | Depth | Vessel | Month | Target catch weight* |
| *B. eatonii* | RSTS | Poisson | Count | 8841 | 2356 | 0.27 | 42.66 | ● | ● | ● | | | ● |
| | | | Binary | | | 0.36 | 31.43 | ● | ● | ● | | | |
| | Icefish trawl | Negative binomial | Count | 18999 | 2085 | 0.18 | 34.27 | ● | | | | ● | ● |
| | | | Binary | | | 0.29 | 42.82 | ● | | | | | ● |
| | Toothfish trawl | Negative binomial | Count | 36328 | 12191 | 0.08 | 29.35 | ● | ● | ● | ● | ● | ● |
| | | | Binary | | | 0.85 | 83.9 | ● | ● | | ● | ● | ● |
| | Toothfish longline | Negative binomial | Count | 42356 | 12986 | 0.23 | 60.34 | ● | ● | ● | ● | ● | ● |
| | | | Binary | | | 0.88 | 86.18 | ● | ● | ● | | ● | |
| *B. murrayi* | RSTS | Poisson | Count | 7691 | 2356 | 0.29 | 41.85 | ● | ● | ● | | | |
| | | | Binary | | | 0.35 | 29.83 | ● | ● | ● | | | |
| | Icefish trawl | Negative binomial | Count | 11345 | 2085 | 0.04 | 19.2 | ● | | | | | ● |
| | | | Binary | | | 0.55 | 52.39 | ● | | | | | ● |
| | Toothfish trawl | Negative binomial | Count | 28811 | 12191 | 0.36 | 45.06 | ● | ● | ● | | ● | |
| | | | Binary | | | 0.86 | 81.56 | ● | ● | | ● | ● | |
| *B. irrasa* | RSTS | Poisson | Count | 4488 | 2356 | 0.54 | 42.17 | ● | ● | ● | | | ● |
| | | | Binary | | | 0.23 | 19.38 | ● | ● | ● | | | |
| | Icefish trawl | Negative binomial | Count | 7149 | 2085 | 0.16 | 44.38 | ● | | | | ● | ● |
| | | | Binary | | | 0.57 | 59.86 | ● | | | | | ● |
| | Toothfish trawl | Poisson | Count | 11108 | 12191 | 0.31 | 30.89 | ● | ● | ● | ● | ● | ● |
| | | | Binary | | | 0.39 | 37.69 | ● | ● | ● | ● | ● | |
| | Toothfish longline | Negative binomial | Count | 90337 | 12986 | 0.30 | 33.85 | ● | ● | ● | ● | ● | ● |
| | | | Binary | | | 0.56 | 56.95 | ● | ● | ● | | ● | ● |

*log transformed

## Skate tagging

A total of 24 215 skates have been tagged at HIMI between 2001 and 2020. Of those, 252 *B. eatonii*, 196 *B. irrasa* and 9 *B. murrayi* have been recaptured, representing an overall recapture rate of 1.9%. For both *B. eatonii* and *B. murrayi* the Kernel Density Estimation (KDE) depicting 10% core recaptures and releases falls within the same region to the east of Heard Island (Figure 11.9). For *B. irrasa*, the 10% KDE polygons for core release and recapture areas overlap, but show a different distribution with the core area for releases to the south-east of the core area for recaptures. The geographical extent of all 10% KDE polygons for core release and recapture areas for each species comprises the bounding box for a proposed skate tagging area (Figure 11.10). The depth distribution of releases reflects that of recaptures for *B. eatonii*, whereas for *B. irrasa* tags are less likely to be recaptured in waters deeper than 1400 m (Figure 11.11).

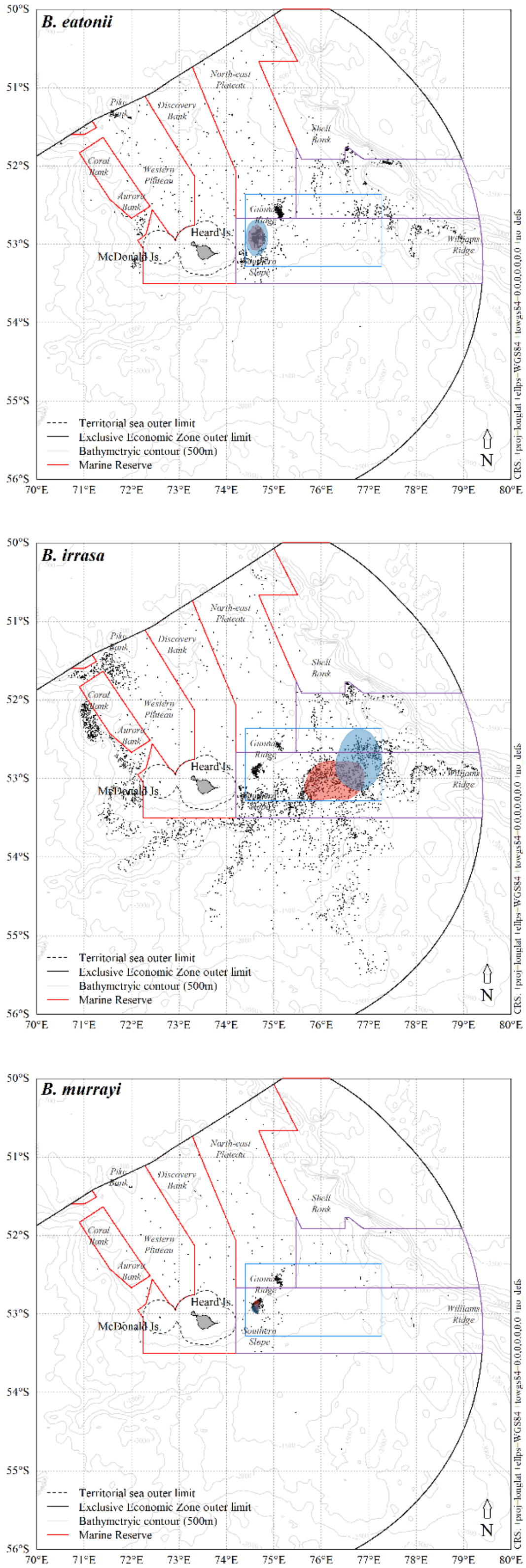



**Figure 11.9:** Core (10% kernel utilization distribution) tag release (red) and recapture (blue) locations for skate (*Bathyraja* spp.) at HIMI.

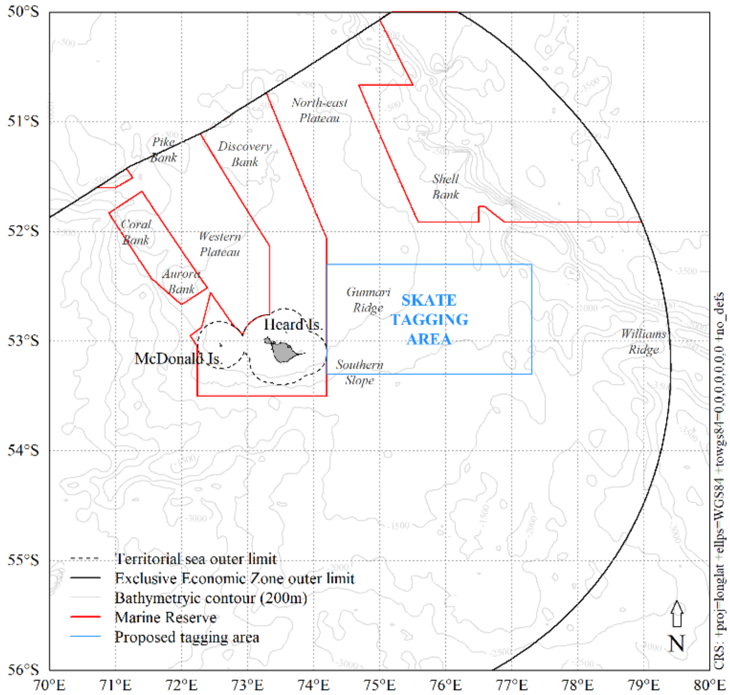



**Figure 11.10:** Proposed skate (*Bathyraja* spp.) tagging area (bounding box: xmin = 74.20455, xmax = 77.3, ymin = -53.3, ymax = -52.3) at HIMI.

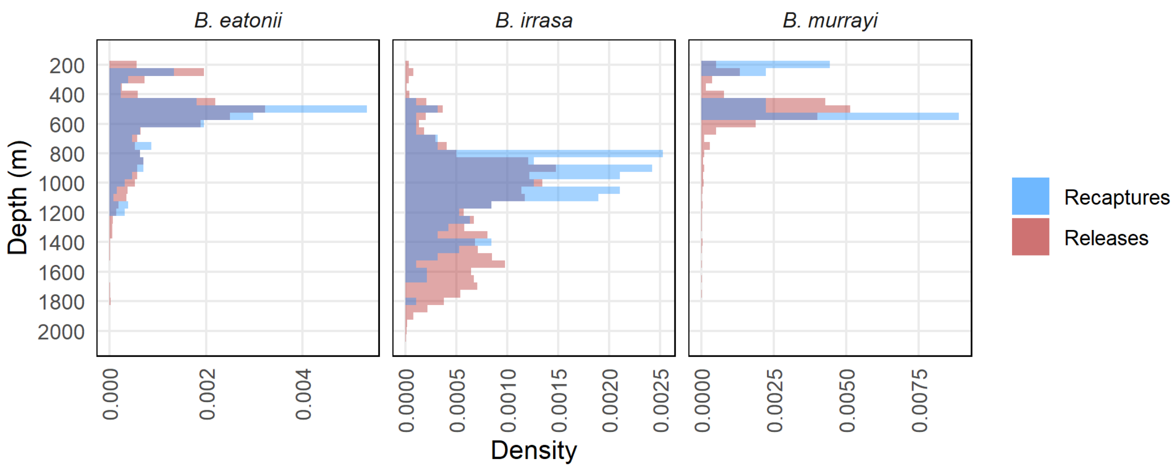



**Figure 11.11:** Skate (*Bathyraja* spp.) tag releases and recaptures by depth strata at HIMI.

## Projection model parameters

*Growth (age-at-length)*

The derived von Bertalanffy growth parameters from Wong et al. (2021) and Verdouw and Hutchins (2009) for each species indicate that *B. murrayi* exhibits the fastest and *B. irrasa* the slowest growth (Figure 11.12, Table 11.5). For *B. eatonii* and *B. irrasa* the growth function parameters derived by Wong et al. (2021) were faster than those determined by Verdouw and Hutchins (2009) and from ecologically similar species. Growth parameters used in the previous bycatch assessment for skates at HIMI (Constable et al. 1998) showed slightly lower $L_\infty$ for *B. irrasa* and *B. eatonii*, but vastly higher $L_\infty$ for *B. murrayi*. The skate species *B. griseocauda*, *Raja rhina* and *B. kincaidii* were selected as ecologically similar species for comparison due to similarities in latitudinal and depth distribution, total length and maximum age.

**Table 11.5:** Von Bertalanffy growth parameters for aged skates at HIMI from Wong et al. (2021) and unpublished data from Verdouw and Hutchins (2009), compared to growth of ecologically similar species, and growth parameters used by Constable et al. (1998).

| Species | | $L_\infty$ | $K$ | $t_0$ | Reference |
|---|---|---|---|---|---|
| ***B. eatonii*** | | 1269 | 0.079 | -0.93 | Verdouw & Hutchins, 2009 |
| | | 879 | 0.5 | -0.77 | Wong et al. (2021) |
| | *B. griseocauda* | 1669 | 0.064 | -0.61 | Bücker (2006) |
| ***B. irrasa*** | | 1381 | 0.133 | 2.2 | Verdouw & Hutchins, 2009 |
| | | 1329 | 0.175 | -1.45 | Wong et al. (2021) |
| | *R. rhina* | 2039 | 0.04 | -1.868 | Gburski et al. (2007) |
| ***B. murrayi*** | | 682 | 0.076 | -2.22 | Verdouw & Hutchins, 2009 |
| | | 544 | 0.206 | -0.39 | Wong et al. (2021) |
| | *B. kincaidii* | 558 | 0.21 | -2.1 | Perez et al. (2011) |
| ***Bathyraja spp.*** | | 1050 | 0.215 | 0 | Constable et al. (1998) |

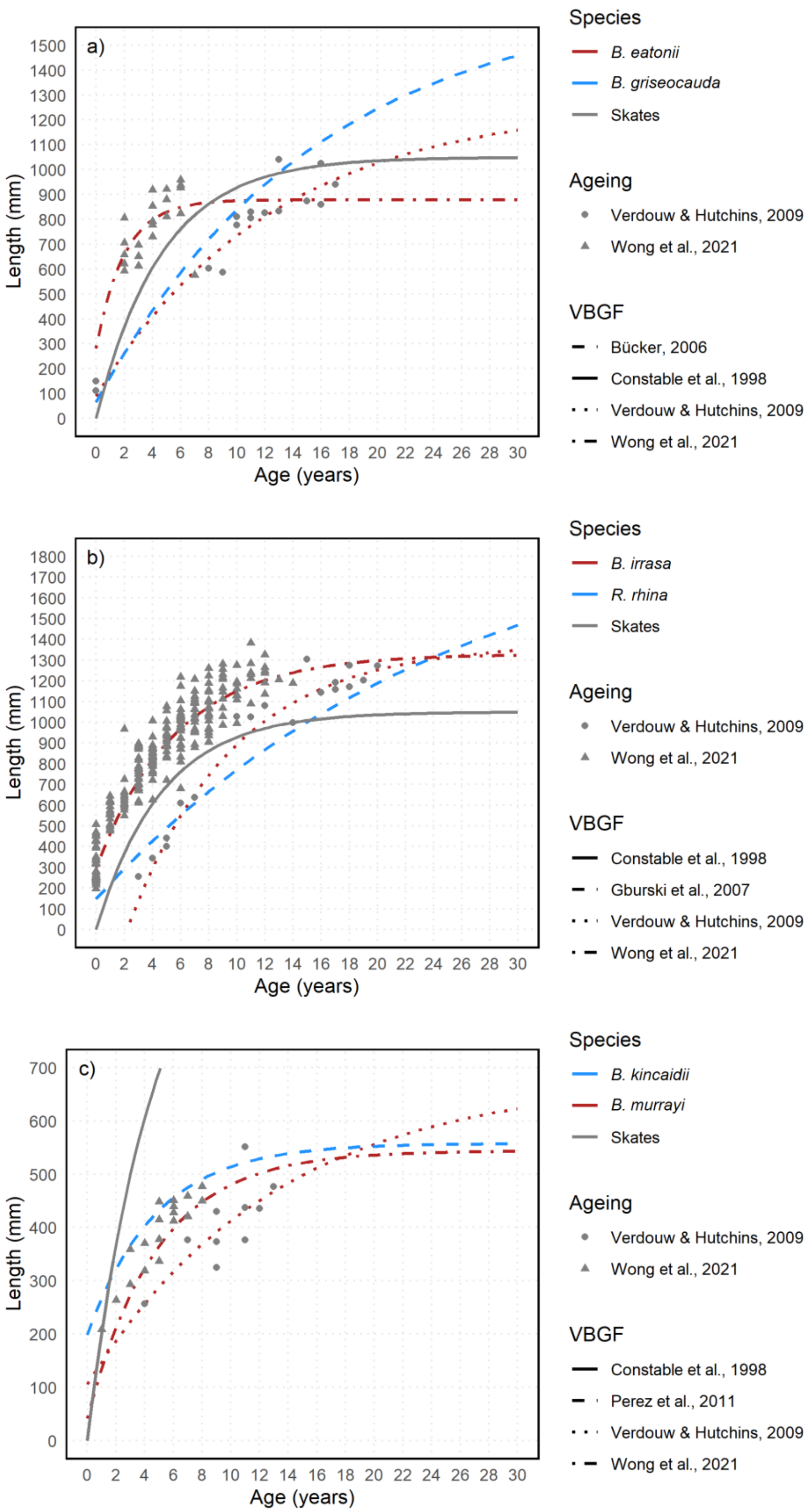



**Figure 11.12:** Von Bertalanffy growth functions for aged skates at HIMI from Wong et al. (2021) and unpublished data from Verdouw and Hutchins (2009), compared to growth of ecologically similar species and the function used by Constable et al. (1998).

*Weight-at-length*

A total of 146 038 skates were measured for length and weight during the RSTS and commercial trawl longline operations since 1997. The calculated weight-at-length relationship for *B. eatonii* and *B. irrasa* were similar to the previous skate bycatch assessment by Constable et al. (1998) (Table 11.6, Figure 11.13). However, the results for *B. murrayi* showed individuals are smaller and lighter than assumed by Constable et al. (1998).

**Table 11.6:** Estimated weight-at-length parameters for skate (*Bathyraja* spp.) fitted to data from the annual RSTS and commercial trawl and longline fisheries at HIMI, and parameters estimated by Constable et al. (1998).

| Species | Sex | n | *a* | *b* | $r^2$ | Reference |
|---|---|---|---|---|---|---|
| *B. eatonii* | | 53220 | 1.75 E-9 | 3.19 | 0.98 | This study |
| | F | 25605 | 1.70 E-9 | 3.20 | 0.98 | |
| | M | 25996 | 1.76 E-9 | 3.19 | 0.98 | |
| *B. irrasa* | | 67789 | 3.13 E-9 | 3.11 | 0.98 | This study |
| | F | 37064 | 2.16 E-9 | 3.17 | 0.99 | |
| | M | 29832 | 6.02 E-9 | 3.01 | 0.98 | |
| *B. murrayi* | | 25029 | 5.43 E-9 | 3.04 | 0.96 | This study |
| | F | 11954 | 3.76 E-9 | 3.10 | 0.96 | |
| | M | 11847 | 6.41 E-9 | 3.00 | 0.97 | |
| *Bathyraja* spp. | | 246 | 1.47 E-10 | 3.24 | 0.97 | Constable et al. (1998) |

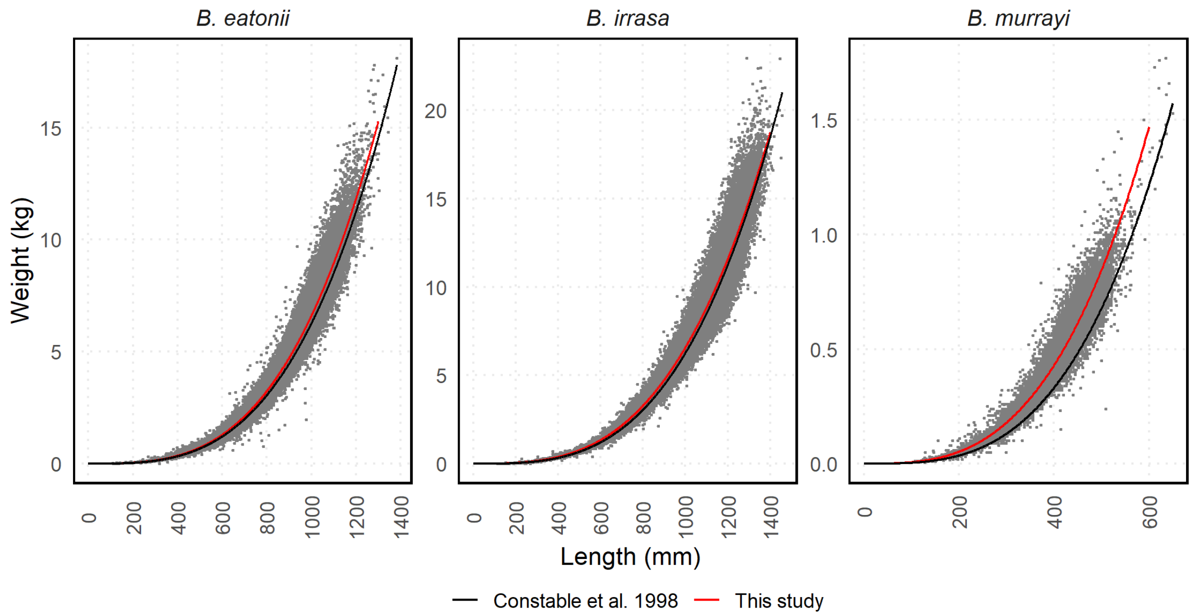



**Figure 11.13:** Estimated weight-at-length functions for skate (*Bathyraja* spp., red lines) fitted to data from the annual RSTS and commercial trawl and longline fisheries at HIMI, and function estimated by Constable et al. (1998, black lines).

*Maturity*

Length-at-maturity was estimated using a dataset consisting of 62 720 individuals (19 186 *B. eatonii*; 37 612 *B. irrasa*; 5 922 *B. murrayi*). Females were found to mature at greater lengths compared to males across all three species (Table 11.7, Figure 11.14). Amongst the three species, *B. irrasa* showed the largest $L_{50}$ of 1119 mm and *B. murrayi* the smallest of 461 mm.

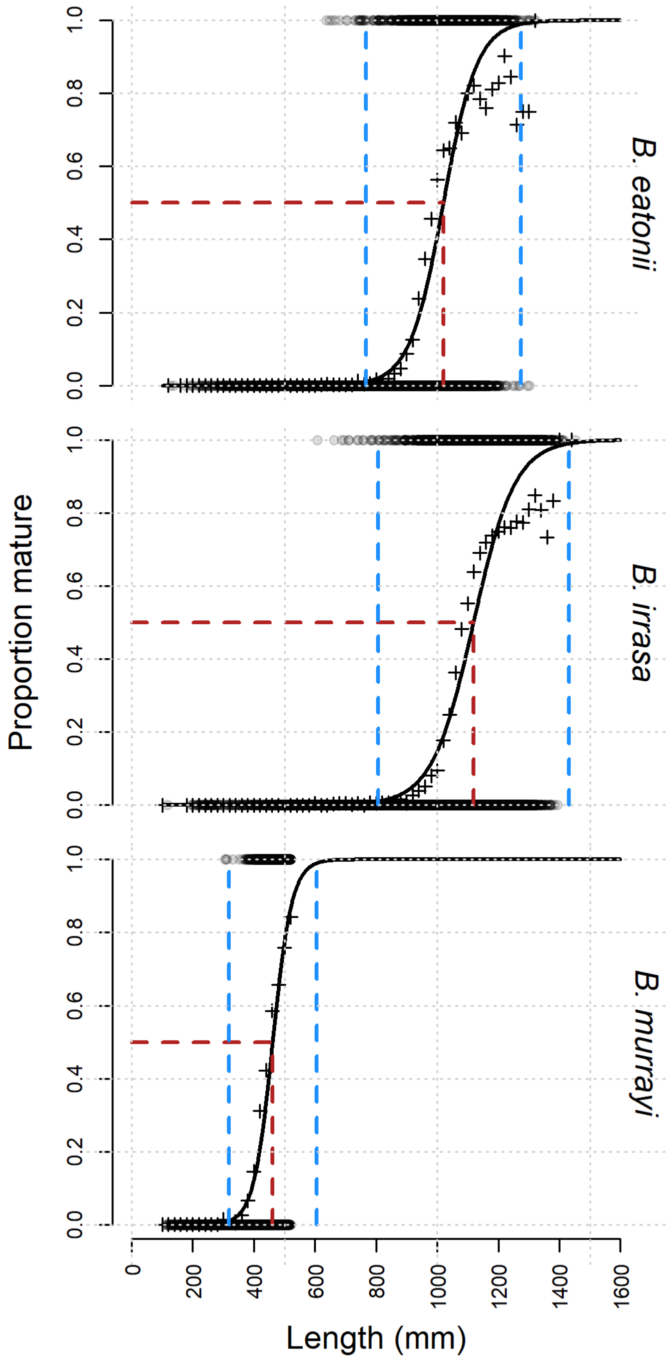



**Figure 11.14:** Estimated length-at-maturity ogives for skate (*Bathyraja* spp.) at HIMI. Red lines correspond to $L_{50}$, the length at which 50% of the sampled population was mature, while blue lines correspond to the range of lengths over which individuals reach maturity. Black points represent raw data (0 = immature, 1 = mature).

**Table 11.7:** Estimated length-at-maturity parameters for skate (Bathyraja spp.) at HIMI. $L_{50}$ and $L_{90}$ are the lengths at which 50% and 90% of the sampled population was mature.

| Species | Sex | $L_{50}$ | $L_{90}$ |
|---|---|---|---|
| *B. irrasa* | Combined | 1119.0 | 1268.0 |
| | Male | 1095.5 | 1213.8 |
| | Female | 1165.4 | 1326.9 |
| *B. eatonii* | Combined | 1020.4 | 1141.3 |
| | Male | 997.3 | 1100.1 |
| | Female | 1084.5 | 1226.7 |
| *B. murrayi* | Combined | 461.4 | 528.6 |
| | Male | 455.3 | 519.2 |
| | Female | 485.8 | 582.9 |

*Recruitment*

Annual age class densities for each species from the random stratified trawl survey (RSTS) were determined as annual recruitment input parameters for the GYM assessment (Figure 11.15).

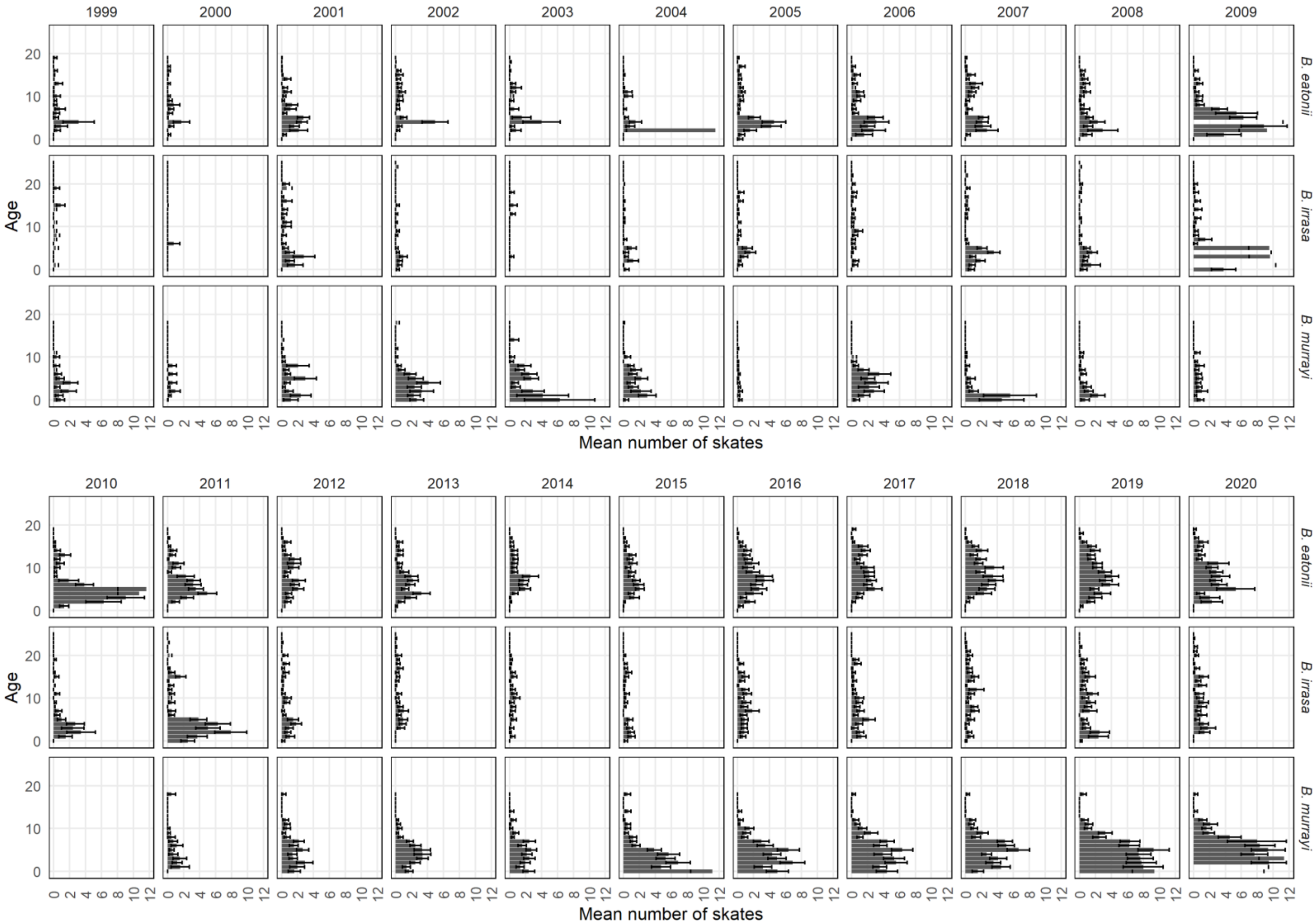



**Figure 11.15:** Annual age class density transformed from length class for skate (*Bathyraja* spp.) from the random stratified trawl survey (RSTS) at HIMI.

*Fishing selectivity*

No reliable information was available on how the three skate species were selected by the RSTS, and trawl and longline fisheries. An empirical cumulative density function was used to approximate the range of lengths between zero and full fishing selection. In the base case ('lower' scenario), an initial peak in the length distributions (even if minor) after which the distribution attenuates was used to define the upper limit of the range. For *B. eatonii,* this range was between 170 mm and 460 mm*,* for *B. irrasa* between 204 mm and 940 mm, and for *B. murrayi* between 120mm to 330 mm (Figure 11.16). In an alternative ('higher') scenario, full selectivity was considered to occur (at the lower end of) an absolute peak in the length frequency distributions.

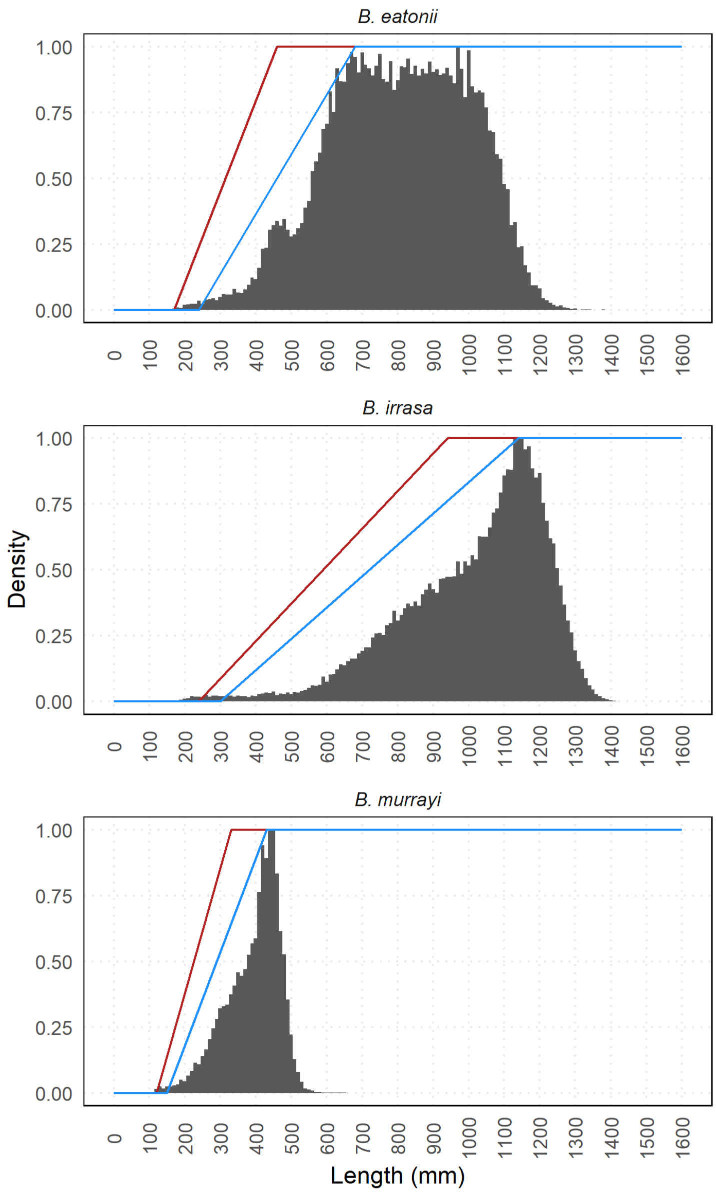



**Figure 11.16:** Length-frequency distributions of skate (*Bathyraja* spp.) caught between 1997 and 2020 in the RSTS and commercial trawl and longline fisheries at HIMI, and estimated lower (red) and higher (blue) fishing selectivities.

**Survey biomass**

All three *Bathyraja* species have shown an increasing trend in biomass estimates from the RSTS between 1999 and 2020 (Figure 11.17). For *B. murrayi* the highest catches in this period occurred in 2020, with a strong upward trend after many years of relatively low estimated biomass. For *B. irrasa*, the RSTS overlaps only with the shallow part in less than 1000 m depth of the species distribution and does not reflect the deeper habitat where this species is primarily found. Therefore, the annual biomass estimates are likely to underestimate the true population biomass.

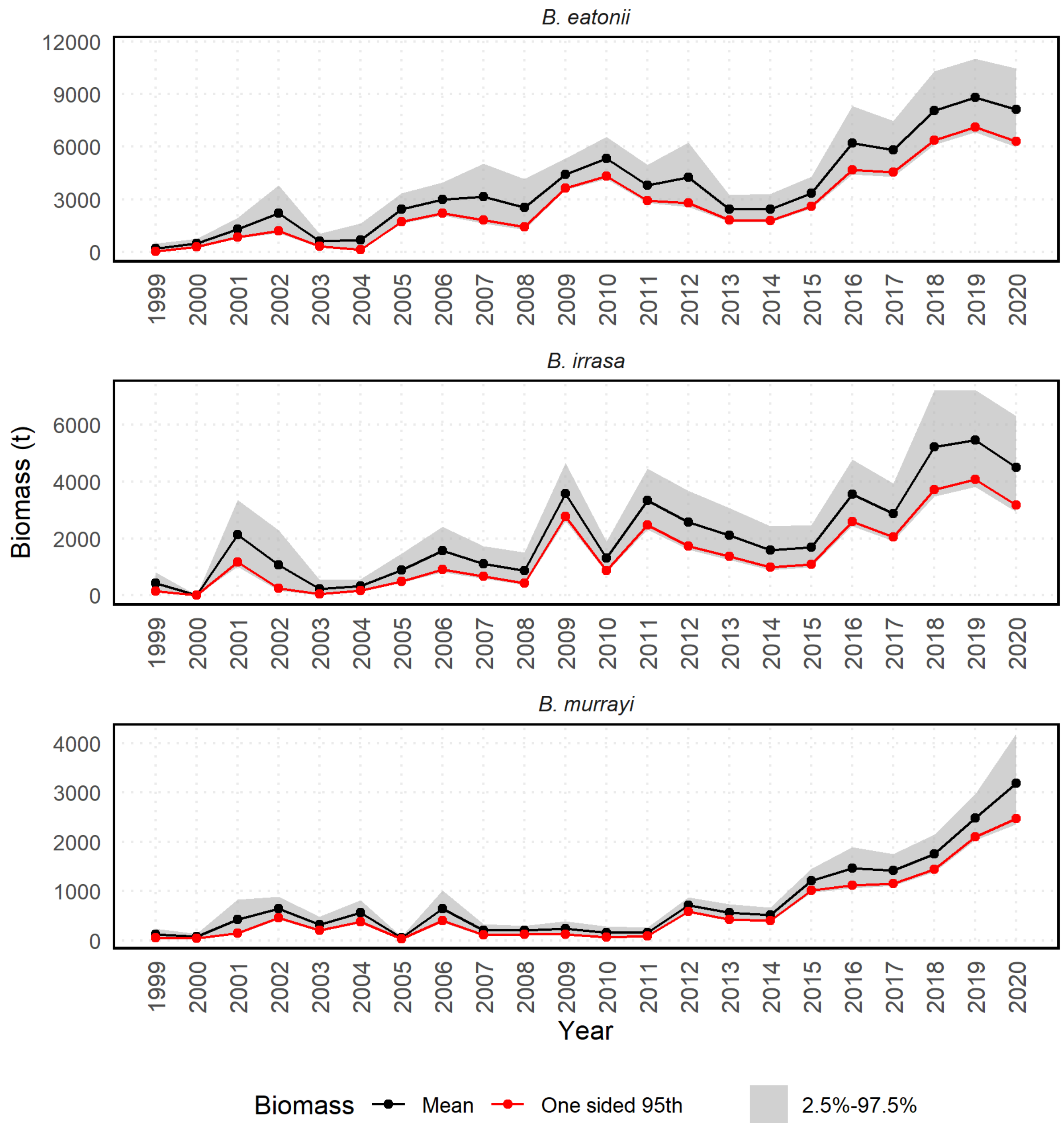



**Figure 11.17:** Estimated biomass for skate (*Bathyraja* spp.) caught between 1999 and 2020 in the random stratified trawl survey (RSTS) at HIMI.

**Precautionary yield**

Based on the different scenarios of life history and fisheries input parameters for the GYM assessment, the proportion of the fish population that can be removed *(*γ) for *B. eatonii* and *B. murrayi* ranged between 0.015 - 0.025 and 0.018-0.029, respectively (Table 11.8). For these two species, the mean projected SSB did not drop below 75% of $SSB_0$ and the depletion probability was 0 or close to 0 (Figure 11.18 and 11.20). In contrast, maximum *γ* for *B. irrasa* was 0.022 however five of the sixteen scenarios resulted in a high depletion probability even when *γ* was zero, with the mean projected *SSB* dropping below 75% of $SSB_0$ and more than 10% of the 10 000 population trajectories falling below 20% of $SSB_0$ (Figure 11.19). The five scenarios that failed to meet CCAMLR requirements represented models with slower growth, later recruitment and 50% and 100% post-release mortality. Particularly the scenarios with a higher assumed fishing-induced mortality, i.e. assuming that only a proportion or none of the released skates would survive, are concerning and require further investigation.

The long-term precautionary yield was calculated by multiplying the proportion of the fish population that can be removed (*γ*) with the average estimated biomass from the RSTS between 2010 and 2020. The results suggested that the long-term precautionary yield, when the three skate species were combined, ranged between 106 t and 234 t (Table 11.8).

**Table 11.8:** Results of the assessments using the Generalised Yield Model (GYM) to estimate the proportion of the fish population that can be removed (Gamma γ), the probability of depletion, and associated precautionary yields (when γ is multiplied with the average estimated biomass from the RSTS between 2010 and 2020) for skate (*Bathyraja* spp.) at HIMI.

| | | **Gamma (γ)** | | | **Probability of depletion** | | | **Precautionary yield (tonnes)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Description** | ***B. eatonni*** | ***B. irrasa*** | ***B. murrayi*** | ***B. eatonni*** | ***B. irrasa*** | ***B. murrayi*** | ***B. eatonni*** | ***B. irrasa*** | ***B. murrayi*** | **Total** |
| **Base** | Growth: Comparative species | 0.016 | 0.015 | 0.025 | 0 | 0 | 0 | 85 | 47 | 31 | 163 |
| **2** | Age structure | 0.020 | 0.020 | 0.029 | 0 | 0.003 | 0 | 107 | 62 | 36 | 205 |
| **3** | Growth: Wong et al. 2021 | 0.025 | 0.022 | 0.027 | 0 | 0 | 0 | 133 | 68 | 33 | 234 |
| **4** | Growth: Verdouw & Hutchins 2009 | 0.015 | 0.018 | 0.018 | 0 | 0 | 0 | 78 | 55 | 22 | 155 |
| **5** | Slow growth | 0.015 | 0 | 0.025 | 0 | 0.132 | 0 | 82 | 0 | 31 | 113 |
| **6** | Fast growth | 0.017 | 0.016 | 0.026 | 0 | 0 | 0 | 89 | 51 | 32 | 172 |
| **7** | Low mortality | 0.017 | 0.018 | 0.021 | 0 | 0 | 0 | 89 | 57 | 26 | 172 |
| **8** | High mortality | 0.016 | 0.014 | 0.029 | 0 | 0.002 | 0 | 88 | 43 | 36 | 167 |
| **9** | Recruitment age 3 | 0.016 | 0.015 | 0.026 | 0 | 0 | 0 | 86 | 47 | 32 | 165 |
| **10** | Recruitment age 4 | 0.016 | 0 | 0.026 | 0 | 0.253 | 0 | 85 | 0 | 32 | 117 |
| **11** | Recruitment age 5 | 0.016 | 0 | 0.026 | 0 | 0.466 | 0.001 | 84 | 0 | 32 | 116 |
| **12** | Recruitment ages 2-5 | 0.018 | 0.015 | 0.025 | 0 | 0 | 0 | 96 | 48 | 31 | 175 |
| **13** | Higher selectivity | 0.017 | 0.015 | 0.026 | 0 | 0 | 0 | 91 | 47 | 33 | 171 |
| **14** | +50% released bycatch | 0.016 | 0 | 0.026 | 0 | 0.670 | 0 | 83 | 0 | 31 | 114 |
| **15** | +100% released bycatch | 0.014 | 0 | 0.025 | 0 | 0.958 | 0 | 75 | 0 | 31 | 106 |
| **16** | 30-year projection | 0.016 | 0.016 | 0.023 | 0 | 0.003 | 0 | 85 | 48 | 29 | 162 |

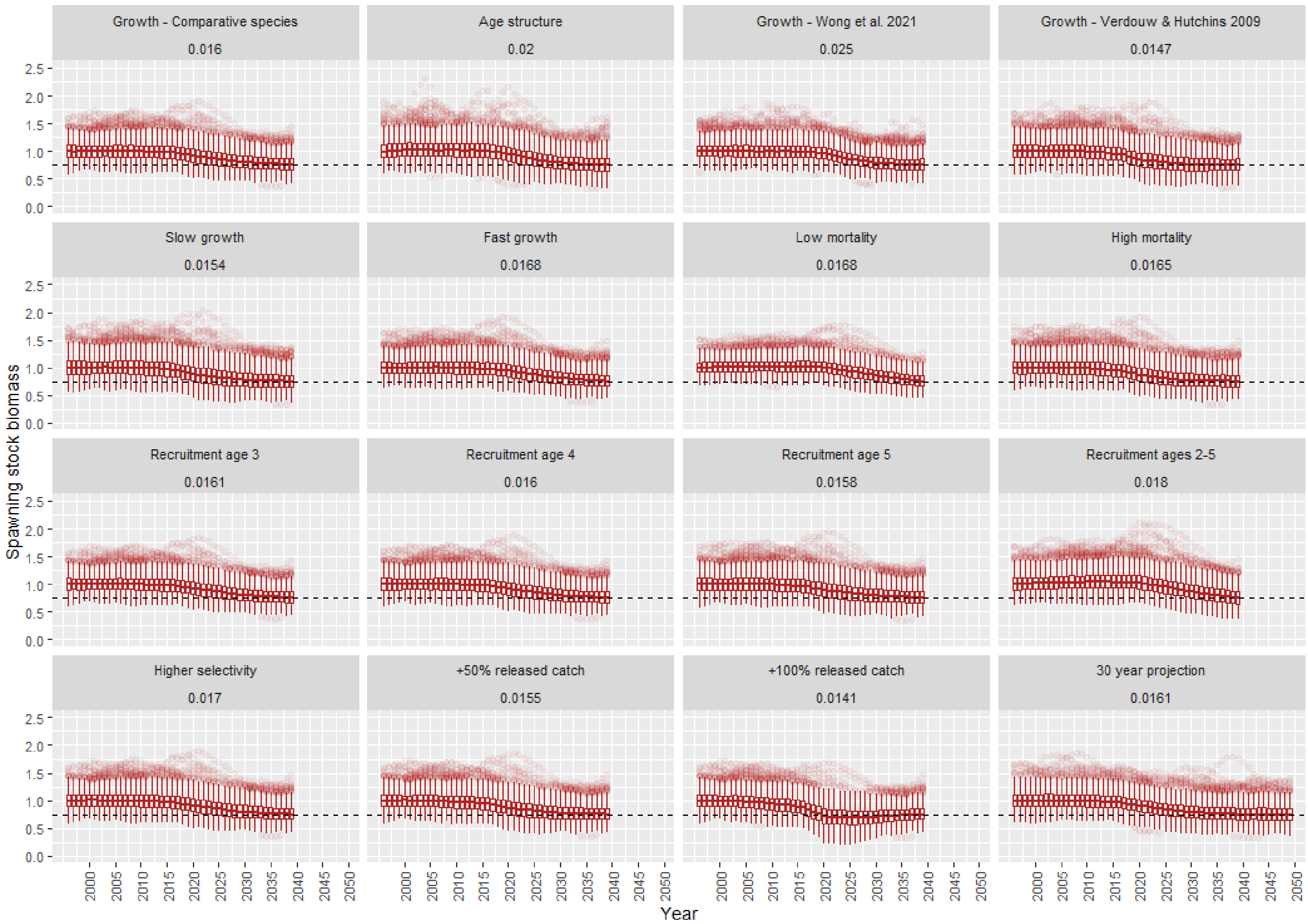



**Figure 11.18.** Spawning stock biomass projections using the GYM for different assessment scenarios (see Tables 11.1 and 11.2) for *Bathyraja eatonii* at HIMI.


**Figure 11.19.** Spawning stock biomass projections using the GYM for different assessment scenarios (see Tables 11.1 and 11.2) for *Bathyraja irrasa* at HIMI.

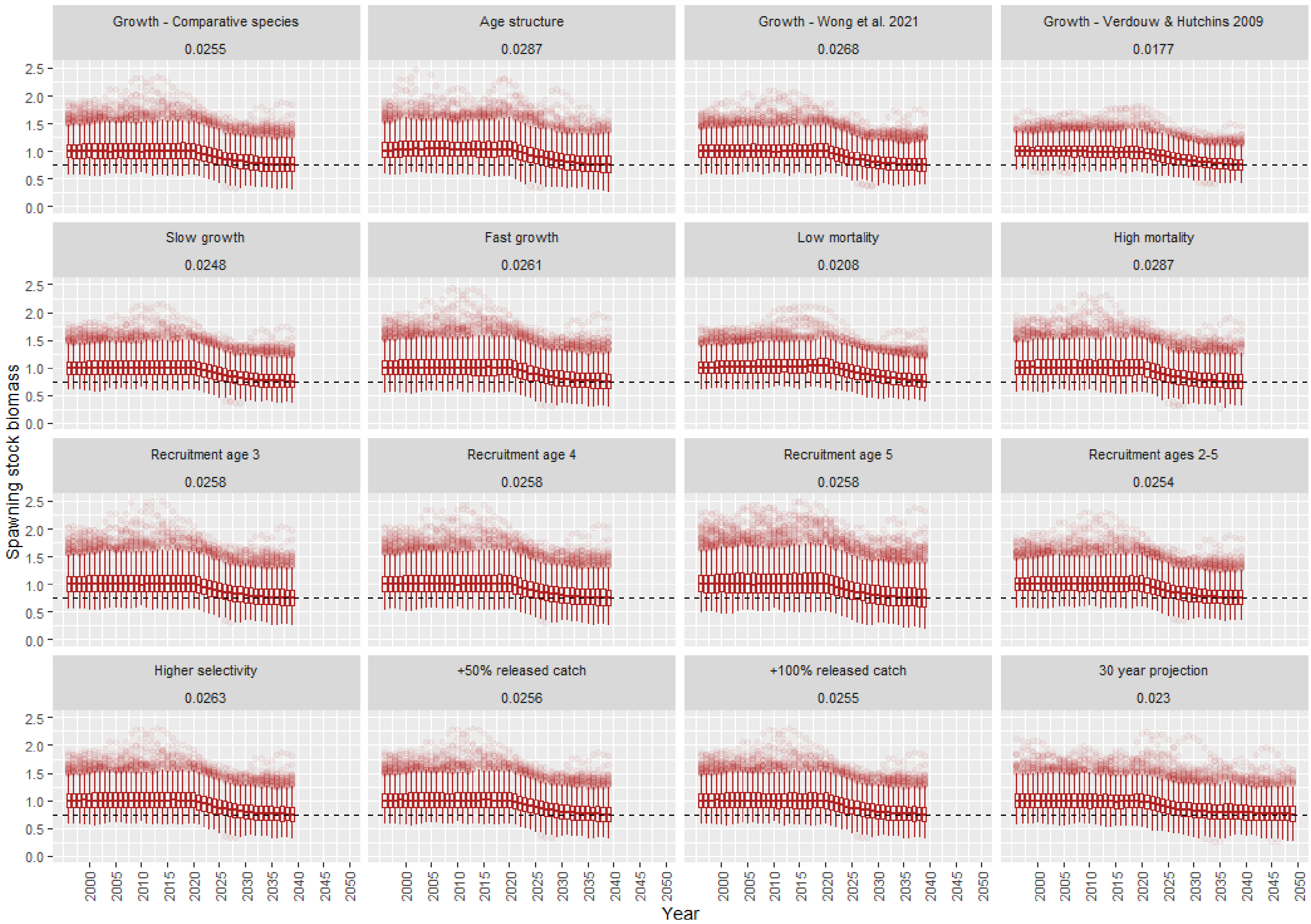



**Figure 11.20.** Spawning stock biomass projections using the GYM for different assessment scenarios (see Tables 11.1 and 11.2) for *Bathyraja murrayi* at HIMI.

## 11.4 Discussion

Here, we present the first species-specific bycatch history and preliminary bycatch assessment for three species of skates (*Bathyraja* spp.) caught in fisheries operating in the HIMI region (CCAMLR Division 58.5.2).

The assessment of historical total skate bycatch identified large annual catches of *B. eatonii* in the Icefish trawl fishery and *B. irrasa* in the Toothfish longline fishery in recent years (2013-2020). In the longline fishery, the annual total bycatch was based on the data from the scaled observer partial counts multiplied by the average weight of each species.

While the observer counts encompass a considerable proportion (~45%) of the total haul, the scaling process is not immune to sampling biases. If skates are clustered along the line and captured in the observer partial count, then total skate bycatch can be overestimated. Conversely, if clusters are missed in the count, an underestimate of total skate bycatch could result. Anecdotal evidence from scientific observers working in the Kerguelen Toothfish fishery within the French EEZ suggests that *B. eatonii* is more likely to exhibit clustering along the line compared to *B. irrasa,* however this is yet to be fully quantified (Pers. Comm. C. Péron 2020).

Furthermore, a deviation of observer sampling (species identification, weights and measurements) of skates from random sampling may introduce bias into the scaling of the observer partial counts. Considering that *B. irrasa*, the largest species, is the predominant species caught in the Toothfish longline fishery, a tendency to over-selecti other species with typically smaller individuals for ease of handling may reduce the average weight of skates in a haul and decrease the scaled total bycatch estimates. On the other hand, depth of capture and size of the skate may influence its post-capture condition (Knotek et al. 2018), where larger *B. irrasa* may be more likely to be in poorer condition and retained than the other species. Therefore, if retention and subsequent sampling of skates favours individuals in poor condition, then the average weight of skates in a haul may be biased high and increase the scaled total bycatch estimates.

In addition, skates are mostly classified to the taxonomic level of order (Rajiformes) only in the observer partial counts. Following Nowara et al. (2017), the proportion of species caught in all hauls in a 1.0 x 0.5 degree block for a year was used to split the skate counts to species level. The predominance of *B. irrasa* in the annual bycatch may smooth the presence of *B. eatonii* and *B. murrayi* caught in longline hauls and thus increase the average weight of skates in the haul. The effect of this potential biases in observer counts could be reduced by increasing the number of skates sampled on each haul and identifying skates to species level in the observer partial counts.

Currently there is no evidence to indicate observer sampling is non-random, however these scenarios highlight the importance of random sampling of skates that are to be weighed and measured. In this study, the total bycatch from the scaled observer partial counts reflects a very high standard of observer coverage (~45%) compared to other domestic fisheries (~10%).

It is expected that the proportion of retained skate bycatch of total skate bycatch should show minor variability over the duration of the fishery as the decision to retain a skate is based on its condition measured against the CCAMLR Skate Condition guidelines. Fluctuations in the annual proportion of retained skate bycatch may relate to changes in fishing depth or changes in the composition of skate species caught influencing the condition assessed at the roller or on the trawl deck. With a recent and considerable decline in the proportion of skates retained in the Toothfish longline fishery, it is imperative that further research is directed towards a better understanding of the environmental or social drivers that influence the proportion of retained skate bycatch.

In this study we estimated standardised bycatch rates for skates caught at HIMI similar to Nowara et al. (2017). The standardised bycatch rates modelled for the RSTS corroborate the recent increasing trend in biomass estimates on the Kerguelen Plateau. The recent (2017-2020) increase in population biomass seen in the RSTS may be a contributing factor to the observed increase in standardised bycatch rates of *B. eatonii* in the Icefish trawl fishery. However, the mechanisms driving the decline (2009-2018) in standardised bycatch rates for *B. irrasa* caught in the Toothfish longline fishery is unclear, with an opposing trend observed in the biomass estimates.

The current tag recapture rates for all three species of skate are very low. For *B. irrasa*, the depth distribution of releases does not correspond to the depth of recaptures, and very few tags from *B. irrasa* are recaptured in waters deeper than 1600 m. Depth of capture is a known predictor of post-release survival for other species of skates (Knotek et al., 2018). However, to investigate whether the skates caught in deeper waters of the HIMI region have lower survival, a post-release survival study using satellite pop-up tags is required.

In the past, tags have been released across the whole HIMI region. Our results show that the core areas representing the greatest number of recaptures and releases for each species occurs in an area to the east of Heard Island. We propose a new tagging area to concentrate tagging effort and improve recapture probability. This new area includes both plateau and slope habitats across a wide depth range and has been subject to considerable fishing effort over the last ten years, therefore it is expected that this area will encompass the primary habitat for all three skate species and maintain good fishing effort into the future.

By combining multiple sources of data on *B. eatonii, B. irrasa* and *B. murrayi,* we established reliable input parameters to construct species-specific population projection models. This comprehensive bycatch assessment represents an advancement on the previous assessment by integrating biological data collected during fishing operations, new ageing data, scenarios of fishing mortality, and other life-history information based on a literature review of deep-water, high latitude skates.

The growth function derived from the ageing study by Wong et al. (2021) shows faster growth for *B. eatonii* and *B. irrasa* than that predicted by Verdouw and Hutchins (2009) and those from an ecologically similar species, whereas the results for *B. murrayi* were more consistent across studies. However, the sample sizes for both *B. eatonii* and *B. murrayi* were very small in this study, and the small number of *B. eatonii* aged represented only a narrow range of total lengths. Accurately estimating age from elasmobranch vertebrae is inherently challenging due to the vertebrae structure and deposition of growth layers. However, accurate growth estimates are essential as the growth input parameter can have a significant effect on the precautionary yield estimates from the population projection model. To derive accurate growth estimates for *B. eatonii* and *B. murrayi,* future ageing studies are recommended.

All three skate species have shown an increasing trend in biomass in the RSTS over the last ten years. The main driver of this trend is unclear and further research is required to identify if a recovery from previous illegal fishing operations is being observed or a response in recruitment due to increased productivity on the plateau. Currently, the RSTS encompasses the core habitat of two of the three species. For *B. irrasa*, the length distributions for the RSTS, which covers shallow waters of the plateau (<1000 m), shows highest densities of smaller younger individuals, whereas highest densities of larger and older *B. irrasa* are found in the Toothfish longline fishery which operates in deeper slope waters. Given the distribution of *B. irrasa* reaches into deeper habitats, it is likely that the biomass estimates from the RSTS are not representative of the population biomass. To reduce uncertainty in the modelling, we suggest a multi-fleet stock assessment is undertaken.

All but five scenarios from the population projection models met the criteria of median escapement of the spawning stock at the end of a 20-year projection period of 75% of the pre-exploitation spawning biomass and a lower than 10% probability of depletion below 20% of the median pre-exploitation spawning biomass (Constable et al. 1998). The five scenarios that failed to meet CCAMLR requirements were all for *B. irrasa* and represent models with slower growth, later recruitment and 50% and 100% post-release mortality. The recommended precautionary yield for all species combined ranged from 106 to 234 tonnes and could form the basis for species specific bycatch limits.

For each scenario, the recommended precautionary yield was split between the Icefish fishery and Toothfish fishery. If just the retained catch is considered as a measure of bycatch, we see an almost 50-50 split between the fisheries, except for the five scenarios where the population projection models for *B. irrasa* did not meet the CCAMLR decision rules for escapement and probability of depletion. However, when total catch is considered as the measure of bycatch, the allocated bycatch limit is much lower and generally skewed toward the Toothfish fishery. This is due to the high catches and the low recommended precautionary yield from the population model of *B. irrasa*.

Currently, only retained skates are counted towards fishery removals, but the overall fisheries-induced mortality may be substantially higher due to the high number of skates released after capture and the unknown, but potentially low, post-release survival. Post-release survival becomes increasingly important as the scale of live releases increases. With ~90% of all skate bycatch in the HIMI longline fishery being released alive as per the Skate and Ray Handling Guidelines, it is imperative that post-release survival is quantified to get an accurate estimate of total fishing-induced mortality.

It is expected that the proportion of retained skate bycatch of total skate bycatch should show minor variability over the duration of the fishery as the decision to retain a skate is based on its condition which is measured against the CCAMLR Skate Condition guidelines. Fluctuations in the annual proportion of retained skate bycatch may relate to changes in fishing depth or changes in the composition of skate species caught influencing the condition assessed at the roller or on the trawl deck. With a recent and considerable decline in the proportion of skates retained in the Toothfish longline fishery, further research needs to be directed towards understanding the drivers that influence the proportion of retained skate bycatch, and the CCAMLR Skate Condition guidelines should be reviewed.

## 11.5 Conclusion

By combining multiple data sources for skates (*Bathyraja* spp.) from the HIMI region, we have been able to select plausible life-history and fishing scenarios as input parameters into the GYM population projection model to determine a range of precautionary yields for long-term population viability. Where input parameters could not be determined from available data, we follow a qualitative stepwise approach to obtain quantitative estimates from other species based on taxonomic, ecological and life history similarities. In doing so, this study has provided the first estimates of long-term annual yield for individual skate species observed in the HIMI fisheries and a framework for setting and allocating bycatch limits for data-poor species in the Southern Ocean. Evidence-based and accurate bycatch limits can provide industry the confidence to develop long-term plans to mitigate and avoid skate bycatch in HIMI waters.

# Chapter 12: Standardisation of Antarctic Toothfish catch rates in the Ross Sea exploratory longline fishery

Dale Maschette, Simon Wotherspoon and Philippe Ziegler

**This Chapter is based on:**

Maschette D., Wotherspoon S. and Ziegler P. (2019) Exploration of CPUE standardisation variances in the Ross Sea (Subareas 88.1 and 88.2A South of 70°S) Antarctic Toothfish (*Dissostichus mawsoni*) exploratory longline fishery. Document WG-SAM-2019/25, CCAMLR, Hobart, Australia

## Abstract

Catch rates or catch per unit of effort (CPUE) are used for data-poor exploratory fisheries without integrated assessments in the CPUE by seabed area method to estimate stock biomass in the interim of collecting sufficient tag recaptures. Here, we address the two questions: (1) which unit of effort should be used for catch rates in mixed longline fisheries, and (2) how do different parameters such as gear type, vessel, fishing season, month, bait, fishing depth and area affect estimates of trend and magnitude of catch rates.

Using data from the Ross Sea Antarctic Toothfish fishery, we compared effort units including length of line (km), total number of hooks per line, and a combination of total number of hooks per line for autoline and Spanish line and total number of clusters for trotline (hooks/cluster) with Generalised Linear Models (GLMs). The model with total hook numbers was preferred with the lowest Akaike's Information Criterion (AIC), however standardised catch rates over the fishing season differed little between the models with the three effort units, so the effect of the choice of effort unit on the estimated standardised catch rates is small.

The parameters with the largest effects in the catch rate models were vessel, gear and bait, with vessels showing by far the largest effect size. This confirms previous advice that research fishing is conducted with a high level of spatial and temporal overlap between vessels and gear types to allow for a meaningful standardisation of variables such as catch rates.

To assist in future quality checking of data, we also recommend a new reporting field in the C2 form for the number of droplines per line deployed.


## 12.1 Introduction

Catch rates or catch per unit of effort (CPUE) are used for data-poor exploratory fisheries without integrated assessments in the CPUE by seabed area method to estimate stock biomass (WG-FSA-18 paras. 4.1-4.8) in the interim of collecting other, more robust indicators of stock size such as data based on tag recaptures. Since 2011, CCAMLR has used catch per length of line as catch rate measure in mixed-gear longline fisheries (SC-CAMLR-XXX, para. 5.33). However, the questions about the most appropriate effort unit for CPUE has been raised a number of times, and WG-FSA-17 (para. 4.20) and WG-FSA-18 (para. 4.30) recommended that methods be developed to define appropriate effort measures for longline gear types to calculate catch rates. Additionally, WG-FSA-17 discussed difficulties in standardising CPUE on trotlines by using the number of hooks, making comparison with Spanish longline and autoline problematic (WG-FSA-17, para. 3.65).

WG-FSA-18 also discussed how data from different gear types used in exploratory fisheries can be analysed and summarised. In response to concerns raised as to potential difficulties in post-hoc estimation of the effects of different longline types on results from multi-vessel research (WG-FSA-18, paras. 4.28 and 4.109), WG-FSA-18 noted that a standardisation of a parameter can adjust for, and remove the impact of, confounding factors other than that of interest. It recalled that a number of standardisation methods exist and are used routinely within CCAMLR working groups to control for the potential effects of factors such as gear type, vessel, area and fishing depth that are confounding with the variable of interest (WG-FSA-18, paras. 4.29 and 4.111).

Standardisation methods, particularly Generalized Linear Models (GLMs), Generalised Linear Mixed Models (GLMMs), Generalised Additive Models (GAMs) and Generalised Additive Mixed Models (GAMMs) are used in fisheries worldwide (Maunder & Punt 2004) and have been widely applied to data in CCAMLR Toothfish and krill fisheries. For example, Agnew and Croxall (1999) used GLMs to explore seabird mortality in Patagonian Toothfish (*Dissostichus eleginoides*) fisheries; Gasiukov & Bibik (2000) were among the first to utilize GAMs in CCAMLR whilst exploring drivers of historic Toothfish catch rates around South Georgia and Shag rocks; Dunn and Hanchet (2006) used GLMMs to standardise catch rates of Antarctic Toothfish (*D. mawsoni*) in the Ross Sea; Kasatkina & Gasyukov (2011) and Gasyukov & Kasatkina (2011, 2013) used GLMMs to standardise catch rate indices in the krill fishery in Area 48; Wiff et al. (2013) used GAMs and GAMMs in the Toothfish fishery in Subarea 48.6, Ying et al. (2017) used GAMs in the krill fishery in Subarea 48.1; and Yates et al. (2017) used GAMMs to explore a range of habitat models for *D. mawsoni* in Divisions 58.4.1 and 58.4.2.

Here we address the two questions:

(1) Which unit of effort should be used for catch rates in mixed longline fisheries?

(2) How do different parameters such as gear type, vessel, bait, fishing depth and area affect catch rates?

To address these questions, we use generalised linear models (GLMs) and data from the Antarctic Toothfish fishery in the Ross Sea south of 70°S.

## 12.2 Methods

### Data Selection

This study included fine-scale catch and effort data from CCAMLR. We used data from the Antarctic Toothfish fishery in the Ross Sea (Subareas 88.1 and 88.2A south of 70°S) collected during the seasons 2002/03–2018/19 on 62 commercial fishing vessels from 13 CCAMLR Members. Data from this fishery was chosen as they provided a long-term dataset of multiple gear types each season with large spatial and temporal overlap. This allowed to evaluate both effort units and the effect sizes of the parameters associated with CPUE.

In total, 15,273 longline deployments were conducted with depths ranging from 156 – 2155 m, with a mean of 1080 m. Longline gear types included autoline (66.8% of lines), Spanish longline (19.4%) and trotline (13.8%). Sea ice extent generally limited fishing to the months of December through to March.

Only 10 hauls were conducted within SSRU 88.1G and were on contiguous habitat with SSRU 88.1H so these data were pooled together. Additionally, a small number of hauls were isolated from the main data set east of 18°E and were removed (N = 7). Additionally, data cleaning involved the removal of hauls with a soak time greater than 100 hours (N = 49), soak time less than 6 hours (N = 146), and unusual hook numbers in relation to line length (N = 5). Hauls with missing line length (N = 26), total hooks (N = 67) or catch (N = 92) were also removed from the dataset to create a consistent data set for which the results could be compared with the Akaike's information criterion (AIC). A number of discrepancies between calculated hooks and reported hooks were seen in the data and these are discussed in 12.5 Appendix 1. The final data set contained 14 484 hauls with 67%, 19.3% and 13.7% from autoline, Spanish line and trotline respectively.

Three units of effort were investigated:

(1) Length of line (km)
(2) Total number of hooks per line
(3) Total number of hooks per line for autoline and Spanish line and total number of clusters for trotline (henceforth referred to as hooks/clusters).

**Model Fitting and selection**

GLMs are the most common method for standardising catch per unit of effort (CPUE). When some parameters to be modelled include predictors which should be treated as random variables, GLMMs are often used and allow for interactions between for example fishing season and other categorical variables (Maunder and Punt 2004). GAMs and GAMMs are an extension of GLMs and GLMMs and replace the linear predictor with an additive predictor in the form of a smooth function. Additive model types are most commonly used when aiming to explore habitat models which include environmental data, as well as fisheries data, for one or more species and uses the smooth functions to deal with the complexity associated with many non-linear fits.

Here we fitted GLMs to CPUE using R version 3.5.3 with the *stats::glm* function (R Core Team 2018). Models were fitted to reported catch weight assuming a Gamma distribution with a log offset to adjust for effort. Each model fit was assessed using standard models diagnostics, including deviance explained and Pearson's correlation. Models were also fitted with a log-normal distribution but in all cases the Gamma distribution was preferred by model diagnostics and only these results are presented here.

Models were compared using the AIC, where the model with the lowest AIC was considered optimal and models within 2 AIC were considered equivalent (Burnham and Anderson 2002; Whittingham et al. 2006). In order to fit an index of CPUE standardised for fishing effects, we fitted models for each of the three effort measures which adjusted for a number of model parameters; fishing season, month, gear type, vessel, bait, soak time, depth and SSRU. No information was available on skippers which are also likely to influence CPUE given their level of experience in fishing for Toothfish in the region. For each effort measure we used reverse stepwise model selection, removing one parameter at a time and comparing model fits using AIC.

### Assessing the importance of variables

To assess the relative importance of each model parameter, the fraction deviance explained and the Pearson correlation of observed and fitted catch weights were computed for each single-parameter deletion. In order to allow for comparison across the competing measures of effort, the null deviance was calculated excluding the log effort offset, and the fraction deviance explained was calculated as the difference between the deviance and the null deviance as a fraction of the null deviance.

### Effect sizes

For each categorical model parameter, a measure of effect size was computed by calculating the ratio of the maximum and minimum predicted CPUE across the levels of that parameter when all other parameters in the model were held constant. The ratio of maximum and minimum predicted CPUE across vessels was also calculated for the 38 out of 62 vessels that had fished in more than one season to mitigate the potential effect of the low experience of 25 vessels (and maybe skippers) which had fished in only one single season.

### Standardized index of CPUE

A standardized index of CPUE was determined by predicting CPUE for each season from the best fitting model. Model parameters (gear, bait, vessel, month and SSRU) were held at their most common value, with a depth of 1200m and 24hr soak time, for each respective effort unit. A standardized index was produced by scaling the predicted CPUE to unit geometric mean of 1.

## 12.3 Results

### Model fitting and selection

For each unit of effort (line length, total hooks and hooks/clusters), the best fitting model was the model containing all parameters:

Toothfish Catch ~ Bait + Depth + Gear + Month + Season + Soak Time + SSRU + Vessel + offset(log(Effort))

with a log effort offset to ensure catch is proportional to effort.

Fitted parameters for each effort model are shown in Figures 1 – 3 with model fits in 12.6 Appendix 2. The saturated models had the lowest AIC and thus performed best in the reverse stepwise model selection for each effort measure, with the exception of depth in line length models, however the reduction in the AIC was less than 1 and thus the reduced model was assumed equivalent to the saturated model (Table 12.1). Across all three effort measures, removing depth resulted in the closest AIC to the saturated model, conversely the removal of vessel resulted in the worst AIC.

Of the three effort measures fitted, using total hook numbers was the model with the lowest AIC (243 794) when compared to that of hooks/clusters (243 859) and line length (244 128, Table 12.1). The saturated model for total hook numbers also had the highest deviance explained (44.98%) and the highest Pearson correlation (0.589) of any model (Table 12.2).

**Table 12.1:** Model results for the saturated models and reverse stepwise model selections when one parameter was removed at a time for three units of effort (line length (km), number of hooks, and number of hooks/clusters) using generalised linear models fitted to catch and effort data from the Ross Sea Toothfish fishery south of 70°S. Df = Degrees of freedom, Deviance = model deviance reported by R, AIC = Akaike's Information Criterion. For each effort type, bold indicates the model with the lowest AIC or an AIC within 2 of the lowest AIC, underlined is the lowest AIC across all models.

| **Model** | **Line length (km)** | | | **Number of hooks** | | | **Number of hooks/clusters** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Df** | **Deviance** | **AIC** | **Df** | **Deviance** | **AIC** | **Df** | **Deviance** | **AIC** |
| Saturated | 107 | 7046 | 244 128 | 107 | 6895 | 243 794 | 107 | 6924 | 243 859 |
| -Bait | 91 | 7255 | 244 550 | 91 | 7109 | 244 234 | 91 | 7165 | 244 356 |
| -Depth | 106 | 7046 | 244 127 | 106 | 6896 | 243 795 | 106 | 6927 | 243 863 |
| -Gear | 105 | 7072 | 244 181 | 105 | 6923 | 243 852 | 105 | 7417 | 244 920 |
| -Month | 104 | 7140 | 244 328 | 104 | 6987 | 243 993 | 104 | 7011 | 244 047 |
| -Season | 91 | 7320 | 244 688 | 91 | 7192 | 244 414 | 91 | 7224 | 244 484 |
| -Soak Time | 106 | 7176 | 244 409 | 106 | 7042 | 244 118 | 106 | 7066 | 244 172 |
| -SSRU | 101 | 7297 | 244 659 | 101 | 7156 | 244 357 | 101 | 7184 | 244 417 |
| -Vessel | 46 | 8164 | 246 297 | 46 | 8019 | 246 017 | 46 | 8034 | 246 046 |

**Table 12.2:** Model results for the saturated models and reverse stepwise model selections when one parameter was removed at a time for three units of effort (line length (km), number of hooks, and number of hooks/clusters) using generalised linear models fitted to catch and effort data from the Ross Sea Toothfish fishery south of 70°S. DE = deviance explained, Pearson = Pearson correlation, and AIC = Akaike's Information Criterion. For each effort type bold indicates the model with the lowest AIC or an AIC within 2 of the lowest AIC, underlined is the lowest AIC across all models.

| **Model** | **Line Length (km)** | | | **Number of hooks** | | | **Number of hooks/clusters** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **DE (%)** | **Pearson** | **AIC** | **DE (%)** | **Pearson** | **AIC** | **DE (%)** | **Pearson** | **AIC** |
| Saturated | 43.78 | 0.581 | 244 128 | 44.98 | 0.589 | 243 794 | 44.75 | 0.584 | 243 859 |
| -Bait | 42.11 | 0.549 | 244550 | 43.28 | 0.562 | 244 234 | 42.83 | 0.555 | 244 356 |
| -Depth | 43.77 | 0.58 | 244 127 | 44.97 | 0.588 | 243 795 | 44.72 | 0.583 | 243 863 |
| -Gear | 43.57 | 0.578 | 244 181 | 44.76 | 0.585 | 243 852 | 40.81 | 0.484 | 244 920 |
| -Month | 43.03 | 0.573 | 244 328 | 44.25 | 0.581 | 243 993 | 44.05 | 0.576 | 244 047 |
| -Season | 41.59 | 0.557 | 244 688 | 42.61 | 0.561 | 244 414 | 42.35 | 0.557 | 244 484 |
| -Soak Time | 42.74 | 0.549 | 244 409 | 43.81 | 0.585 | 244 118 | 43.61 | 0.581 | 244 172 |
| -SSRU | 41.77 | 0.572 | 244 659 | 42.9 | 0.579 | 244 357 | 42.76 | 0.576 | 244 417 |
| -Vessel | 34.86 | 0.488 | 246 297 | 36.01 | 0.488 | 246 017 | 35.89 | 0.483 | 246 046 |

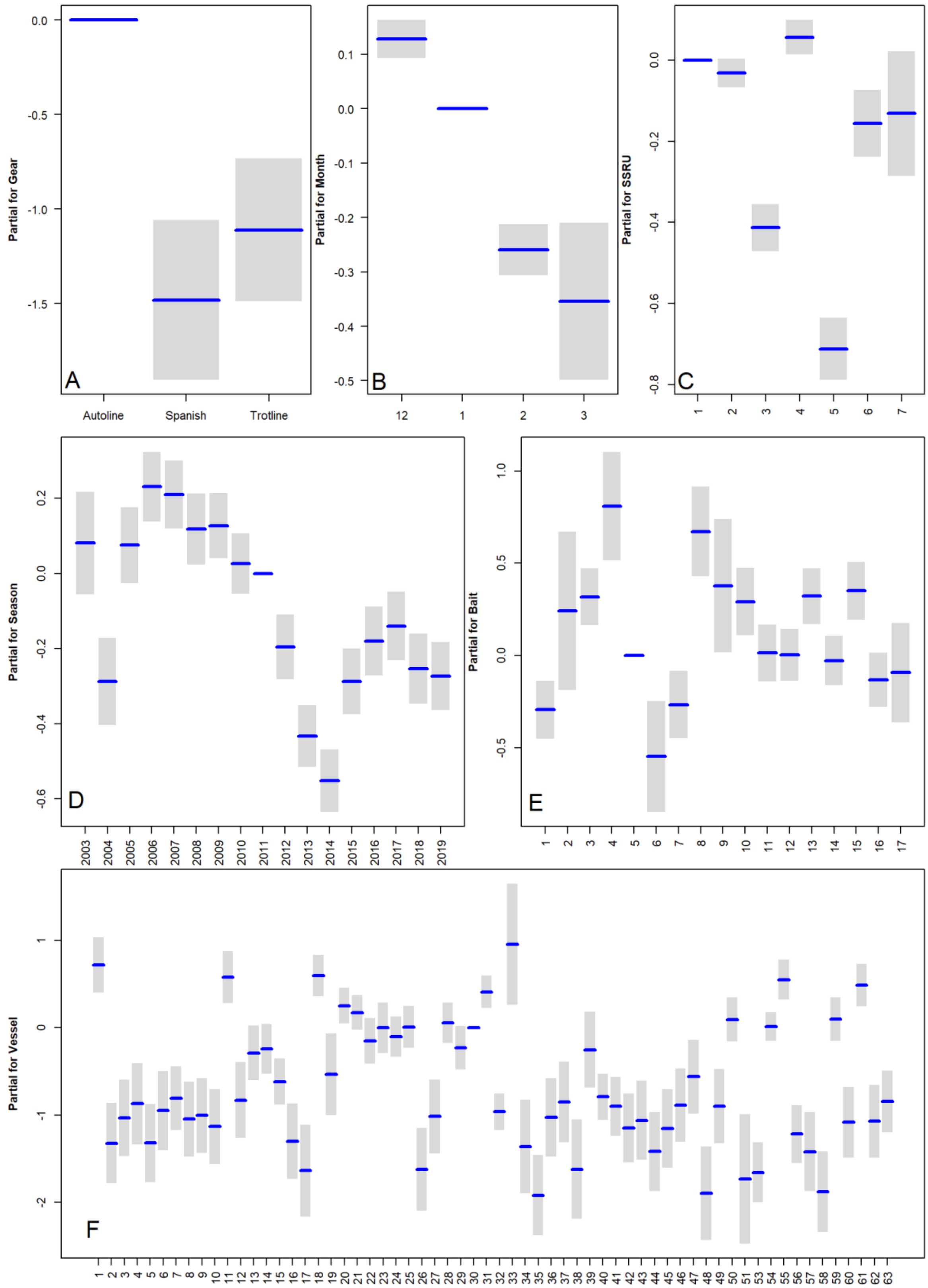



**Figure 12.1:** Partial fits of the saturated GLM to CPUE with line length as the effort measure for gear type (A), month (B), SSRU (C), season (D), bait type (E), and vessel (F) in the Ross Sea Toothfish fishery.

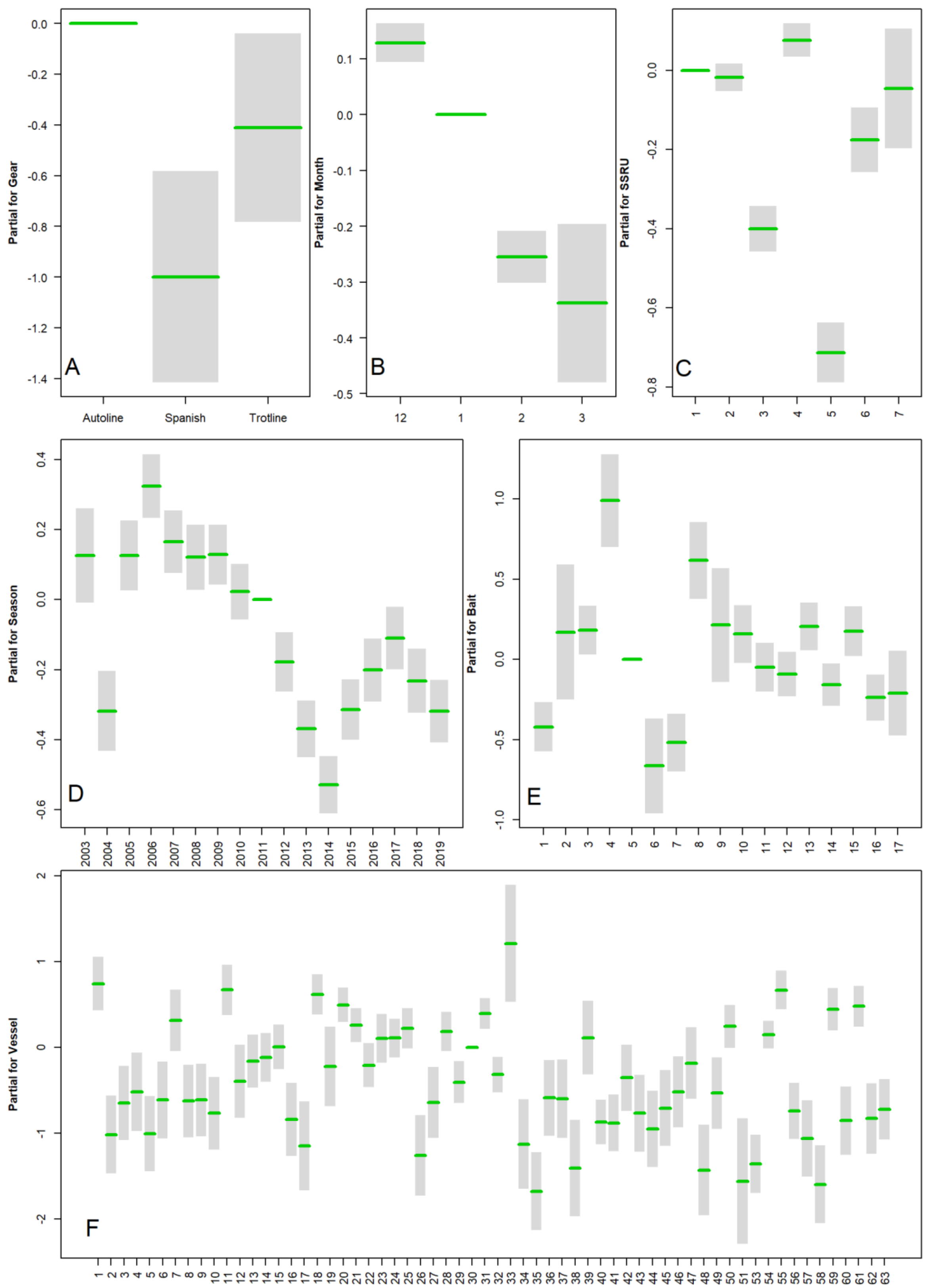



**Figure 12.2:** Partial fits of the saturated GLM to CPUE with total hooks as the effort measure for gear type (A), month (B), SSRU (C), season (D), bait type (E), and vessel (F) in the Ross Sea Toothfish fishery.

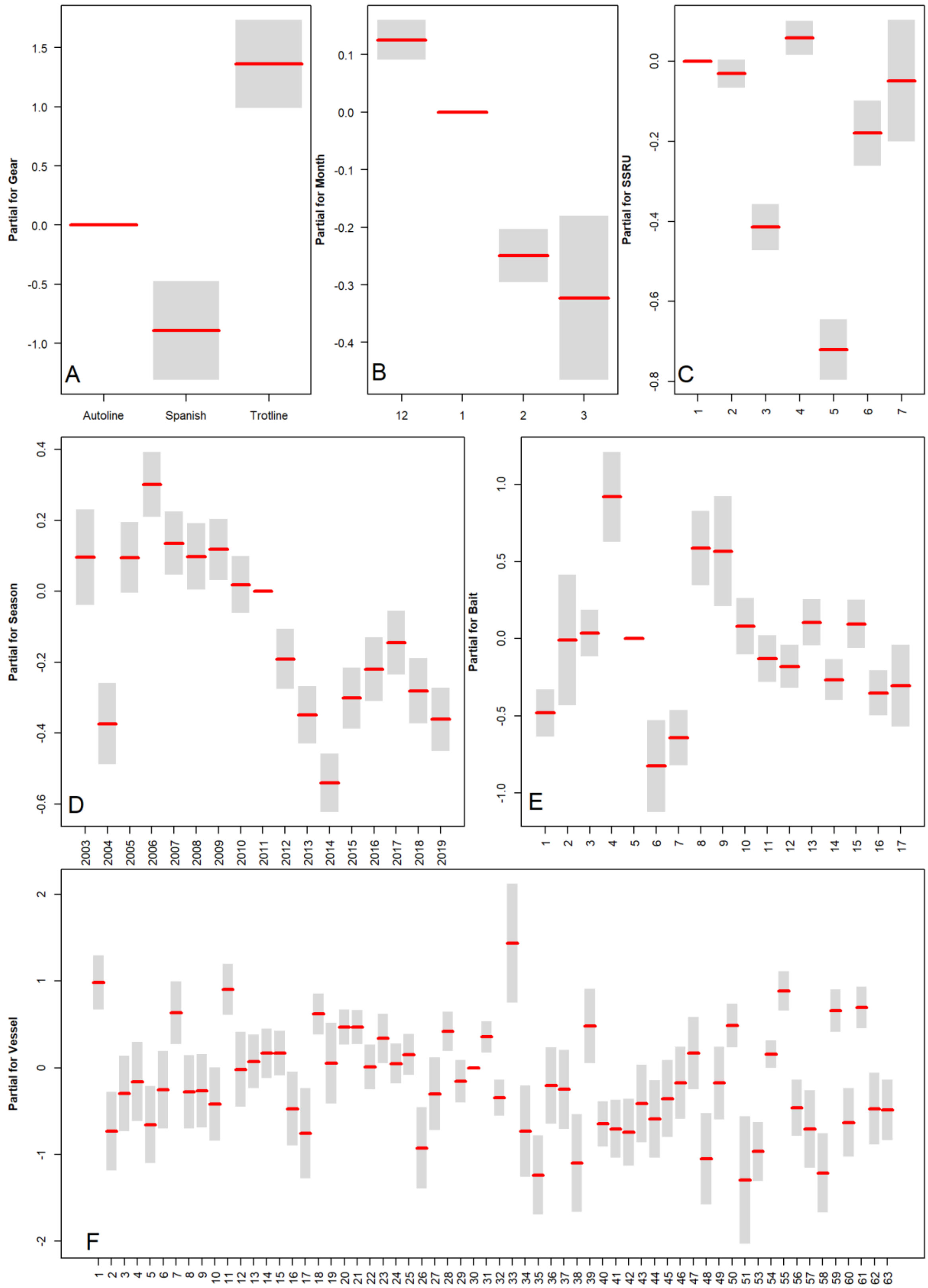



**Figure 12.3:** Partial fits of the saturated GLM to CPUE with hook/cluster as the effort measure for gear type (A), month (B), SSRU (C), season (D), bait type (E), and vessel (F) in the Ross Sea Toothfish fishery.

### Effect sizes

We use the ratio of maximum to minimum predicted CPUE across all levels of a model parameter as a measure of effect size, to explore how much variation each model parameter contributes to the overall model.

Effect sizes were calculated for the parameters of each saturated effort model (Table 12.3). The effect sizes are multiplicative, so for example the effect size of 1.62 for month in the model with line length as effort measure means that the predicted CPUE in December (the best month) would be 1.62 higher than the CPUE in March (the worst month).

The parameters with the largest effect sizes in the models for all three units of effort were vessel, gear and bait (Table 12.3). Vessels showed by far the largest effect size across all effort types (15.44 – 18.04). When only the vessels were included which had fished for more than one season, the effect sizes (8.17 – 11.35) was still the largest for the models with line length and number of hooks effort measures, and equal to the gear effect size for the model with number of hooks/clusters.

### Standardized index of CPUE

While the CPUE model with the number of hooks as effort measure was preferred based on the AIC, the standardized indices of predicted CPUE were similar for all three effort measures (Figure 12.4). All indices showed the same overall pattern, including a declining trend from 2006 – 2014, and only relatively minor differences in CPUE predicted between the line length model and the two hook-based models in 2006 and 2007.

**Table 12.3:** Effect sizes of model parameters for the saturated models for three units of effort (line length (km), number of hooks, and number of hooks/clusters) using generalised linear models fitted to catch and effort data from the Ross Sea Toothfish fishery south of 70°S. Values in brackets for the vessel parameter are the effect sizes for vessels which have fished for more than one year. Note that effect sizes are the ratio of maximum to minimum predicted CPUE across all levels of a model parameter. *based on minimum to maximum values in the data.

| Parameter | Line length (km) | Number of hooks | Number of hooks/clusters |
|---|---|---|---|
| Bait | 3.89 | 5.22 | 5.72 |
| Depth* | 1.05 | 1.08 | 1.11 |
| Gear | 4.4 | 2.72 | 9.49 |
| Month | 1.62 | 1.59 | 1.56 |
| Season | 2.18 | 2.34 | 2.32 |
| Soak Time* | 2.21 | 2.32 | 2.29 |
| SSRU | 2.16 | 2.2 | 2.18 |
| Vessel | 17.76 (11.35) | 18.04 (9.66) | 15.44 (8.17) |

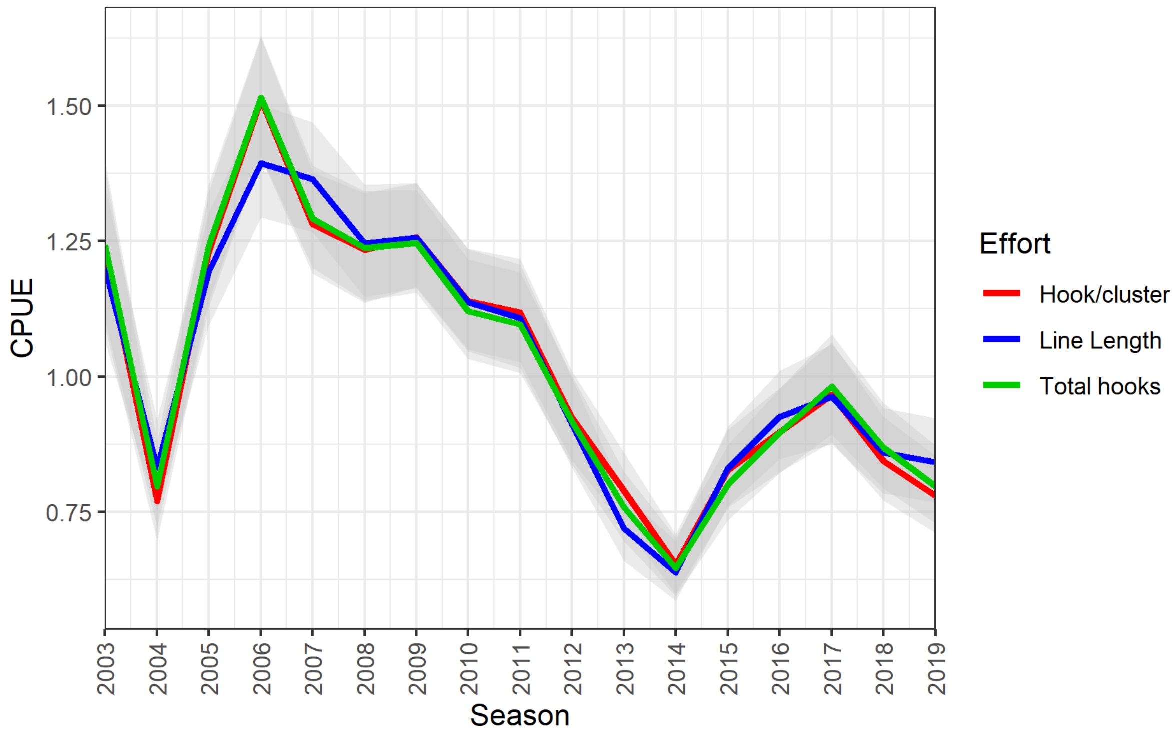



**Figure 12.4:** Standardised CPUE indices, scaled to a geometric mean of 1, with line length (green line), number of hooks (blue line) or number of hooks/clusters (red line) as effort measure with 95% upper and lower confidence intervals (grey) using generalised linear models fitted to catch and effort data from the Ross Sea Toothfish fishery south of 70°S.

## 12.4 Discussion

Comparing length of line (km), total number of hooks per line, and a combination of total number of hooks per line for autoline and Spanish line and total number of clusters for trotline (hooks/cluster) as effort units to be used for catch rates with Generalised Linear Models (GLMs), the model with total hook numbers was preferred with the lowest Akaike's Information Criterion (AIC). It is intuitive that hooks are the logical effort unit, as they catch and retain fish on autoline and Spanish longline, while for trotline the equivalent unit is the cluster of hooks. It is then perhaps noteworthy that the hooks/cluster model did not perform as well as other models. This indicates that Toothfish densities are rarely so high that catch rates are constrained by the number of hooks set. However, standardised catch rates over the fishing season differed little between the models with the three effort units, so the effect of the choice of effort unit on the estimated standardised catch rates is small.

When considering the effect size of individual model parameters across all three tested measures of effort, vessel, gear and bait type were the largest drivers of variation, with vessel showing by far the largest effect size. A large part of the vessels effect size is driven by vessels which have only fished for a single year, likely indicating a 'learning period' for either the skipper and crew on a new vessel, and/or the operation of a vessel on unfamiliar fishing grounds. Without vessels which had only fished a single year, the vessel effect size was reduced by approximately 47%. However, vessel was still the dominant contributor to variation in the model with number of hooks as effort measures, with a multiplier of 9.66 from the worst to the best performing vessel, which was almost twice the effect size of bait, and almost four times that of gear.

The results found here are consistent with previous catch rate standardisations (e.g. Dunn and Hanchet 2016, Yates et al., 2017), indicating that many factors influence catch rates, particularly vessel, gear and bait, and to a lesser extent season, month, area, fishing depth and soak time. This indicates that as long as analysts are rigorous in checking their data, choosing model types and evaluating model fits, assessing CPUE from multi-vessel, multi gear fleets is tractable and useful. However, we recommend that Toothfish research fishing is conducted with a high level of spatial and temporal overlap between vessels and gear types to allow for a meaningful standardisation of variables such as catch rates, mean length or sex ratio (Yates et al. 2017). This is not a new recommendation – for example it was part of the recommendations for research plans in 2011 when the conservation measures applying to research plans in data poor exploratory fisheries was first substantially changed. A number of existing research plans do this already, including the one for Toothfish fishing in Divisions 58.4.1 and 58.4.2 where the catch allocation system provides access for multiple vessels and gear types in research blocks (WG-FSA-18/59). Similarly, research fishing conducted in Subarea 48.6 is conducted by three vessels, using two gear types and ensures spatial overlap of vessels and gears in a research block to assess vessel effects in their respective research plan (SC-CAMLR 2018, para. 3.131).

## 12.5 Appendix 1: Hooks reported compared to hooks calculated

As part of the data exploration, we compared the reported number of hooks for each line with the calculated number of hooks which was for autoline and Spanish line:

$$Hooks = \frac{line\ length}{Hook\ spacing}$$

and for trotline:

$$Hooks = \frac{line\ length}{dropline\ spacing} \times dropline\ clusters\ \times hooks\ per\ clusters$$

Some discrepancies were seen between reported and calculated hooks among all gear types. However, the differences for trotline were larger than for the other gear types, primarily due to a number of hauls reported with either 300 or 450 clusters per dropline (N = 76), which seems unrealistically high. After removing these hauls, the differences between reported and calculated hook numbers showed mostly linear data patterns (Figure 12A1.1) indicating some systematic error in reporting. For trotline, the four linear data patterns observed were ratios of 5/3:1, 2:1, 3:1, 4:1 and 5:1 and could be caused by reporting the total number of hooks per dropline in the "number of clusters per dropline" or "number of hooks per cluster" fields in the C2 forms. This error in reporting could explain the ratios seen for 3:1, 4:1, 5:1 and most of those with 2:1. A possible explanation for the hauls with a calculated hook ratio of 5/3:1 could be a miss-reporting in the number of hooks per clusters of 5 where in fact there were 3.

To assist in future quality checking of data, we recommend a new reporting field in the C2 form for the number of droplines per line deployed.

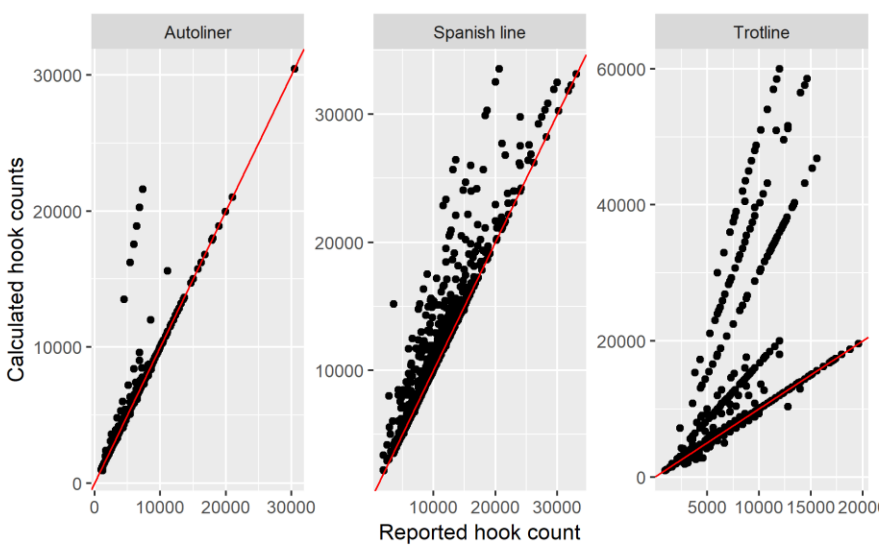



**Figure 12A1.1:** Calculated and reported hook counts by gear type in the Ross Sea Antarctic Toothfish fishery. Note 76 hauls with calculated hooks greater than 60 000 were removed from trotline. Red lines indicate 1:1 ratio.

While we used the reported line length and hook numbers in the analysis for this paper, the number of clusters in trotline hauls needed to be calculated by dividing the reported hook numbers by the number of hooks per cluster. To correct the above discrepancies in relation to "number of clusters per dropline" or "number of hooks per cluster" fields, instances where the calculated hook ratios present were equal or greater than 2:1 (N = 385), were corrected by dividing the larger number reported by the smaller (Table 12A1.1). In addition, for those hauls with a ratio of 5/3:1 (N = 267), the number of hooks per cluster were replaced with 3.

These changes appear to correct the majority of the differences seen in the C2 data, however there are still some differences in the remaining trotline data. This also highlights the importance of QC rules on incoming C2 data to detect discrepancies which can be checked and corrected at the time. This is particularly important as discrepancies appear through time (Table 12A1.2).

As shown in Figure 12A1.1, there are also discrepancies between calculated and reported hook counts in the Spanish line data, and to a much lesser extent the autoline data. It is unclear which data collection field is likely to cause these (line length, hook spacing or hooks reported) but these data warrant further checking.

**Table 12A1.1:** Hooks per cluster and clusters per dropline for trotline hauls where calculated hooks and reported hooks per line showed a ratio equal or greater than 2.

| Clusters per | Hooks per cluster | | | |
|---|---|---|---|---|
| dropline | 5 | 12 | 15 | 20 |
| 2 | 7 | - | - | - |
| 3 | - | 78 | 19 | - |
| 4 | 12 | 57 | - | 24 |
| 15 | 43 | - | - | - |

**Table 12A1.2:** Trotline hauls where calculated hooks and reported hooks per line show a ratio equal or greater than 1.2 by season.

| Season | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hauls | 0 | 0 | 0 | 5 | 44 | 60 | 38 | 68 | 0 | 57 | 79 | 64 |

## 12.6 Appendix 2: Diagnostic plots

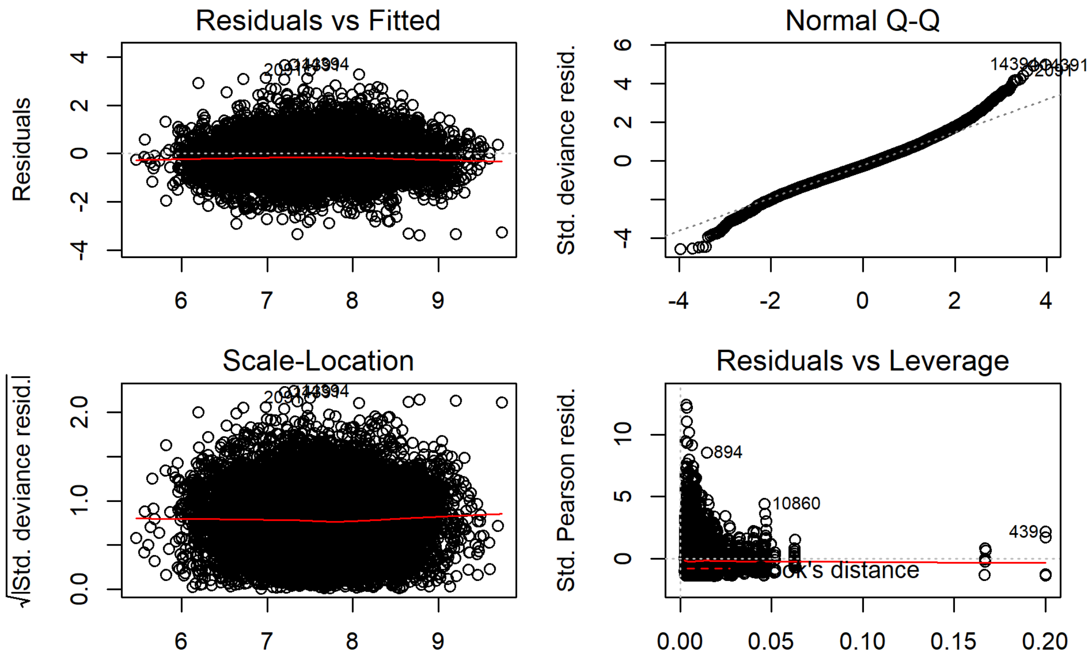



**Figure 12A2.1:** Diagnostic plots of Antarctic Toothfish CPUE standardisation model in the Ross Sea using line length as the unit of effort.

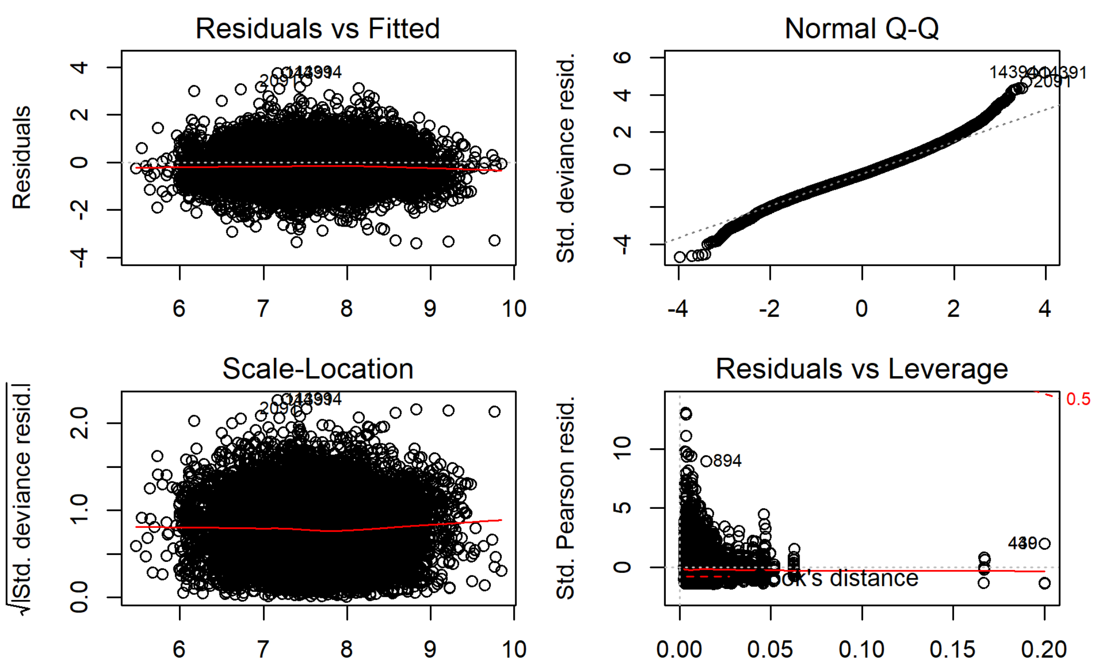



**Figure 12A2.2:** Diagnostic plots of Antarctic Toothfish CPUE standardisation model in the Ross Sea using total number of hooks on line as the unit of effort.

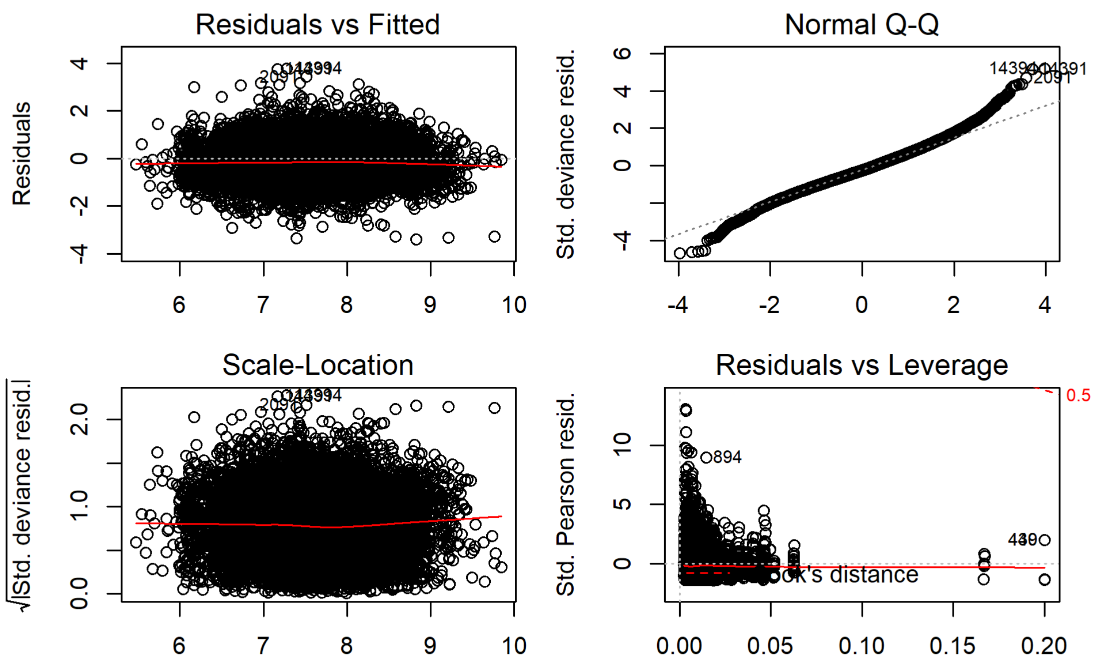



**Figure 12A2.3:** Diagnostic plots of Antarctic Toothfish CPUE standardisation model in the Ross Sea using a combination of hooks and clusters on the line as the unit of effort.

# Chapter 13: Report on the exploratory Toothfish fishery in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2019/20 fishing seasons

Peter Yates, Philippe Ziegler and Genevieve Phillips

**This Chapter is based on:**

Delegations of Australia, France, Japan, Republic of Korea and Spain (2018a) Joint report on exploratory fishing in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2017/18 fishing seasons. Document WG-SAM-18/35 Rev.1, CCAMLR, Hobart, Australia

Delegation of Australia (2019) Report on joint exploratory fishing in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2018/19 fishing seasons. Document WG-SAM-2019/26, CCAMLR, Hobart, Australia

Delegation of Australia (2020d) Report on exploratory fishing in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2019/20 fishing seasons. Document SC-CAMLR-2019/BG/37, CCAMLR, Hobart, Australia

## Abstract

Robust stock assessments and catch limits for *Dissostichus mawsoni* according to CCAMLR decision rules remain to be determined for Divisions 58.4.1 and 58.4.2. Precautionary management arrangements are in place as set out in Conservation Measures 41-11 and 41-05.

The Delegations of Australia, France, Japan, Republic of Korea and Spain developed a multi-member Toothfish exploratory fishery research plans for these Divisions in 2018 and subsequently updated the plan in 2019 and 2020. This plan included research objectives, methods, and milestones in accordance with ANNEX 24-01/A.

This Chapter summaries exploratory fishing activities undertaken by Australia, France, Japan, the Republic of Korea, and Spain between the 2011/12 and 2019/20 fishing seasons, including the quantity of data and samples collected.

## 13.1 Fishing activities

Two (2) fishing voyages took place in the 2020 season, totaling 50 longline deployments (Tables 13.1 and 13.2, Figure 13.1).

Vessels and fishing systems used for exploratory fishing between the 2012 and 2020 seasons are listed in Table 1, and are described at https://www.ccamlr.org/en/compliance/list-authorised-vessels, and the CCAMLR Fishing Gear Library at http://www.ccamlr.org/en/publications/fishing-gear-library).

**Table 13.1:** Numbers of hauls for each vessel by fishing season (pooled across Divisions). Season is abbreviated to the end year.

| Member | Vessel | Gear | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AUS | Antarctic Chieftain | autoliner | | | | | | | 91 | 35 | 41 |
| AUS | Antarctic Discovery | autoliner | | | | | 82 | 29 | 29 | | |
| ESP | Tronio | spanish | | 42 | 83 | | 96 | 74 | 139 | | |
| ESP | Tronio | trotline | | | | | 1 | | | | |
| FRA | Le Saint Andre | autoliner | | | | | | 14 | 32 | 11 | 9 |
| JPN | Shinsei Maru No. 3 | spanish | 6 | | | | | | | | |
| JPN | Shinsei Maru No. 3 | trotline | 16 | 21 | | | | | | | |
| KOR | Hong Jin No. 701 | trotline | 248 | | | | | | | | |
| KOR | Insung No. 3 | spanish | | 10 | | | | | | | |
| KOR | Insung No. 3 | trotline | | 11 | | | | | | | |
| KOR | Kingstar | trotline | | | | 123 | 158 | 146 | | | |
| ZAF | Koryo Maru No. 11 | trotline | 22 | | | | | | | | |

**Table 13.2:** Numbers of hauls per year, vessel and research block since research blocks were introduced in the 2014/15 season. Values were calculated without consideration of research block buffer zones. Season is abbreviated to the end year.

| Research Block | Member | Vessel | Gear | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|
| 5841_1 | AUS | Antarctic Chieftain | autoliner | | | | 20 | | |
| | ESP | Tronio | spanish | | | | 24 | | |
| | FRA | Le Saint Andre | autoliner | | | | 24 | | |
| | KOR | Kingstar | trotline | | 31 | | | | |
| 5841_2 | AUS | Antarctic Chieftain | autoliner | | | | 38 | | |
| | ESP | Tronio | spanish | | | 1 | 53 | | |
| | KOR | Kingstar | trotline | 25 | 37 | 34 | | | |
| 5841_3 | AUS | Antarctic Discovery | autoliner | | 19 | | | | |
| | ESP | Tronio | spanish | | | 22 | | | |
| | KOR | Kingstar | trotline | 74 | 63 | 75 | | | |
| 5841_4 | AUS | Antarctic Discovery | autoliner | | 13 | | | | |
| | KOR | Kingstar | trotline | 6 | | | | | |
| 5841_5 | AUS | Antarctic Discovery | autoliner | | | | 9 | | |
| | ESP | Tronio | spanish | | | | 2 | | |
| | KOR | Kingstar | trotline | 10 | 11 | 26 | | | |
| 5841_6 | AUS | Antarctic Discovery | autoliner | | 50 | 29 | 20 | | |
| | ESP | Tronio | spanish | | 44 | 51 | 60 | | |
| 5842_1 | AUS | Antarctic Chieftain | autoliner | | | | 33 | 35 | 41 |
| | FRA | Le Saint Andre | autoliner | | | 14 | 8 | 11 | 9 |
| | KOR | Kingstar | trotline | 8 | | 11 | | | |
| Outside | ESP | Tronio | spanish | | 52 | | | | |
| | ESP | Tronio | trotline | | 1 | | | | |
| | KOR | Kingstar | trotline | | 16 | | | | |

Since the 2012 season, 1569 longline hauls have been deployed from 23 fishing voyages (Figure 13.2). Fishing depths varied across areas; and overall they ranged from 606-2591 m, with a mean of 1334 m (Figure 13.3). Fishing has occurred within research blocks, within research block buffer zones (as set out in Conservation Measure 41-01, ANNEX 41-01/B), and in other areas as part of depletion experiments and tagging undertaken by Spain (WG-SAM-16/10). Locations outside of research blocks are hereafter referred to as 'outside'.

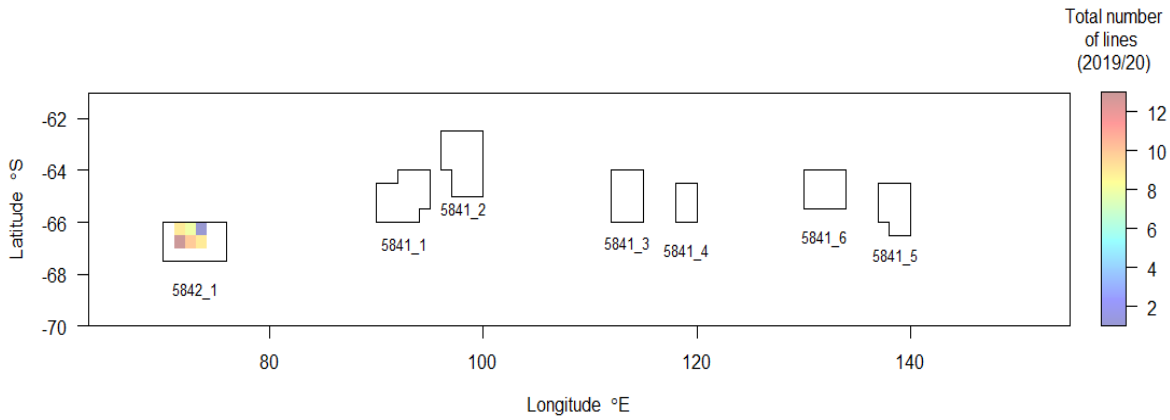



**Figure 13.1:** Spatial distribution of fishing effort during the 2019/20 season. Shading indicates the number of longlines deployed. Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

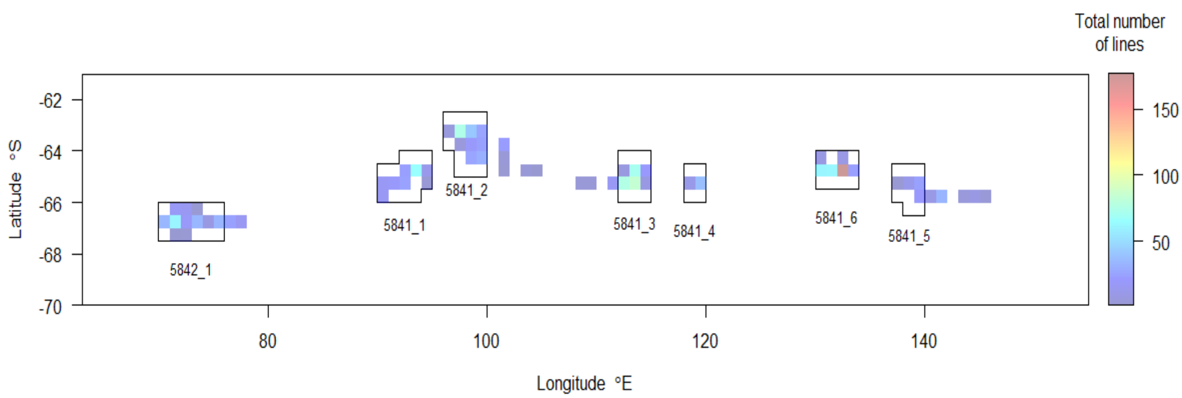



**Figure 13.2:** Spatial distribution of fishing effort since the 2011/12 season. Shading indicates the number of longlines deployed. Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

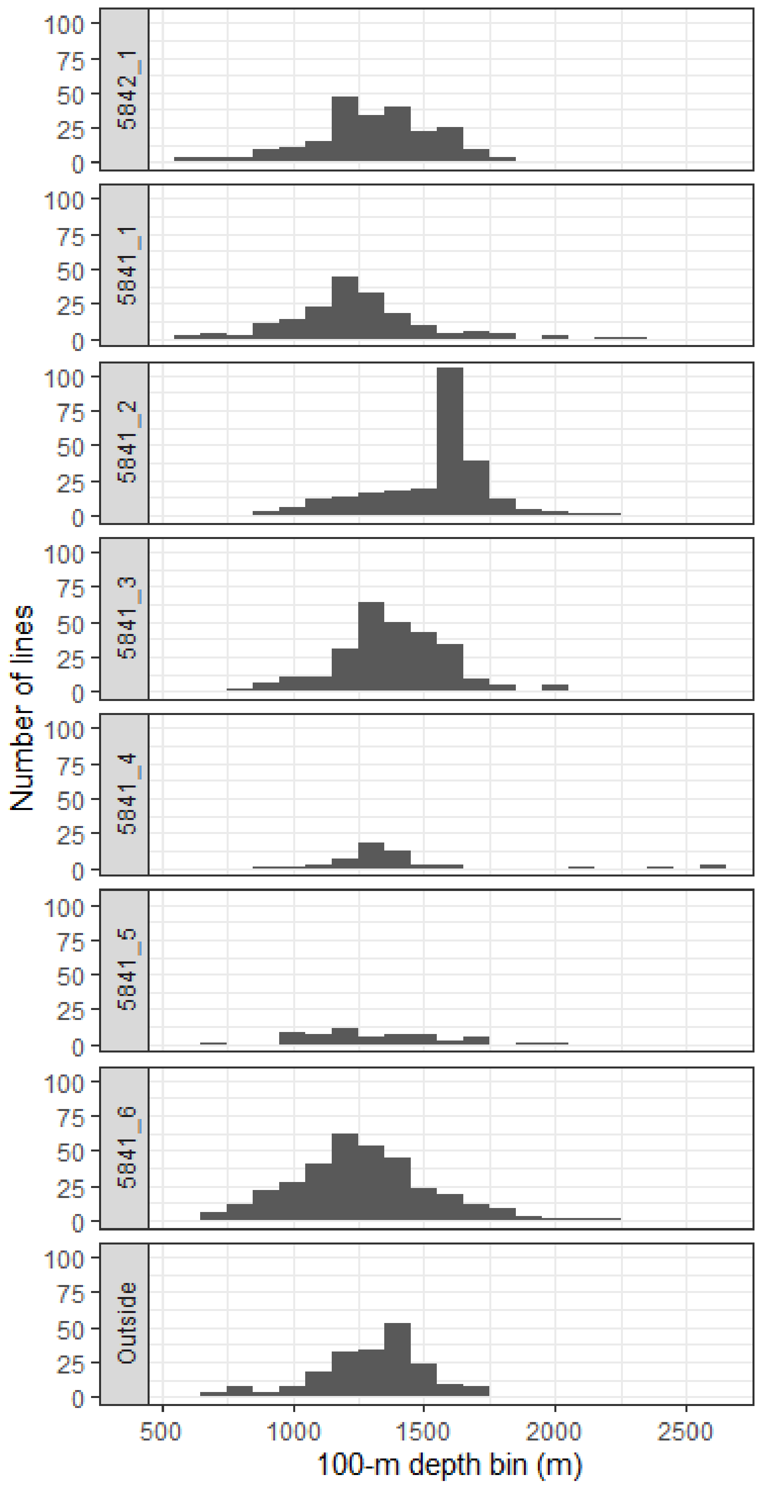



**Figure 13.3:** Depth distribution of lines in Research Blocks of Divisions 58.4.1 and 58.4.2. Outside = lines outside of research blocks.

## 13.2 Total catches

Total catches of *D. mawsoni*, *D. eleginoides* (grouped together) and *Macrourus* spp. were 1554.2, and 136.3 tonnes, respectively (Tables 13.3a and 13.3b).

Catches of *D. eleginoides* were very low and did not exceed 2.8 % of catches of *D. mawsoni* in any Research Block in any season.

'Outside' catches were calculated without consideration of research block buffer zones.

**Table 13.3a:** Summary of total catches of D. mawsoni (tonnes) across research blocks, Members, and seasons. Season is abbreviated to the end year.

| Research Block | Member | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|
| 5841_1 | KOR | 81.98 | 2.95 | | | 79.68 | | | | |
| | AUS | | | | | | | 21.09 | | |
| | ESP | | | | | | | 25.05 | | |
| | FRA | | | | | | | 50.03 | | |
| 5841_2 | KOR | 16.43 | 0.11 | | 15.40 | 42.57 | 50.50 | | | |
| | ESP | | | 54.15 | | | 0.63 | 43.12 | | |
| | AUS | | | | | | | 52.56 | | |
| 5841_3 | KOR | 28.30 | | | 71.33 | 56.18 | 51.02 | | | |
| | AUS | | | | | 3.84 | | | | |
| | ESP | | | | | | 19.33 | | | |
| 5841_4 | KOR | 22.39 | | | 9.95 | | | | | |
| | AUS | | | | | 12.10 | | | | |
| 5841_5 | KOR | | | | 25.70 | 34.91 | 31.68 | | | |
| | AUS | | | | | | | 6.41 | | |
| | ESP | | | | | | | 1.11 | | |
| 5841_6 | KOR | 8.22 | | | | | | | | |
| | ESP | | 23.22 | 24.98 | | 49.85 | 45.08 | 54.55 | | |
| | AUS | | | | | 35.54 | 9.72 | 11.34 | | |
| 5842_1 | KOR | 22.08 | | | 9.62 | | 19.96 | | | |
| | JPN | | 3.73 | | | | | | | |
| | FRA | | | | | | 14.64 | 14.15 | 16.45 | 18.00 |
| | AUS | | | | | | | 27.74 | 33.25 | 40.07 |
| Outside | KOR | 18.15 | | | | 14.56 | | | | |
| | ZAF | 12.84 | | | | | | | | |
| | ESP | | 21.46 | 22.19 | | 72.37 | | | | |

**Table 13.3b:** Summary of total catches of Macrouridae (tonnes) across research blocks, Members, and seasons. Season is abbreviated to the end year.

| Research Block | Member | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|
| 5841_1 | AUS | | | | | | | 1.16 | | |
| | ESP | | | | | | | 0.62 | | |
| | FRA | | | | | | | 2.41 | | |
| | KOR | 0.46 | 0.01 | | | 0.42 | | | | |
| 5841_2 | AUS | | | | | | | 8.30 | | |
| | ESP | | | 0.90 | | | 0.01 | 3.62 | | |
| | KOR | 0.27 | 0.07 | | 0.20 | 0.65 | 1.36 | | | |
| 5841_3 | AUS | | | | | 6.40 | | | | |
| | ESP | | | | | | 1.11 | | | |
| | KOR | 0.13 | | | 1.13 | 1.21 | 5.84 | | | |
| 5841_4 | AUS | | | | | 5.00 | | | | |
| | KOR | 0.34 | | | 0.09 | | | | | |
| 5841_5 | AUS | | | | | | | 2.84 | | |
| | ESP | | | | | | | 0.01 | | |
| | KOR | | | | 0.48 | 0.75 | 2.03 | | | |
| 5841_6 | AUS | | | | | 10.95 | 10.59 | 11.52 | | |
| | ESP | | 1.58 | 1.54 | | 7.84 | 4.73 | 4.63 | | |
| | KOR | 0.36 | | | | | | | | |
| 5842_1 | AUS | | | | | | | 4.01 | 1.61 | 2.01 |
| | FRA | | | | | | 1.19 | 1.09 | 0.60 | 0.30 |
| | JPN | | 0.07 | | | | | | | |
| | KOR | 0.08 | | | 0.02 | | 0.11 | | | |
| Outside | ESP | | 3.13 | 4.03 | | 15.01 | | | | |
| | KOR | 0.07 | | | | 0.61 | | | | |
| | ZAF | 0.78 | | | | | | | | |

## 13.3 Spatial and depth distributions of catch

Total *D. mawsoni* catch has occurred in all research blocks within Division 58.4.1 and research block 5842_1 within Division 58.4.2 (Figure 13.4). Catch rates were variable across the area, whereas catch rates of *Macrourus* spp. were only high within research blocks 5851_5 and 5841_6 and SSRU 58.4.1H (Figures 13.5 and 13.6).

Total catches of target species were highest between 1000 - 1600 m deep (Figure 13.7). Total catches declined in depths shallower than 1000 m and deeper than 1500 m. Fishing in deeper water resulted in a higher proportion of bycatch. These observations are supported by the species distribution modelling undertaken previously (WG-FSA-17/18, WG-FSA-17/23, WG-FSA-18/28).

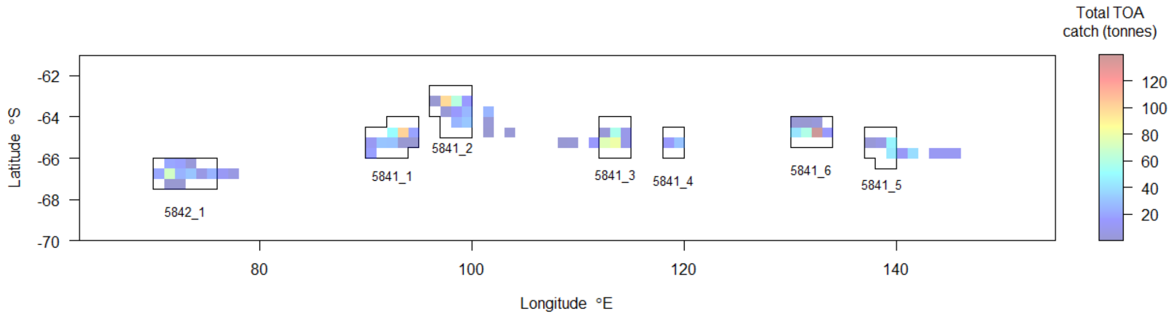



**Figure 13.4:** Spatial distribution of Dissostichus mawsoni catch since the 2011-12 season. Shading indicates total catch (tonnes). Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

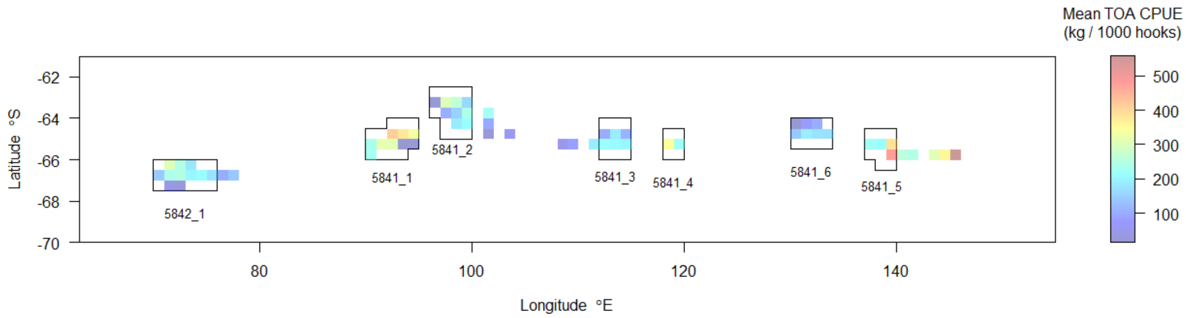



**Figure 13.5:** Mean catch rates of Dissostichus mawsoni since the 2011-12 season. Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

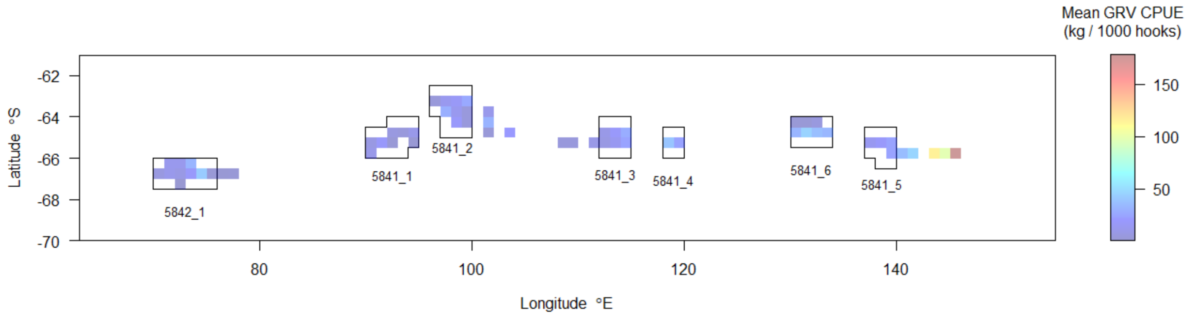



**Figure 13.6:** Mean catch rates of Macrourus spp. since the 2011-12 season. Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

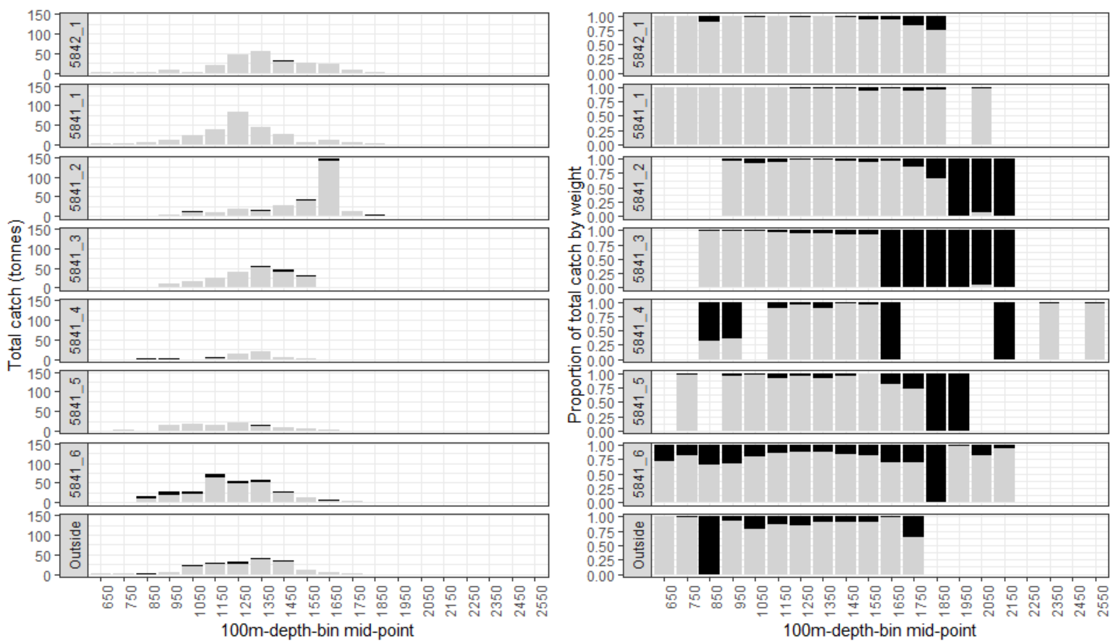



**Figure 13.7:** Total catches of Dissostichus mawsoni (grey) and Macrourus spp. (black) species across depth bins and locations. Left panel = total catch in tonnes, right panel = relative proportions of Dissostichus mawsoni and Macrourus spp.

## 13.4 Biological Sampling

In total, 34,745 and 30,594 *D. mawsoni* were measured for total length and weight, respectively; and 34,102 and 30,236 were assessed for sex and macroscopic maturity stage, respectively (Table 13.4). *Dissostichus mawsoni* ranged in size from 136–2110 mm total length, with a mean total length of 1367 mm.

**Table 13.4:** Number of Dissostichus mawsoni sampled for biological parameters. Data are for all vessels and voyages pooled. Season is abbreviated to the end year.

| Research Block | Season | Member | Length | Weight | Maturity | Sex |
|---|---|---|---|---|---|---|
| 5841_1 | 2012 | KOR | 1772 | | 1772 | 1772 |
| | 2013 | KOR | 86 | | | 83 |
| | 2016 | KOR | 593 | | 593 | 593 |
| | 2018 | AUS | 589 | 589 | | 585 |
| | 2018 | ESP | 650 | 650 | | 647 |
| | 2018 | FRA | 787 | 787 | 787 | 787 |
| 5841_2 | 2012 | KOR | 517 | | 517 | 517 |
| | 2013 | KOR | 2 | 2 | 2 | 2 |
| | 2014 | ESP | 1216 | | | |
| | 2015 | KOR | 340 | 340 | | 339 |
| | 2016 | KOR | 563 | 563 | | |
| | 2017 | ESP | 15 | 15 | 15 | 15 |
| | 2017 | KOR | 559 | 559 | 559 | 559 |
| | 2018 | AUS | 1240 | 1240 | | 1231 |
| | 2018 | ESP | | | | 999 |
| 5841_3 | 2012 | KOR | 255 | | 255 | 255 |
| | 2015 | KOR | 1598 | 1598 | | |
| | 2016 | AUS | | | | |
| | 2016 | KOR | 884 | | | |
| | 2017 | ESP | 438 | 438 | | |
| | 2017 | KOR | 1017 | 1017 | 1017 | 1017 |
| 5841_4 | 2012 | KOR | 554 | | 554 | 554 |
| | 2015 | KOR | 163 | 163 | | 162 |
| | 2016 | AUS | | | | |
| 5841_5 | 2015 | KOR | 327 | 327 | | |
| | 2016 | KOR | 344 | 344 | | |
| | 2017 | KOR | 443 | 443 | | 442 |
| | 2018 | AUS | | 165 | | 165 |
| | **2018** | **ESP** | **27** | **27** | **27** | **27** |

| Research Block | Season | Member | Length | Weight | Maturity | Sex |
|---|---|---|---|---|---|---|
| 5841_6 | 2012 | KOR | 393 | | 393 | 392 |
| | 2013 | ESP | 575 | | | |
| | 2014 | ESP | 645 | | | |
| | 2016 | AUS | | | | |
| | 2016 | ESP | 1493 | | | |
| | 2017 | AUS | 287 | 287 | 287 | 282 |
| | 2017 | ESP | 1177 | | | |
| | 2018 | AUS | | 301 | | 300 |
| | 2018 | ESP | 1261 | | | |
| 5842_1 | 2012 | KOR | 881 | | 881 | 881 |
| | 2013 | JPN | 131 | 131 | 131 | 131 |
| | 2015 | KOR | 207 | 207 | 207 | 207 |
| | 2017 | FRA | | | | |
| | 2017 | KOR | 204 | 204 | | 202 |
| | 2018 | AUS | 1014 | 1014 | | 1010 |
| | 2018 | FRA | 276 | 276 | 276 | 276 |
| | 2019 | AUS | | | | 1059 |
| | 2019 | FRA | 357 | 357 | | 348 |
| | 2020 | AUS | 1305 | | | 1083 |
| | 2020 | FRA | 300 | 300 | 300 | 300 |
| Outside | 2012 | KOR | 1204 | | 1204 | 1204 |
| | 2012 | ZAF | 193 | 193 | 193 | 193 |
| | 2013 | ESP | 555 | | | |
| | 2014 | ESP | 864 | | | |
| | 2016 | ESP | 1976 | | | |
| | 2016 | KOR | 287 | 287 | | |
| **TOTAL** | | | **34,745** | **30,594** | **30,236** | **34,102** |

## 13.5 Otolith Collection and Ageing

A total of 13,462 otolith pairs were sampled from measured *D. mawsoni*. Summaries of the numbers of *D. mawsoni* otolith samples across length bins, Members, research blocks and seasons are provided in Tables 13.5 to 13.7.

Preliminary age-frequency histograms for each research block from Australian and Spanish data are plotted in Figures 13.8a and 13.8b. The median age across all research blocks is 16 years (S.D. = +/- 0.71 years).

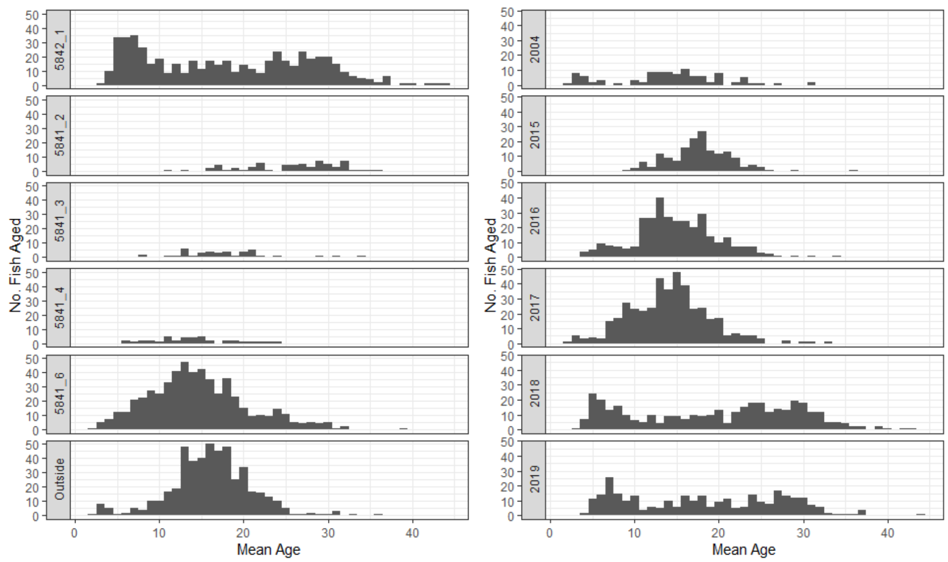



**Figure 13.8a:** Age-frequency plots of fish aged by Australian researchers by research block

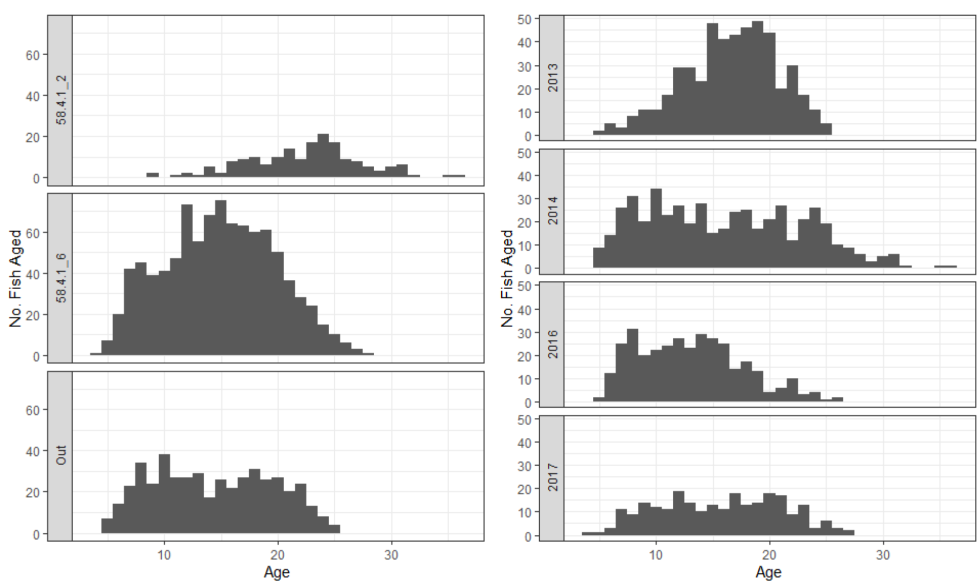



**Figure 13.8b:** Age-frequency plots of fish aged by Spanish researchers by research block and season

**Table 13.5:** Number of Dissostichus mawsoni sampled for otoliths in each 50-mm length bin between seasons 2011/12-2019/20.

| 50-mm length-bin lower limit | AUS | ESP | FRA | JPN | KOR | ZAF | Total |
|---|---|---|---|---|---|---|---|
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 250 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 350 | 0 | 0 | 0 | 0 | 2 | 0 | 2 |
| 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 450 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 500 | 3 | 0 | 0 | 0 | 0 | 0 | 3 |
| 550 | 5 | 9 | 0 | 3 | 0 | 0 | 17 |
| 600 | 29 | 17 | 1 | 8 | 7 | 0 | 62 |
| 650 | 95 | 35 | 6 | 2 | 10 | 0 | 148 |
| 700 | 100 | 51 | 15 | 6 | 27 | 0 | 199 |
| 750 | 73 | 46 | 10 | 3 | 26 | 0 | 158 |
| 800 | 64 | 63 | 10 | 4 | 28 | 0 | 169 |
| 850 | 61 | 63 | 8 | 3 | 24 | 0 | 159 |
| 900 | 33 | 72 | 11 | 0 | 19 | 0 | 135 |
| 950 | 50 | 92 | 14 | 2 | 33 | 0 | 191 |
| 1000 | 54 | 92 | 8 | 3 | 43 | 0 | 200 |
| 1050 | 75 | 105 | 19 | 2 | 63 | 0 | 264 |
| 1100 | 106 | 129 | 29 | 2 | 79 | 0 | 345 |
| 1150 | 128 | 162 | 33 | 6 | 119 | 0 | 448 |
| 1200 | 173 | 200 | 55 | 6 | 150 | 0 | 584 |
| 1250 | 217 | 288 | 66 | 17 | 223 | 0 | 811 |
| 1300 | 318 | 336 | 97 | 7 | 297 | 0 | 1055 |
| 1350 | 394 | 454 | 92 | 14 | 429 | 0 | 1383 |
| 1400 | 449 | 439 | 75 | 9 | 462 | 0 | 1434 |
| 1450 | 473 | 398 | 64 | 10 | 534 | 0 | 1479 |
| 1500 | 318 | 408 | 37 | 7 | 392 | 0 | 1162 |
| 1550 | 280 | 267 | 16 | 4 | 293 | 0 | 860 |
| 1600 | 201 | 195 | 9 | 2 | 202 | 0 | 609 |
| 1650 | 115 | 113 | 3 | 1 | 106 | 0 | 338 |
| 1700 | 48 | 84 | 0 | 0 | 51 | 0 | 183 |
| 1750 | 16 | 32 | 0 | 0 | 28 | 0 | 76 |
| 1800 | 12 | 17 | 0 | 1 | 10 | 0 | 40 |
| 1850 | 3 | 6 | 0 | 0 | 2 | 0 | 11 |
| 1900 | 0 | 3 | 0 | 0 | 5 | 0 | 8 |
| 1950 | 1 | 2 | 0 | 0 | 1 | 0 | 4 |
| 2100 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |

**Table 13.6:** Number of Dissostichus mawsoni otolith samples by season and Member. Numbers of otoliths aged are in parentheses. Season is abbreviated to the end year.

| Member | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| KOR | 315 | 85 | 0 | 1028 (346) | 899 (308) | 1339 (200) | | | | 3666 |
| ZAF | | | | | | | | | | 0 |
| ESP | | 696 (492) | 1262 (497) | | 562 (341) | 387 (245) | 1273 | | | 4180 (1575) |
| JPN | | 122 | | | | | | | | 122 |
| AUS | | | | | 344 (330) | 212 (202) | 2547 (375) | 307 (305) | 503 | 3913 (1212) |
| FRA | | | | | | 145 | 310 | 132 | 92 | 679 |

**Table 13.7:** Number of Dissostichus mawsoni otolith samples by season and Research Block. Season is abbreviated to the end year.

| Research Block | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|
| 5841_1 | 70 | 83 | | | 189 | | 1053 | | |
| 5841_2 | 39 | 2 | 453 | 204 | 167 | 282 | 1288 | | |
| 5841_3 | 5 | | | 620 | 402 | 770 | | | |
| 5841_4 | 47 | | | 62 | 40 | | | | |
| 5841_5 | | | | 92 | 81 | 294 | 78 | | |
| 5841_6 | 99 | 305 | 374 | | 715 | 491 | 665 | | |
| 5842_1 | 28 | 122 | | 50 | | 246 | 1046 | 439 | 595 |
| Outside | 27 | 391 | 435 | | 211 | | | | |
| TOTAL | 315 | 903 | 1262 | 1028 | 1805 | 2083 | 4130 | 439 | 595 |

## 13.6 Tagging

A total of 14,050 *D. mawsoni* were tagged and released between December 2004 and March 2020 (Figure 13.9, Table 13.8). There have been 106 tag recaptures of *D. mawsoni* which could be matched with their release event (Table 13.9, Figures 13.10 and 13.11), 24 of which were released and recaptured during the same season. Excluding within-season season recaptures, time at liberty ranged from 311 to 4041 days, and minimum straight-line distances travelled between capture events ranged from 1 to 6620 km (Table 13.8).

Similar to last year, tagged fish have been recaptured from all research blocks except 5841_4 (Figure 13.10). In 2020, six fish were recaptured, one of which was released previously in the same season (Table 13.8).

**Table 13.8:** Number of Dissostichus mawsoni recaptures and releases in each season and research block. Within-season recaptures are excluded. Season is abbreviated to the end year.

| Season | 5841_1 REL | 5841_1 REC | 5841_2 REL | 5841_2 REC | 5841_3 REL | 5841_3 REC | 5841_4 REL | 5841_4 REC | 5841_5 REL | 5841_5 REC | 5841_6 REL | 5841_6 REC | 5842_1 REL | 5842_1 Rec | Outside REL | Outside REC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 42 | | 108 | | 98 | | | | | | 106 | | 47 | | 379 | |
| 2006 | 177 | | 100 | | 78 | | | | 106 | | 6 | | 107 | | 31 | 6 |
| 2007 | 58 | 1 | 127 | | 435 | | 80 | | 355 | | 8 | | 86 | | 287 | 1 |
| 2008 | | | 384 | 3 | 18 | | | | 410 | | 153 | 1 | 377 | | 465 | 3 |
| 2009 | | | 426 | 1 | 56 | | 104 | | | | | | 46 | | 22 | 1 |
| 2010 | | | 156 | 1 | | | | | 119 | 1 | | | | | | 1 |
| 2011 | 123 | | 224 | 1 | | | | | 37 | 2 | 14 | | | | 14 | |
| 2012 | 384 | | 122 | | 118 | | 138 | | | | 50 | | 117 | | 152 | |
| 2013 | 29 | | | | | | | | | | 120 | | 21 | | 111 | 1 |
| 2014 | | | 281 | 1 | | | | | | | 139 | | | | 114 | 4 |
| 2015 | | | 84 | | 355 | | 50 | | 135 | 3 | | | 82 | | | |
| 2016 | 401 | 1 | 215 | | 296 | 4 | 61 | | 178 | | 441 | | | | 440 | 1 |
| 2017 | | | 261 | 1 | 358 | 4 | | | 177 | 1 | 287 | 4 | 186 | | | 2 |
| 2018 | 523 | 1 | 484 | 14 | | | | | 34 | | 330 | 5 | 226 | | | 1 |
| 2019 | | | | | | | | | | | | | 258 | 4 | | 1 |
| 2020 | | | | | | | | | | | | | 323 | 4 | | 2 |
| **TOTAL** | **1737** | **3** | **2972** | **22** | **1812** | **8** | **433** | **0** | **1551** | **7** | **1654** | **10** | **1876** | **8** | **2015** | **24** |

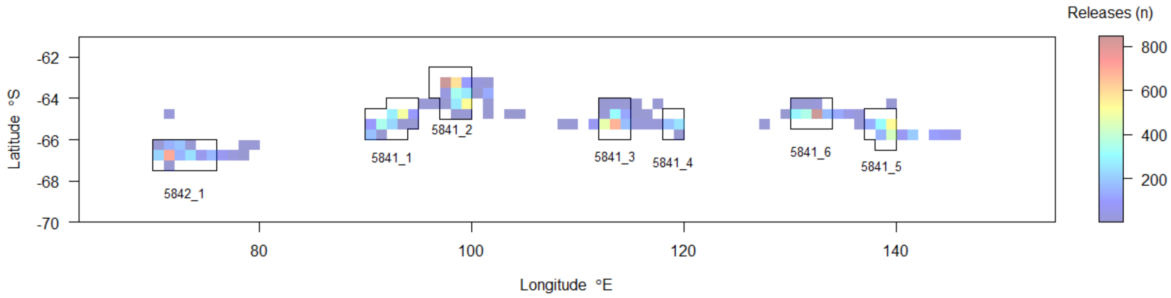



**Figure 13.9:** Spatial distribution of tagged-and-released *Dissostichus mawsoni* since the 2011-12 season. Shading indicates total number of releases. Raster cells are of size 1° longitude and 0.5° latitude. Black lines = CCAMLR Research Blocks. Map datum = WGS84.

**Table 13.9:** Tagging rates and size-overlap statistics for vessels that participated in the 2019-20 season.

| Vessel | Member | Rate | Tag-size Overlap |
|---|---|---|---|
| Antarctic Chieftain | AUS | 5.55 | 79.6 |
| Le Saint Andre | FRA | 5.55 | 85.1 |

**Table 13.10:** Summary of recaptured *Dissostichus mawsoni* with matched release and recapture events. Season is abbreviated to the end year.

| Release season | Release Member | Recapture season | Recapture Member | Sex | Release length (cm) | Days at liberty | Min. distance travelled (km) |
|---|---|---|---|---|---|---|---|
| 2005 | ESP | 2005 | ESP | M | 86.7 | 33 | 25 |
| 2005 | ESP | 2006 | URY | F | 89.2 | 374 | 9 |
| 2005 | ESP | 2006 | ESP | M | 129.5 | 318 | 13 |
| 2005 | ESP | 2006 | ESP | M | 108.6 | 336 | 14 |
| 2005 | ESP | 2006 | ESP | M | 117.0 | 344 | 30 |
| 2005 | ESP | 2006 | ESP | M | 110.3 | 351 | 13 |
| 2005 | ESP | 2006 | ESP | M | 101.3 | 406 | 22 |
| 2005 | ESP | 2008 | URY | M | 137.6 | 1130 | 981 |
| 2006 | CHL | 2007 | RUS | M | 59.0 | 365 | 3563 |
| 2006 | ESP | 2007 | ESP | M | 82.8 | 387 | 3 |
| 2006 | ESP | 2008 | NAM | M | 104.0 | 707 | 10 |
| 2006 | ESP | 2017 | JPN | M | 81.2 | 4041 | 3378 |
| 2006 | KOR | 2010 | JPN | F | 68.0 | 1454 | 23 |
| 2007 | ESP | 2007 | NAM | M | 108.0 | 12 | 6 |
| 2007 | ESP | 2007 | ESP | M | 137.0 | 78 | 12 |
| 2007 | ESP | 2007 | KOR | M | 119.0 | 31 | 13 |
| 2007 | ESP | 2008 | ESP | M | 99.0 | 391 | 1728 |
| 2007 | ESP | 2008 | ESP | M | 81.0 | 419 | 150 |

| Release season | Release Member | Recapture season | Recapture Member | Sex | Release length (cm) | Days at liberty | Min. distance travelled (km) |
|---|---|---|---|---|---|---|---|
| 2007 | ESP | 2008 | KOR | F | 126.0 | 414 | 26 |
| 2007 | ESP | 2008 | NAM | M | 97.0 | 375 | 35 |
| 2007 | ESP | 2008 | AUS | M | 124.0 | 450 | 1071 |
| 2007 | KOR | 2007 | KOR | F | 89.0 | 15 | 4 |
| 2007 | KOR | 2013 | FRA | M | 90.0 | 2114 | 2527 |
| 2007 | NAM | 2010 | JPN | M | 85.0 | 1008 | 7 |
| 2008 | JPN | 2009 | URY | M | 88.0 | 384 | 339 |
| 2008 | JPN | 2017 | FRA | F | 97.0 | 3443 | 2250 |
| 2008 | KOR | 2015 | KOR | U | 78.0 | 2536 | 15 |
| 2008 | KOR | 2011 | KOR | NA | 83.0 | 1096 | 1 |
| 2008 | KOR | 2015 | KOR | F | 85.0 | 2541 | 2 |
| 2008 | KOR | 2015 | KOR | F | 88.0 | 2542 | 14 |
| 2008 | NAM | 2008 | KOR | M | 124.0 | 49 | 17 |
| 2008 | NAM | 2009 | KOR | M | 126.0 | 425 | 120 |
| 2008 | NAM | 2018 | JPN | F | 66.0 | 3682 | 2433 |
| 2009 | KOR | 2009 | KOR | M | 101.0 | 5 | 24 |
| 2009 | KOR | 2010 | JPN | NA | 106.0 | 336 | 18 |
| 2009 | KOR | 2018 | AUS | F | 80.0 | 3247 | 419 |
| 2010 | JPN | 2011 | ESP | M | 129.0 | 372 | 71 |
| 2010 | JPN | 2011 | KOR | M | 77.0 | 392 | 4 |
| 2011 | ESP | 2014 | ESP | M | 122.0 | 1096 | 23 |
| 2012 | KOR | 2016 | KOR | M | 80.0 | 1482 | 4 |
| 2013 | ESP | 2014 | ESP | F | 126.0 | 374 | 2 |
| 2013 | ESP | 2014 | ESP | M | 115.0 | 378 | 47 |
| 2013 | ESP | 2014 | ESP | F | 112.0 | 379 | 2 |
| 2013 | ESP | 2016 | ESP | F | 115.0 | 1089 | 9 |
| 2013 | ESP | 2017 | ESP | F | 60.0 | 1430 | 27 |
| 2014 | ESP | 2014 | ESP | F | 147.0 | 2 | 3 |
| 2014 | ESP | 2014 | ESP | F | 154.0 | 1 | 2 |
| 2014 | ESP | 2018 | AUS | M | 102.0 | 1443 | 4 |
| 2015 | KOR | 2016 | KOR | F | 144.0 | 367 | 7 |
| 2015 | KOR | 2016 | KOR | M | 154.0 | 365 | 5 |
| 2015 | KOR | 2016 | KOR | M | 150.0 | 370 | 10 |
| 2015 | KOR | 2017 | KOR | F | 154.0 | 733 | 15 |
| 2015 | KOR | 2017 | KOR | M | 140.0 | 745 | 280 |
| 2015 | KOR | 2017 | KOR | M | 147.0 | 749 | 16 |
| 2015 | KOR | 2017 | ESP | NA | 136.0 | 735 | 30 |
| 2015 | KOR | 2018 | AUS | M | 139.0 | 1070 | 2 |
| 2016 | AUS | 2016 | AUS | F | 158.0 | 6 | 9 |
| 2016 | AUS | 2016 | AUS | F | 148.0 | 7 | 13 |
| 2016 | AUS | 2018 | ESP | F | 112.0 | 719 | 3 |
| 2016 | AUS | 2017 | AUS | F | 132.0 | 324 | 6 |

| Release season | Release Member | Recapture season | Recapture Member | Sex | Release length (cm) | Days at liberty | Min. distance travelled (km) |
|---|---|---|---|---|---|---|---|
| 2016 | ESP | 2016 | ESP | M | 106.0 | 14 | 2 |
| 2016 | ESP | 2017 | ESP | M | 120.0 | 355 | 2 |
| 2016 | ESP | 2017 | ESP | F | 143.0 | 363 | 37 |
| 2016 | ESP | 2017 | ESP | M | 112.0 | 372 | 910 |
| 2016 | ESP | 2018 | ESP | F | 136.0 | 742 | 13 |
| 2016 | KOR | 2017 | KOR | M | 129.0 | 377 | 16 |
| 2016 | KOR | 2018 | AUS | F | 153.0 | 712 | 700 |
| 2017 | AUS | 2018 | ESP | M | 113.0 | 364 | 26 |
| 2017 | ESP | 2017 | KOR | M | 131.0 | 8 | 29 |
| 2017 | FRA | 2019 | FRA | F | 110.0 | 704 | 11 |
| 2017 | KOR | 2018 | ESP | M | 133.0 | 372 | 365 |
| 2017 | KOR | 2018 | ESP | F | 137.0 | 375 | 377 |
| 2017 | KOR | 2018 | ESP | F | 152.0 | 343 | 4 |
| 2017 | KOR | 2018 | AUS | M | 144.0 | 311 | 18 |
| 2017 | KOR | 2018 | AUS | U | 150.0 | 314 | 3 |
| 2017 | KOR | 2018 | AUS | F | 160.0 | 312 | 29 |
| 2017 | KOR | 2018 | AUS | F | 151.0 | 315 | 16 |
| 2017 | KOR | 2018 | AUS | M | 140.0 | 320 | 3 |
| 2017 | KOR | 2018 | AUS | F | 148.0 | 321 | 6 |
| 2017 | KOR | 2018 | AUS | M | 151.0 | 316 | 7 |
| 2017 | KOR | 2018 | AUS | F | 141.0 | 318 | 5 |
| 2017 | KOR | 2018 | AUS | M | 161.0 | 320 | 22 |
| 2017 | ZAF | 2020 | UKR | M | 87.0 | 969 | 6620 |
| 2018 | AUS | 2018 | FRA | M | 142.0 | 26 | 24 |
| 2018 | AUS | 2018 | ESP | M | 139.0 | 22 | 20 |
| 2018 | AUS | 2018 | ESP | F | 149.0 | 34 | 15 |
| 2018 | AUS | 2019 | JPN | F | 139.0 | 428 | 3618 |
| 2018 | AUS | 2019 | FRA | F | 82.7 | 394 | 101 |
| 2018 | AUS | 2019 | FRA | M | 99.1 | 404 | 69 |
| 2018 | ESP | 2018 | ESP | U | 140.0 | 7 | 2 |
| 2018 | ESP | 2018 | ESP | F | 153.0 | 3 | 7 |
| 2018 | FRA | 2018 | FRA | M | 136.0 | 5 | 2 |
| 2018 | FRA | 2018 | ESP | F | 122.0 | 16 | 2 |
| 2018 | FRA | 2019 | FRA | M | 121.0 | 362 | 6 |
| 2018 | FRA | 2020 | ZAF | M | 135.0 | 776 | 3562 |
| 2019 | AUS | 2019 | FRA | M | 132.0 | 10 | 29 |
| 2019 | AUS | 2020 | AUS | M | 136.7 | 365 | 24 |
| 2019 | AUS | 2019 | AUS | U | 83.7 | 0 | 679 |
| 2019 | FRA | 2020 | AUS | F | 130.5 | 358 | 4 |
| 2019 | FRA | 2020 | AUS | F | 123.5 | 368 | 61 |
| 2019 | FRA | 2020 | FRA | F | 129.3 | 386 | 13 |
| 2020 | AUS | 2020 | FRA | M | 118.0 | 21 | 5 |

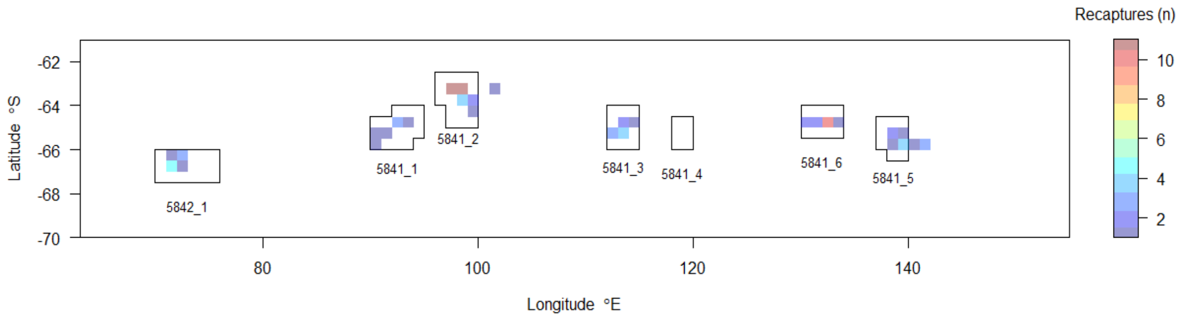



**Figure 13.10:** Spatial distribution of tagged and recaptured D. mawsoni since the 2011-12 season. Shading indicates total number of recaptures. Raster cells are of size 1° longitude and 0.5° latitude. Grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

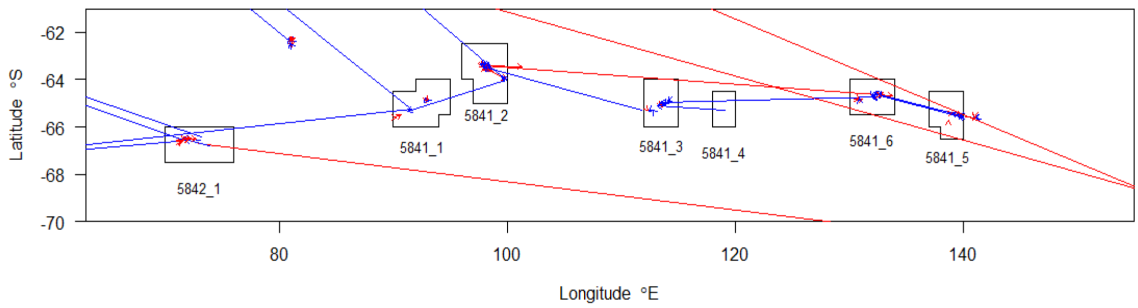



**Figure 13.11:** Tagging and recapture locations for recaptured D. mawsoni. Arrows represent the shortest distance (and direction) between tagging and recapture locations for each individual. Blue arrows = westward movements, red arrows = eastward movements, grey lines = SSRU boundaries, black lines = CCAMLR Research Blocks. Map datum = WGS84.

## 13.7 Environmental data collection

Between the 2014-15 and 2019-20 seasons, measurements of biotic and abiotic sea conditions were taken using conductivity, temperature, and depth (CTD) recorders attached to longlines (Table 11). Additionally, underwater video cameras (BVCs) were deployed by Australia in the 2015-16, 2017-18, 2018-19 and 2019-20 seasons.

**Table 13.11:** Number of CTD and BVC deployments

| Season | Member | CTD | BVC |
|---|---|---|---|
| 2015 | AUS | | |
| 2015 | KOR | | |
| 2016 | AUS | 33 | 15 |
| 2016 | KOR | | |
| 2017 | AUS | 17 | 12 |
| 2017 | KOR | 33 | |
| 2018 | AUS | 74 | 48 |
| 2018 | ESP | | 3 |
| 2019 | AUS | 3 | 3 |
| 2019 | FRA | 6 | |
| 2020 | AUS | 2 | 7 |
| 2020 | FRA | 2 | |

## 13.8 Acknowledgements

We would like to acknowledge and thank Australian Longline Pty Ltd., Pêche Avenir, Pesquerias Georgia S.L., SUNWOO Corporation, and Taiyo A & F Co. Ltd and the crew and observers aboard the fishing vessels for conducting the surveys, and collecting all data included in this paper. We would also like to acknowledge and thank the CCAMLR Secretariat for their assistance with data requests.

# Chapter 14: Preliminary integrated stock assessment for the Antarctic Toothfish fishery in East Antarctica

Philippe Ziegler

**This Chapter is based on:**

Delegation of Australia (2020e) Preliminary integrated stock assessment for the Antarctic Toothfish (*Dissostichus mawsoni*) fishery in Divisions 58.41 and 58.4.2. Document SC-CAMLR-2019/BG/38, CCAMLR, Hobart, Australia

# Abstract

We present an update of ageing and estimates of biological parameters, and of the single-region integrated stock assessment for Antarctic Toothfish (*Dissostichus mawsoni*) fishery in CCAMLR Divisions 58.4.1 and 58.4.2. The update of ageing and estimates of biological parameters addresses Milestone 1.4, the updated of the stock assessment addresses Milestone 1.6 of the current multi-member research plan for these Divisions (SC-CAMLR-39/BG/10).

The assessment model used all data available from the region, supplemented with parameter estimates from other Toothfish stock assessments. All evaluated assessment models indicated that the Antarctic Toothfish stock in Divisions 58.4.1 and 58.4.2 is unlikely to be depleted by the current level of fishing mortality. Accounting for vessel tagging performance was highly influential in the estimates of $B_0$ and *SSB* status, and we recommend further work to consolidate appropriate estimates of vessel-specific tag survival and detection performance.

The model indicated unresolved issues with the tagging data and a systematic lack of fit to the catch-at-age data. The lack of directed fishing in Division 58.4.1 resulted in spatially-restricted data collected from a single research block in Division 58.4.2 over the last two fishing season. The models indicated that fishing gear has only a minor influence on catch-at-length and catch-at-age compositions and tag-recapture data in this Antarctic Toothfish fishery, particularly relative to vessel and spatial population effects.

Estimates of preliminary catch limits for the two Divisions indicated that the catch limits estimated by the trend analysis are precautionary.

The collaborative approach adopted by the research plan proponents Australia, France, Japan, the Republic of Korea and Spain in Divisions 58.4.1 and 58.4.2 has worked well, with valuable on-water data collection and extensive subsequent data analyses. Based on these analyses, research has now progressed to a stock assessment, highlighting the value of the management procedures, agreed to by CCAMLR in 2011, which requires research plans in exploratory fisheries. However, an expansion of the spatial distribution of catch, tagging and data collection in Divisions 58.4.1 and 58.4.2 beyond a single research block will be required to improve estimates of stock biomass and catch limits in the future.

## 14.1 Introduction

Here, we present an update of ageing, estimates of biological parameters and a single-region integrated stock assessment for the fishery for Antarctic Toothfish (*Dissostichus mawsoni*) in CCAMLR Divisions 58.4.1 and 58.4.2. The update of ageing and estimates of biological parameters addresses Milestone 1.4, the updated of the stock assessment addresses Milestone 1.6 of the current multi-member research plan for these Divisions (SC-CAMLR-39/BG/10).

The first integrated stock assessment for these Divisions was presented in WG-FSA-18/58 Rev.1. This assessment indicated systematic lack of fit to the tag-recapture and catch-at-age data, and there was generally little information in the tag-recapture data to estimate $B_0$.

The authors of that assessment recommended a number of improvements, including:

- Estimation of vessel tag performance and accounting for vessel performance in the tag-recapture data used for the assessment;
- Region-specific or update of estimation for key parameters such as growth and maturity, and tag-shedding rates;
- Inclusion of more ageing data, especially from fish caught by trotline to improve the estimation of trotline selectivity;
- Development of approaches to account for spatial concentration of tag-releases and subsequent recaptures;
- Sensitivity analysis for different levels of IUU catches.

Based on new ageing data that have become available since the last assessment, we have updated the growth model, included the new ageing data into the assessment model, and also accounted for vessel performance in the tag-recapture data.

Unfortunately, there has not been directed fishing in Division 58.4.1 in the last two fishing season (2018/19 and 2019/20) and therefore no further tag-recapture or catch composition data could be collected in this Division. Fishing was confined to one single research block in Division 58.4.2, Catch limits were relatively small (50t and 60t) and tag-recapture collected during the 2018/19 and 2019/20 seasons are used here in this updated assessment.

In addition, Australian scientists aged otoliths from fish caught during autoline operations in 2018 and 2019, and, Korean scientist aged otoliths from fish caught during trotline operations in 2015. Both ageing data sets are also included in this assessment.

## 14.2 Stock hypothesis

For CCAMLR Area 58, three different stock hypotheses have been developed. These hypotheses differ in their assumptions about the locations of spawning grounds and connectivity to other regions. Agnew et al. (2009) proposed two stocks in the region, one to the west centred on Prydz Bay, the other one stretching to the east towards the Ross Sea. Yates et al. (2019) analysed catch rates, mean weight, maturity stage and sex ratios of Antarctic Toothfish in East Antarctica. The distribution of mean weight and maturity indicated the presence of both spawning and nursery grounds on the continental slope, a conclusion which supported the hypothesis of a spawning migration from the Antarctic continent to BANZARE Bank by Taki et al. (2011). Okuda et al. (2018) hypothesised similar distributions of spawning and nursery grounds, but expanded the proposed area to include Subareas 48.6 and 48.2.

In 2018, the CCAMLR Workshop for the Development of a *D. mawsoni* Population Hypothesis for Area 48 brought together available information on Antarctic Toothfish, resulting in three potential population hypotheses (Söffker et al. 2018). These hypotheses included between two and four subpopulations contributing to Antarctic Toothfish in Area 48. All three hypotheses assumed different levels of connectivity between adjacent CCAMLR areas, e.g. between Subarea 48.6 and Division 58.4.2, and between Subareas 48.2 and 88.3.

Using nuclear single nucleotide polymorphisms (SNP) markers, Maschette et al. (2019) evaluated the genetic diversity across Areas 48, 58 and 88. The sampled Toothfish from these areas shared over 99.9% of the observed variation between SNPs sites, indicating that the genetic structuring of Antarctic Toothfish across the Southern Ocean was very weak. While the combination of large-scale egg and larvae dispersal and long-distance fish movement, even at only low levels, would be sufficient to contribute to the dissolution of the genetic stock structure, the actual level of genetic stock exchange could not be determined.

Maschette et al. (2019) concluded that CCAMLR's approach to managing Toothfish fisheries at the levels of Subareas and Divisions was appropriate despite the weak genetic structuring of Antarctic Toothfish across the Southern Ocean. They also highlighted that, given the potential stock linkages between recruits and adult Toothfish from different areas, it was important to apply a management framework to all Toothfish fisheries which ensure biomass levels of each harvested population stay at a level that maintains sufficient recruitment for the long-term sustainability of the fish stocks.

## 14.3 Catch data

Data from Divisions 58.4.1 and 58.4.2 are summarised in Delegation of Australia (2020d) for fishing activities since 2012. However, the fishery started much earlier than this and catches from CCAMLR-authorised vessels since 2003 have been included here.

Table 14.1 presents the estimated catches from 2003 to the end of the fishing season in 2020 based on C2 data. For the assessment, catches were summarised by gear type and fishing season. IUU catch levels were assumed to be similar to those reported in WG-FSA-18/60 and have started in 2004.

**Table 14.1**: Reported catches (tonnes) for autoline, Spanish longline and trotline, and assumed IUU catches in the assessment for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2. Catches exclude quarantined catches.

| Year | Reported catches | | | | Assumed | Total |
|---|---|---|---|---|---|---|
| | Autoline | Spanish | Trotline | Total | IUU | |
| 2003 | 113 | | | 113 | 0 | 113 |
| 2004 | 20 | 7 | | 27 | 800 | 827 |
| 2005 | 60 | 558 | | 618 | 800 | 1418 |
| 2006 | | 661 | | 661 | 800 | 1461 |
| 2007 | | 631 | | 631 | 800 | 1431 |
| 2008 | | 530 | 10 | 540 | 800 | 1340 |
| 2009 | | 111 | 91 | 202 | 800 | 1002 |
| 2010 | | | 68 | 68 | 800 | 868 |
| 2011 | | 111 | 11 | 122 | 800 | 922 |
| 2012 | | | 202 | 202 | 800 | 1002 |
| 2013 | | 46 | 6 | 52 | 800 | 852 |
| 2014 | | 101 | 26 | 127 | 792 | 919 |
| 2015 | | | 212 | 212 | 800 | 1012 |
| 2016 | 51 | 120 | 230 | 401 | 0 | 401 |
| 2017 | 31 | 65 | 153 | 249 | 0 | 249 |
| 2018 | 176 | 124 | | 300 | 0 | 300 |
| 2019 | 50 | | | 50 | 0 | 50 |
| 2020 | 58 | | | 58 | 0 | 58 |

## 14.4 Biological parameters

The biological parameters used in this stock assessment are provided in Table 14.2.

### Length-at-weight

The parameters of the length-at-weight relationship, *a* and *b* were re-estimated by fitting the relationship:

$$W=aL^b$$

where *W* is the weight (t), *L* is the length (mm) of individual Toothfish between 2003-2020 (Figure 14.1, Table 14.2), and were fitted using the nls() function in R (R Development Core Team 2020).

**Table 14.2**: Biological population parameters and their values used in the assessment model for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2.

| Parameters | Specification | Source |
|---|---|---|
| Weight at length *L* (mm to t) | $c$ = 2.2281e-12<br>$d$ = 3.2320 | This paper |
| Size-at-age: | Von Bertalanffy | This paper |
| $L_\infty$ | 1545.0 | |
| $K$ | 0.139 | |
| $t0$ | -0.249 | |
| $CV$ | 0.142 | |
| Maturity | Logistic:<br>$a_{50}$ = 14.45<br>$a_{to95}$ = 6.5 | Parker and Grimes (2010) for TOA in Subarea 88.1/2 |
| Natural mortality *M* | 0.13 | Hanchet et al. 2015 for TOA in Subarea 88.1/2 |
| Stock–recruitment: Steepness *h* | Beverton-Holt, $h$ = 0.75 | Dunn et al. (2006) for Subarea 88.1/2 |
| Ageing error matrix | Yes | Burch et al. (2014) for TOP in Division 58.5.2 |

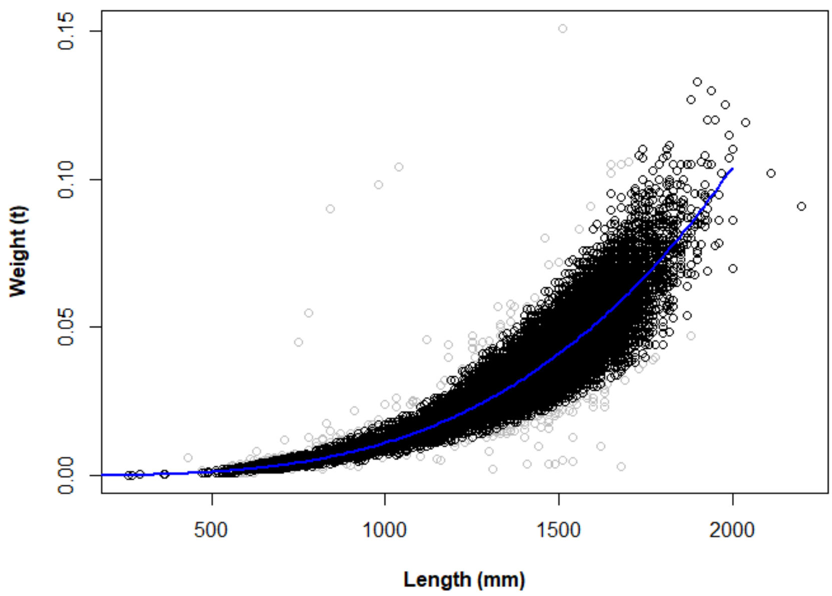



**Figure 14.1:** Estimated length-weight relationship (blue line) fitted to observations from all years 2003-2020 (black dots). Data points considered outliers (outside the 99.9% prediction interval of the linear regression log(Weight)~log(Length), grey dots) were not included in the estimation.

**Length-at-age**

A von Bertalanffy (VB) growth function was estimated following the approach of Candy et al. (2007). The definition of the likelihood function was based on variable probability sampling due to the effect of length-bin sampling on sampling probabilities. Fishing selectivity was poorly known and therefore its effect not investigated. Accounting for length-bin sampling was needed because aged fish were not randomly selected from the catch, with an over-representation of aged fish smaller than 1200 mm and fish larger than 1600 mm compared to the catch (Figure 14.2).

Over 3000 aged fish contributed to the estimation of the growth model. Estimated growth from all available age reading in 2018 and 2020 was largely unchanged (Table 3, Figure 3). Accounting for length-bin sampling resulted in estimated higher $L_\infty$ and higher *K*, but fish tended to grow faster than in the Ross Sea. There were differences in growth estimates when data from individual members were analysed, however it remained unclear whether these differences were based on biological differences in fish sampled in difference areas and/or in the otolith reading interpretation (see e.g. WG-FSA-19/47).

The 2020 growth model that accounted for length-bin sampling and had been fitted to all ageing data was used for the assessment here.

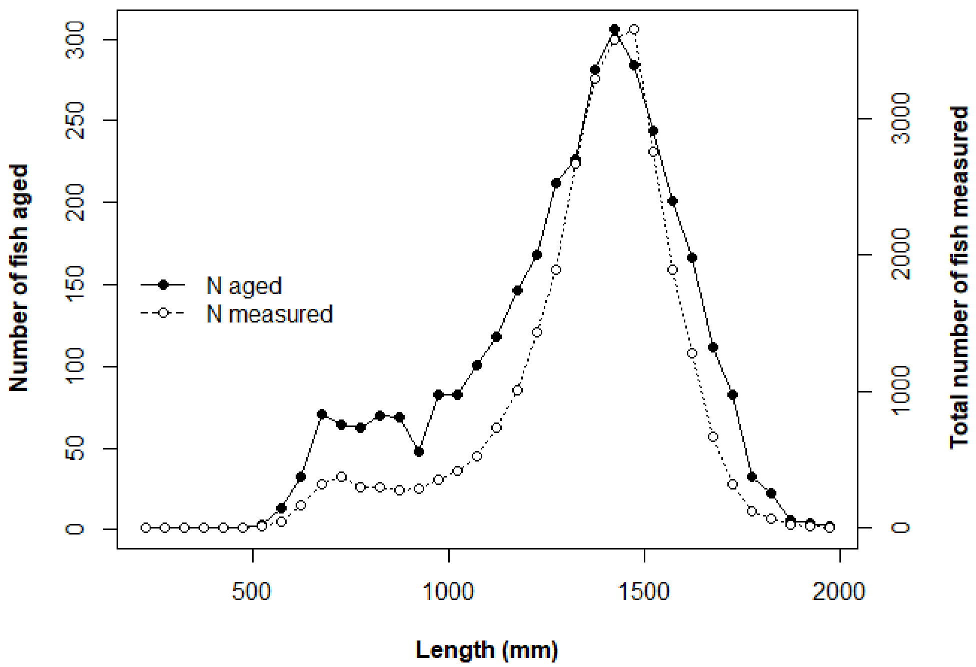



**Figure 14.2**: Number of fish sampled by 50 mm length bins for ageing (black circles) and measured for length overall in the fishery (open circles).

**Table 14.3:** Estimated von Bertalanffy growth parameters for models with available data in 2018 or 2020, using all data or individual members only (Data), and with or without accounting for length-bin sampling (LB sampling).

| Model | Data | LB sampling | $L_\infty$ | $K$ | $t_0$ | $CV$ |
|---|---|---|---|---|---|---|
| 2018 Growth (WG-FSA-18/58 Rev.1) | All | Yes | 1565.7 | 0.146 | -0.10 | 0.015 |
| 2020 Growth (used in assessment here) | All | Yes | 1549.5 | 0.139 | -0.25 | 0.014 |
| 2020 Growth (no length-bin sampling) | All | No | 1625.8 | 0.113 | -0.70 | 0.019 |
| | | | | | | |
| 2020 Growth - Australian reads only | AUS | Yes | 1490.6 | 0.173 | -0.12 | 0.015 |
| 2020 Growth - Spanish reads only | ESP | Yes | 1650.2 | 0.122 | 1.00 | 0.011 |
| 2020 Growth - Korean reads only | KOR | Yes | 1548.5 | 0.141 | 1.00 | 0.010 |

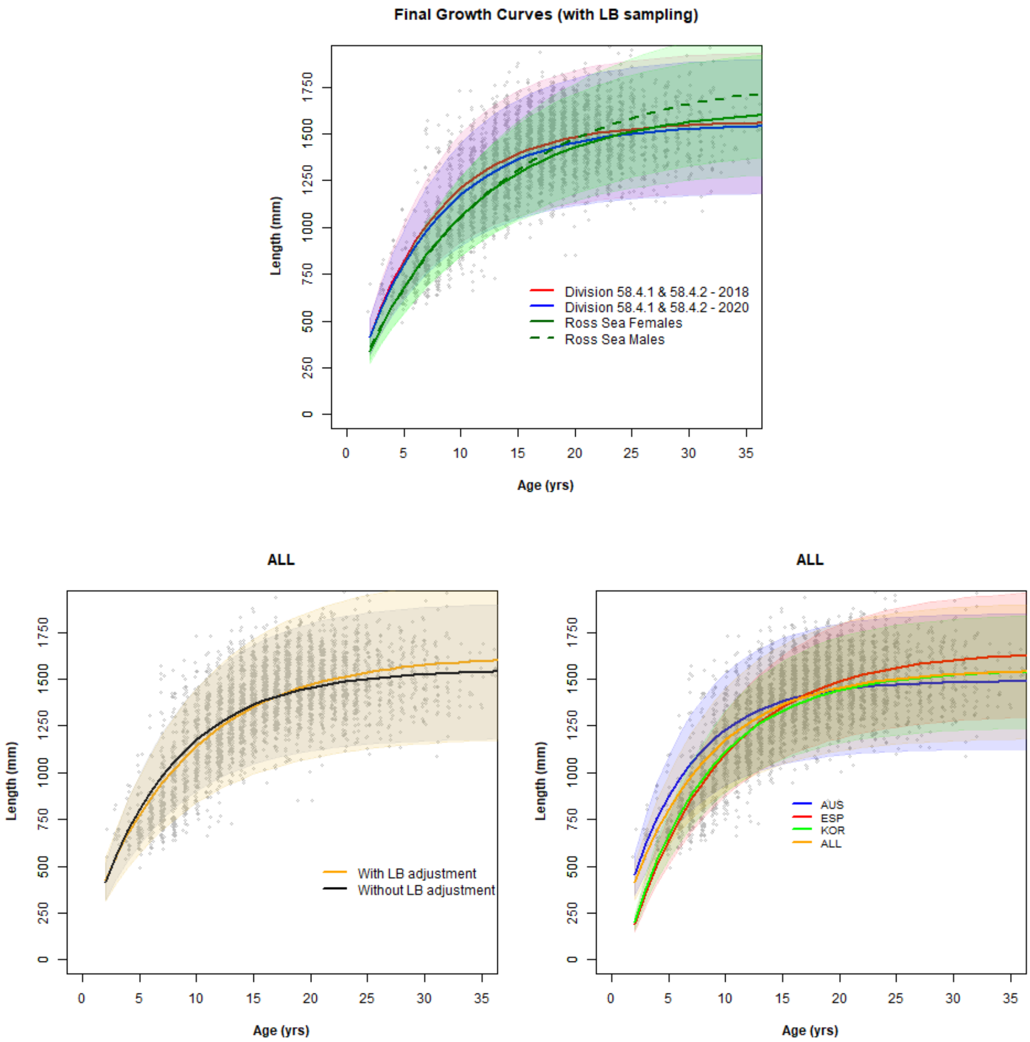



**Figure 14.3:** Length-at-age data (grey dots), and estimated von Bertalanffy growth curves with approximate 95% confidence intervals of the data based on CV for (top) all data available in 2018 (red, WG-FSA-18/58 Rev.1) in 2020 (blue), and males (green solid line) and females (green dashed line) in the Ross Sea (Mormede et al. 2017); (bottom left) for all data available in 2020 with (orange) and without (black) accounting for length-bin sampling; and (bottom right) data by individual member available in 2020.

### Maturity

Only estimates for maturity-at-length were available for this region (Kim et al. 2018). For maturity-at-age, an average of the estimates for males and females from the Ross Sea were taken (Figures 14.4 and Table 14.2, Parker and Grimes 2010).

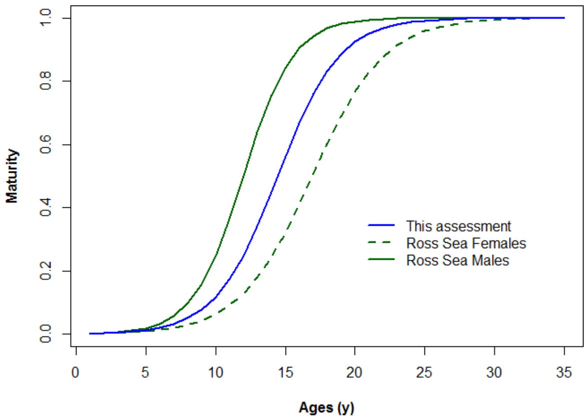



**Figure 14.4:** Maturity-at-age assumed in this assessment (blue), and maturity models for males (green solid line) and females (green dashed line) in the Ross Sea (Parker and Grimes 2010).

### Stock recruitment relationship

Recruitment was assumed to follow a Beverton-Holt relationship, whereby stock- recruitment (SR) is assumed to be a function of the spawning stock biomass (SSB), the virgin spawning stock biomass ($B_0$), and the steepness parameter $h$, defined as $h$ = SR(0.2 $B_0$), where:

$$SR(SSB) = \frac{SSB}{B_0} / \left(1 - \frac{5h-1}{4h}\left(1 - \frac{SSB}{B_0}\right)\right)$$

For Antarctic Toothfish in Divisions 58.4.1 and 58.4.2, the stock recruitment relationship was assumed to have a steepness $h$ = 0.75 following Dunn et al. (2006).

### Natural mortality

An estimate for natural mortality for Antarctic Toothfish was taken from the Ross Sea region and assumed constant across all age classes as $M$ = 0.13 (Table 14.2).

### Ageing error matrix

Burch et al. (2014) estimated an ageing error matrix (AEM) for Patagonian Toothfish (*D. eleginoides*) based on the method of Candy et al. (2012). Since the development of a reference otolith collection, required to estimate an AEM, is still in progress, we used the AEM for *D. eleginoides* here (see Ziegler 2017).

## 14.5. Abundance and other observations

The specifications for the abundance and other observations used in this stock assessment are provided in Table 14.4.

**Table 14.4:** Abundance and other observations used in the assessment for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2.

| Observations | Specifications |
|---|---|
| Tagging data | |
| Release sub-fisheries | Autoline, Spanish longline, trotline |
| Years | 2010–2019 |
| Recapture sub-fisheries | Autoline, Spanish longline, trotline |
| Years | 2011-2020 |
| Tag detection | 0.991 (from Mormede et al. 2017 for Subarea 88.1/2) |
| Tag-release mortality | 0.1 (from Agnew et al. (2011) for TOP in Subarea 48.3) |
| No-growth period | 0.5 y (from Mormede et al. 2017 for Subarea 88.1/2) |
| Tag shedding | 0.0084 (from Dunn et al. 2011 for Subarea 88.1/2) |
| Catch-at-age | Autoline: 2016-2019<br>Spanish longline: 2013-2014, 2016-2017<br>Trotline: 2015 |
| Estimated sample size (ESS) | Estimated (Francis 2011a, 2011b) |
| Catch-at-length (some models) | Autoline: 2003-2005, 2020<br>Spanish longline: 2004-2009, 2011, 2018<br>Trotline: 2008-2014, 2016-2017 |
| Estimated sample size (ESS) | Set to 1 |

### Tagging data

Tag-releases in Divisions 58.4.1 and 58.4.2 were limited to the years 2010-2019 (Table 14.5). In the assessment model, the numbers of longline tag-releases and tag-recaptures used were capped at 6 years at liberty and within-season recaptures were excluded. Tag-release mortality was assumed to be 0.1 (Agnew et al. 2011), and a no-growth period after tagging of 0.5 years was assumed. Estimates for tag-detection rate (99.1%) and tag-shedding rates were taken from the Ross Sea region assessment model (Mormede 2017, Parker and Mormede 2017).

**Table 14.5:** Numbers of longline tag-releases and tag-recaptures that were used in the assessment for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2.

| Year | Releases | Recaptures | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Total |
| 2010 | 210 | 2 | - | - | - | - | - | - | - | - | - | 2 |
| 2011 | 462 | | - | - | 1 | - | - | - | - | - | - | 1 |
| 2012 | 1031 | | | - | - | - | 1 | - | - | - | | 1 |
| 2013 | 281 | | | | 3 | - | 1 | 1 | - | - | - | 5 |
| 2014 | 669 | | | | | - | - | - | 1 | - | - | 1 |
| 2015 | 571 | | | | | | 4 | 4 | 1 | - | - | 9 |
| 2016 | 2032 | | | | | | | 5 | 3 | - | - | 8 |
| 2017 | 1306 | | | | | | | | 14 | 2 | - | 16 |
| 2018 | 592 | | | | | | | | | 2 | - | 2 |
| 2019 | 258 | | | | | | | | | | 4 | 4 |
| **Total** | **7412** | **2** | **0** | **0** | **4** | **0** | **6** | **10** | **19** | **4** | **4** | **49** |

Vessel tagging performance was estimated for vessel tagging and recapturing fish in Divisions 58.4.1 and 58.4.2 since 2011 using the method by Mormede and Dunn (2013). The tagging detection performance could only be estimated for some vessels (Figure 14.5), and the data were too limited to estimate the survival of tagged fish by vessels. Where the local performance could not be estimated, values were taken from the Ross Sea (Parker et al. 2017) if available, or assumed to be 1.

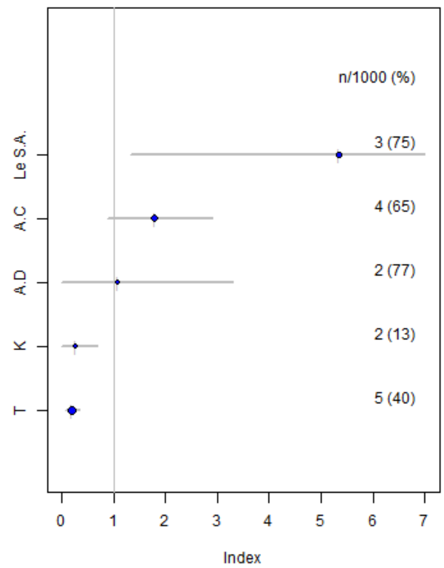



**Figure 14.5:** Indices of relative detection rates of tagged fish by vessel, using the method in Mormede and Dunn (2013) and a reference distance of 20 nm. The circle and vertical bars indicate the index value. The area of each circle is proportional to the number of fish scanned by each vessel in the analysis. The grey vertical line represents an index of 1, where case and control vessels performed identically (i.e. had the same recapture rate). Horizontal bars show the 90% confidence interval. The numbers on the right represent the number of scanned fish from the case fishing events in the analysis, and in brackets the percentage of the scanned fish included in the analysis for each vessel.

## Length and age data

A large number of Toothfish have been measured annually for length and a number otoliths have been aged by Australia for autoline, Spain for Spanish longline and Korea for trotline (Table 14.6). Year-specific age-length keys (ALKs), grouped by 50 mm length bins from 150 to 2000 mm for the autoline for 2016 - 2019, and for Spanish longline in 2013, 2014, 2016 and 2017, and for trotline in 2015, were calculated from the respective age-length samples (Figure 14.6).

**Table 14.6**: Number of Toothfish measured for length or age and used in the assessment by gear type. Age readings were used to calculate age-length keys from the catch-at-length observations (ALKs).

| Year | Lengths | | | Ages | | |
|---|---|---|---|---|---|---|
| | Autoline | Spanish | Trotline | Autoline | Spanish | Trotline |
| 2003 | 5438 | | | | | |
| 2004 | 916 | 299 | | | | |
| 2005 | 2633 | 8510 | | | | |
| 2006 | | 5473 | | | | |
| 2007 | | 8262 | | | | |
| 2008 | | 8066 | 229 | | | |
| 2009 | | 1157 | 2038 | | | |
| 2010 | | | 2763 | | | |
| 2011 | | 1751 | 467 | | | |
| 2012 | | | 5406 | | | |
| 2013 | | 1217 | 192 | | 492 | |
| 2014 | | 3326 | 335 | | 497 | |
| 2015 | | | 2301 | | | 450 |
| 2016 | 1437 | 4467 | 2754 | 331 | 341 | |
| 2017 | 1236 | 2306 | 2307 | 202 | 245 | |
| 2018 | 4299 | 3473 | | 375 | | |
| 2019 | 1707 | | | 305 | | |
| 2020 | 1877 | | | | | |
| **Total** | **19543** | **48307** | **18792** | **1213** | **1575** | **450** |

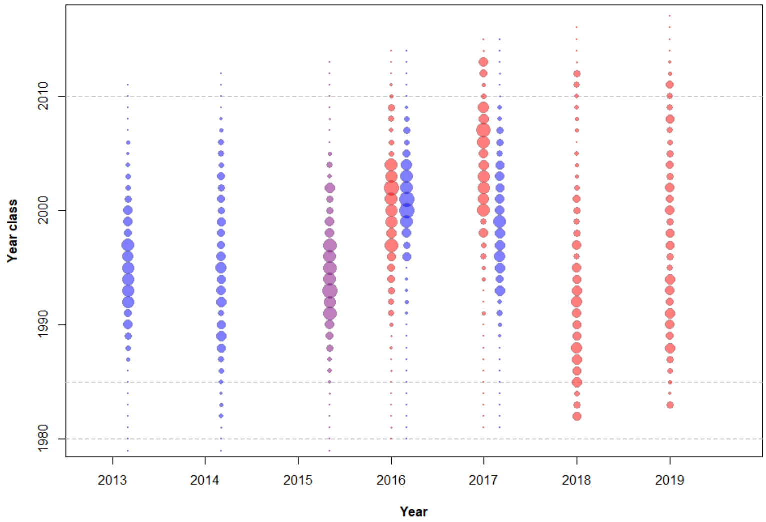



**Figure 14.6**: Bubble plots for the number of fish aged for autoline (red), Spanish longline (blue) and trotline (purple). The numbers of aged fish are relative to the diameter of the circles.

## 14.6. Assessment methods

### Model population dynamics

A single-region, single-sex age-structured CASAL assessment model (Bull et al. 2012) was applied for the assessment with age classes from 1-35 years. CASAL 2.30-2012-03-21 rev. 4648 was used in all instances, following the recommendation of WG-SAM-14 (WG-SAM-14, para. 2.29).

The specifications for the assessment model and estimated parameters are provided in Table 7. The assessment models were run for the period from 1997-2020 and fitted to tag-recaptured data and catch-at-age and (in some model runs) catch-at-length observations (Table 14.5). The annual cycle was divided into three time steps or seasons during which (1) fish recruitment, the first half of natural mortality, and fishing, (2) the second part of natural mortality and spawning, and (3) ageing occurred.

### Starting data and model configuration

The sub-fishery structure for this assessment was based on the three gear types autoline, Spanish longline and trotline. IUU catches from Table 1 were included in the assessment and assumed to have been taken with a selectivity function similar to that of the Spanish longline.

Catch-at-length data grouped by 50 mm length bins from 150 to 2000 mm were used to estimate catch proportions-at-length. Where there were ALKs available, the catch-at-length data were converted to catch-at-age. In some model runs, catch-at-length data were also used with an effective sample size (ESS) set to 1 to minimise their influence on the estimation of fish biomass and year class strength. The initial effective sample size for catch-at-age were derived by assuming a relationship between the observed proportions-at-age $O_j$ and their CVs $c_j$ as estimated from bootstrap sampling that accounted for haul-specific proportions-at-length, the ALK and random ageing error. The estimated effective sample size was then derived using a robust non-linear least squares fit of log($c_j$) ~ log($O_j$) assuming a multinomial distribution.

**Table 14.7**: Model specifications for estimated parameters in the assessment model for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2.

| **Model specifications** | **Specifications** |
|---|---|
| Assessment period | 1997-2020 |
| Age classes | 1–35 y |
| Length classes | 300–2000 mm |
| $B_0$ | Estimated |
| Mean recruitment $R_0$ | Derived from $B_0$ |
| Period of estimated YCS | 1997-2014 |
| $\sigma_R$ for projections | Calculated from YCS 1997–2014 |

| **Estimated parameters** | **Specifications** |
|---|---|
| $B_0$ | Prior: uniform |
| Starting value (bounds) | 50 000 (10 000–100 000) |
| YCS | Prior: lognormal |
| Starting value (bounds) | $\mu$ = 1 (0.001–200), CV = 0.6 |
| Fishing selectivities: | |
| Double plateau normal: | Prior: uniform |
| Sub-fisheries | Autoline, Spanish longline, trotline |
| Starting values (bounds) | $a_1$: 10 (1–20) |
| | $a_2$: 6 (0.1–20) |
| | $\sigma_L$: 1 (0.1–20) |
| | $\sigma_R$: 3 (0.1–20) |
| | $a_{max}$: 1 (1–1) |
| Number of estimated parameters | 31 |

Double-normal-plateau (DNP) fishing selectivity functions were fitted for each sub-fishery. The DNP function was calculated as *f(x)* for age *x* (Bull et al. 2012):

$$f(x) = \begin{cases} a_{\max} 2^{-\left[(x-a_1)/\sigma_L\right]^2} & x \le a_1 \\ a_{\max} & a_1 < x \le a_1 + a_2 \\ a_{\max} 2^{-\left[\{x-(a_1+a_2)\}/\sigma_U\right]^2} & x > a_1 + a_2 \end{cases} \qquad (3)$$

where $a_1$ and $a_1 + a_2$ define the age range at which the ogive takes the value $a_{max}$, and $\sigma_L$ and $\sigma_R$ define the shape of the left-hand and right-hand side of the DNP function such that the ogive takes the value $0.5a_{max}$ at $a = a_1 - \sigma_L$ and $a = a_1 + a_2 + \sigma_R$. In all cases, $a_{max}$ was not estimated but set to 1, i.e. only four parameters were estimated for all DNPs.

**Model estimating procedure**

The assessment model, as summarised in Table 14.4, estimated unfished spawning stock biomass $B_0$, annual year class strength (*YCS*), and the parameters of the selectivity functions for all sub-fisheries (gear types).

All models included penalties for *YCS* and catch. A penalty for *YCS* was intended to force the average of estimated *YCS* towards 1. Strong catch penalties prohibited the model from returning an estimated fishable biomass for which the catch in any given year would exceed the maximum exploitation rate set at $U = 0.995$ for each sub-fishery.

Process error was estimated and added in a number of iterations. Iterative data re-weighting followed the method TA1.8 described by Francis (2011a and 2011b) to allow for correlations within the observed composition data. The reweighting was applied first to the commercial catch composition data of all sub-fisheries, and then to the tag-recapture data.

For catch-at-age composition data, the weight $w_j$ for each age $j$ observed by a sub-fishery or the survey was estimated as:

$$w_j = \frac{1}{\mathrm{var}_i\left[ (O_{iy} - E_{iy}) / \sqrt{(v_{iy} / N_{iy})} \right]} \qquad (4)$$

where $O_{iy}$ is the observed and $E_{iy}$ is the expected proportions for age or length class $i$ in year $y$, $v_{iy}$ is the variance of the expected age or length distribution, and $N_{iy}$ was the number of multinomial cells. The weight was then multiplied with the sample size from the previous step before re-running the model.

For the re-weighting of the tagging data, tag-dispersion $\phi_j$ was estimated for each recapture event $j$ as:

$$\phi_j = \mathrm{var}\left( \frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}}} \right) \qquad (5)$$

where $O_{Ij}$ is the observed and $E_{Ij}$ is the expected number of recaptures in each length bin $i$. Over-dispersion terms for each recapture event were then combined by taking the geometric mean and the log-likelihood for tagging data was modified by multiplying by $1/\phi$.

Only a point estimate (maximum posterior density MPD) and its approximate covariance matrix for all free the parameters as the inverse Hessian matrix were estimated. Due to the quality of the model fit (see Results), no Monte Carlo Markov Chains (MCMCs) sampling was conducted or catch limit estimated.

### Model scenarios

Three model scenarios were tested (Table 14.8).

In Model 1, all vessels were assumed to have equal tagging performance, and catch-at-length data were included. The selectivity functions of autoline, Spanish longline and trotline were estimated individually.

In Model 2, all vessels were assumed to have equal tagging performance, but catch-at-length data were not included. The selectivity functions of autoline, Spanish longline and trotline were estimated individually.

In Model 3, vessels were assumed to have individual tagging performance, and again catch-at-length were not included. The selectivity functions of autoline, Spanish longline and trotline were estimated individually.

In Model 4, vessels were assumed to have individual tagging performance, and again catch-at-length were not included. Here, one common selectivity function was estimated for all three gear types.

**Table 14.8**: Tested model scenarios the assessment model for Antarctic Toothfish in Divisions 58.4.1 and 58.4.2.

| Model | Vessel tagging performance | Catch-at-length | Fishing selectivities |
|---|---|---|---|
| Model 1 | All vessels equal | Yes | Autoline, Spanish longline, trotline |
| Model 2 | All vessels equal | No | Autoline, Spanish longline, trotline |
| Model 3 | Individual vessel performance | No | Autoline, Spanish longline, trotline |
| Model 4 | Individual vessel performance | No | Longline |

### Yield calculations

Catch projection trials accounted for uncertainty surrounding parameter estimates of the model as well as future recruitment variability. In order to integrate across uncertainty in the model parameters, MCMC samples were used for CASAL's projection procedure to obtain 1000 random time series samples of estimated numbers of *YCS* estimates from 1997-2014. The median of the square root of the variance of the YCS numbers provided a robust estimate of the $\sigma_R$ for recruitment required for the lognormal random recruitment generation.

The estimated *CVs* were used to generate the random recruitment from 2015 until the end of the 35-year projection period. Based on this sample of projections for spawning stock biomass, long-term catch limits were calculated following the CCAMLR decision rules:

- Choose a yield $\gamma_1$, so that the probability of the spawning biomass dropping below 20% of its median pre-exploitation level over a 35-year harvesting period is 10% (depletion probability).
- Choose a yield $\gamma_2$, so that the median escapement of the spawning biomass at the end of a 35-year period is 50% of the median pre-exploitation level.
- Select the lower of $\gamma_1$ and $\gamma_2$ as the yield.

The depletion probability was calculated as the proportion of samples from the Bayesian posterior where the predicted future spawning biomass was below 20% of $B_0$ in the respective sample at any time over the 35-year projected period. The level of escapement was calculated as the proportion of samples from the Bayesian posterior where the projected future status of the spawning biomass was below 50% of $B_0$ in the respective sample at the end of the 35-year projection period.

Catch limit estimates were based on the assumption of constant annual catches. The entire remaining future catch was assumed to be taken equally by the three longline types.

## 14.7 Results

**MPD estimates**

Models 1 and 2 which assumed equal vessel tagging performance with either including or excluding catch-at-length data resulted in almost identical estimates of $B_0$ of around 26 274 tonnes and *SSB* status of 0.89 (Table 14.9). This indicated that the catch-at-length did not interfere in the process of estimating biomass and recruitment and was therefore omitted in subsequent models.

When individual vessel tagging performance for survival and detection rates of tagged fish were accounted for in Model 3, the estimated $B_0$ was substantially lower at 15 200 tonnes and the current *SSB* status was 0.75. The impact of the assumed fishing selectivity functions on the model was minor, with similar estimated parameters for individual estimated fishing selectivities (autoline, Spanish longline and trotline) in Model 3 or one single, common fishing selectivity (longline) in Model 4. Model 4 was therefore assumed to be the best and most parsimonious model, with 6 less estimated parameters than Model 3.

**Table 14.9:** MPD estimates of unfished spawning stock biomass $B_0$ in tonnes, SSB status at the end of 2020, $R_0$ (mean recruitment in millions that gives rise to $B_0$), and the objective function (Obj Fun).

| Model | Description | $B_0$ | *SSB status* 2020 | $R_0$ | *Obj Fun* |
|---|---|---|---|---|---|
| | 2018 Model | 29 948 | 0.87 (2018) | 0.56 | |
| 1 | Equal vessel tagging performance, with catch-at-length | 26 124 | 0.89 | 0.54 | 248 |
| 2 | Equal vessel tagging performance | 26 274 | 0.89 | 0.54 | 211 |
| 3 | Individual vessel tagging performance | 15 200 | 0.75 | 0.31 | 219 |
| 4 | Individual vessel tagging performance, one fishing selectivity | 15 026 | 0.74 | 0.31 | 225 |

As expected, only the trajectory of *SSB* changed between Models 2 and 3 while the estimated *YCS* remained similar (Figure 14.7). Based on the estimated selectivity functions in Model 3, the three gear types target and retain young fish in a similar way. When estimated individually, the selectivity for autoline remained high for old fish while it dropped smoothly for Spanish longline and abruptly for fish older than 25 years for trotline (Figure 14.8). The estimated common selectivity function for all gear types in Model 4 was similar to that of Spanish longline in Model 3.

The contributions to the objective function for Model 4 are given in Figure 14.9.

a) Model 2 b) Model 3

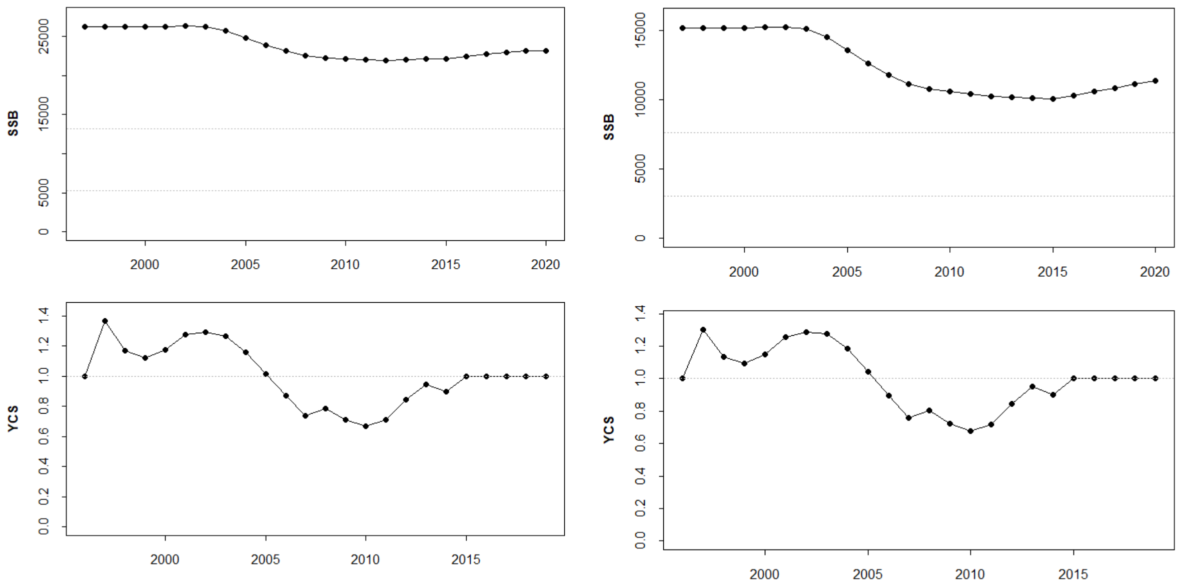



**Figure 14.7:** MPD estimates of SSB and *YCS* for (a) Model 2 and (b) Model 3.

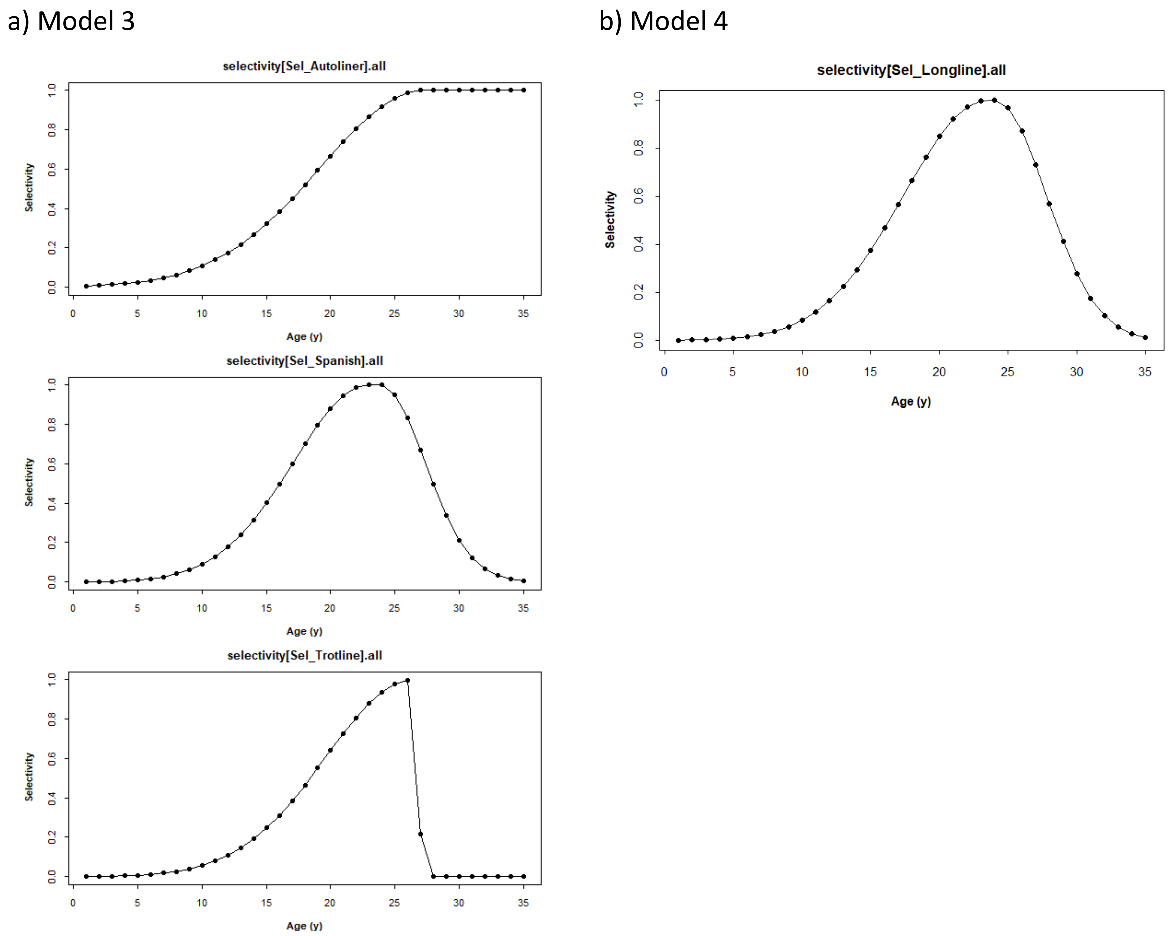



**Figure 14.8:** Estimated selectivity functions for (a) autoline (top left), Spanish longline (top right) and trotline (bottom) in Model 3, and (b) a common longline selectivity function in Model 4**.**

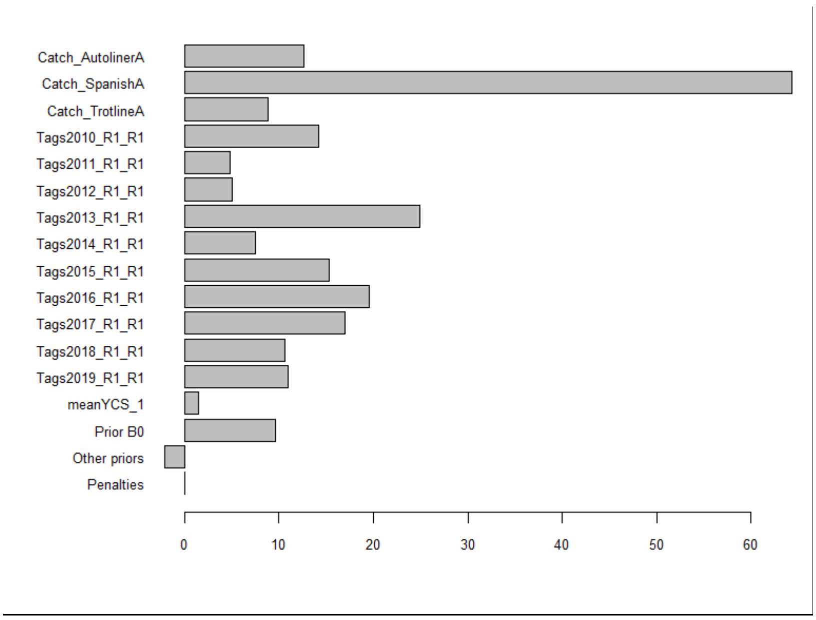



**Figure 14.9:** Contributions to the objective function for Model 4**.**

The fits to the tag-recapture data were similar in all models (Figures 14.10 to 14.12 for Model 4). There was a trend in increasing numbers of observed compared expected recaptures since 2016, possibly driven the increasing concentration of fishing in the western research blocks and the single one in Division 58.4.2 in the two most recent years.

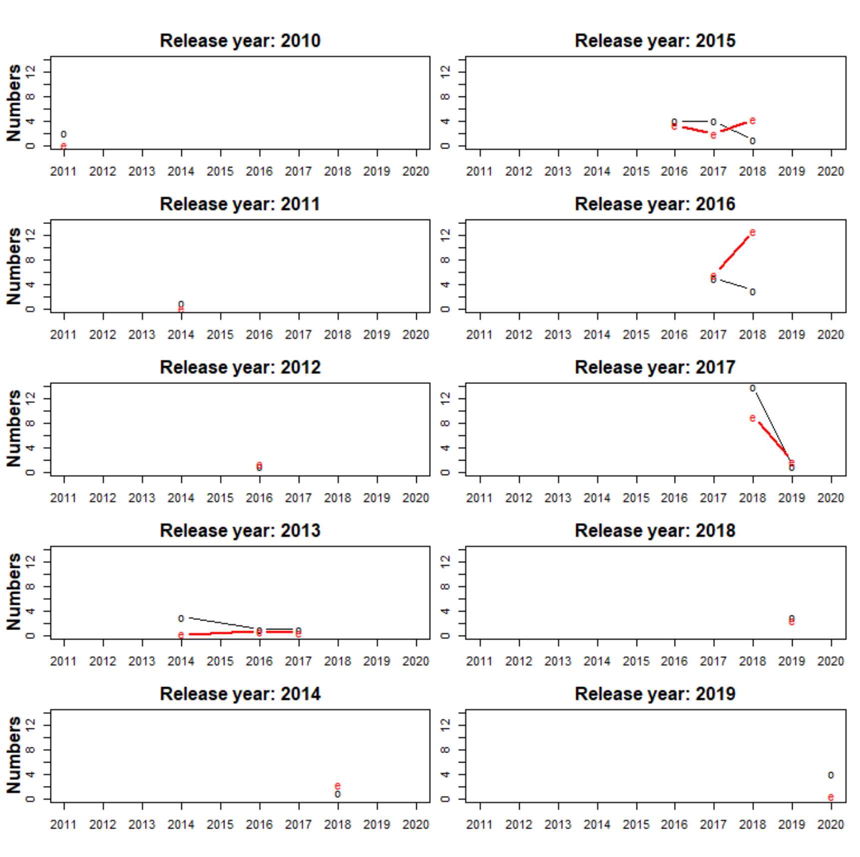



**Figure 14.10:** Numbers of observed (black) and predicted (red) tag recaptures for Model 4.

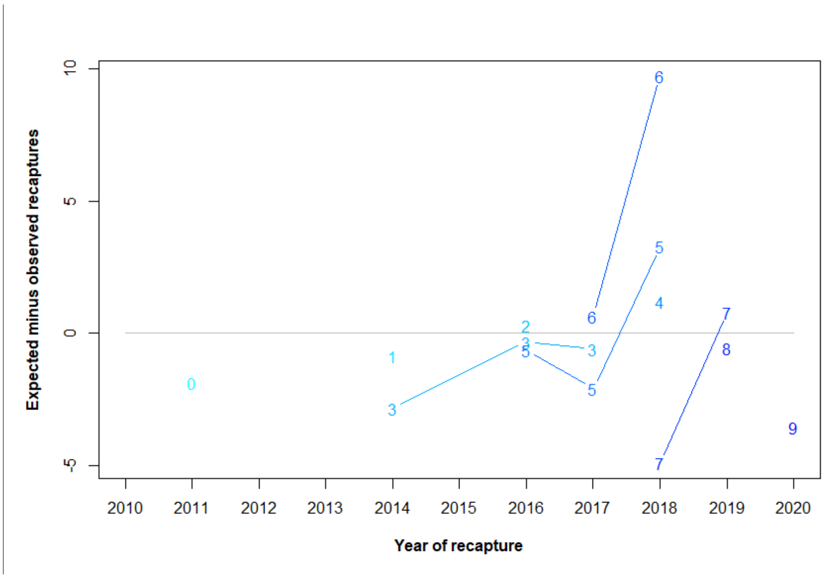



**Figure 14.11:** Numbers of observed minus predicted tag recaptures, colour-coded by release year (0=2010, 1=2011, 2=2012 etc.) for Model 4.

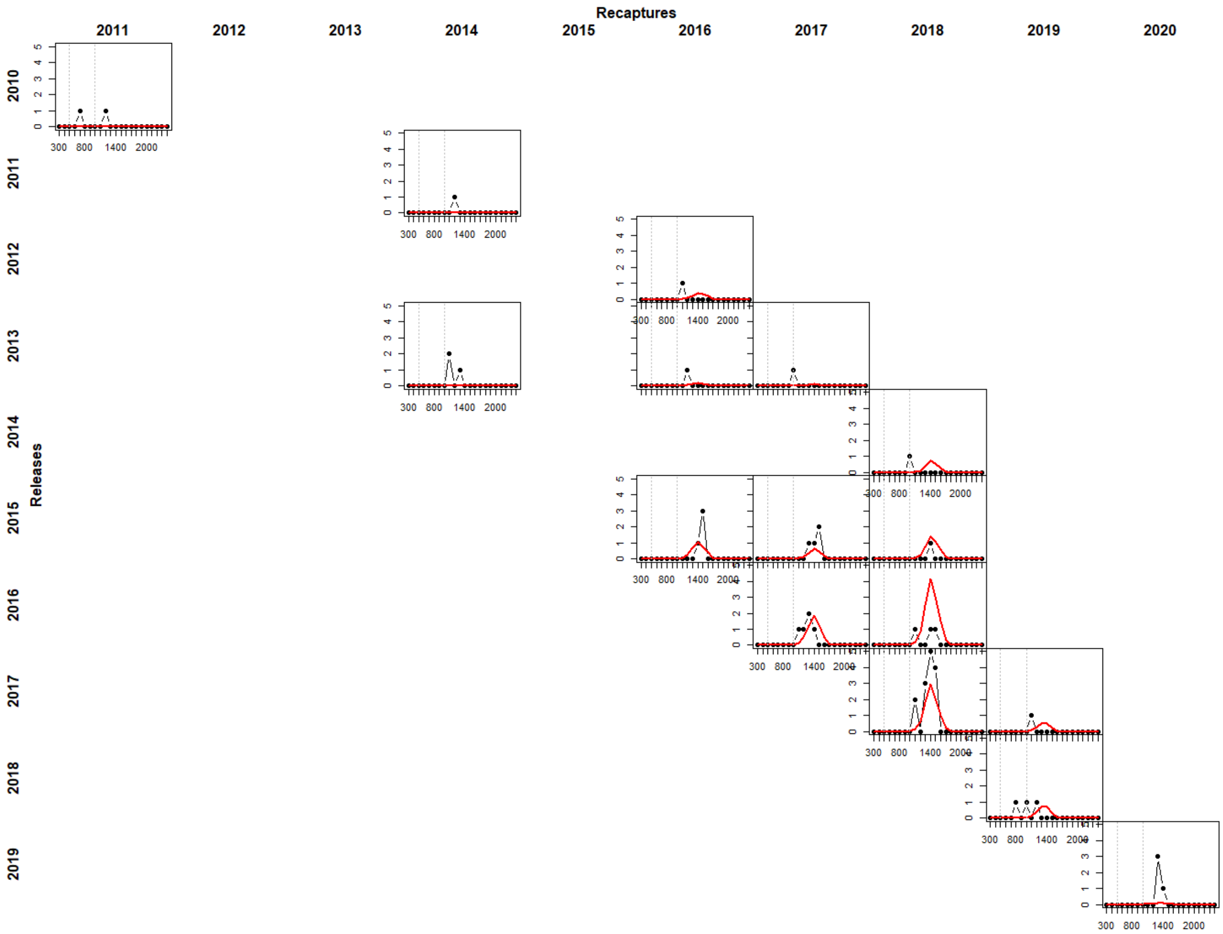



**Figure 14.12:** Numbers of observed (black) and predicted (red) tag recaptures by 100 mm length bins for Model 4.

The catch-at-age data for autoline showed distinct differences between 2016-2017 where fishing occurred and samples were collected across Divisions 58.4.1 and 58.4.2, and 2018-2019 where fishing had only been allowed in a single research block in Division 58.4.2 (Figures 14.13 and 14.14). Age classes in research block 5842_1 appear to be much more broadly distributed than in the research blocks in Division 58.4.1 where also the Spanish longline and trotline age samples originated. The fits to catch-at-age and the residuals indicated an overall and systematic lack of fit (Figure 14.15).

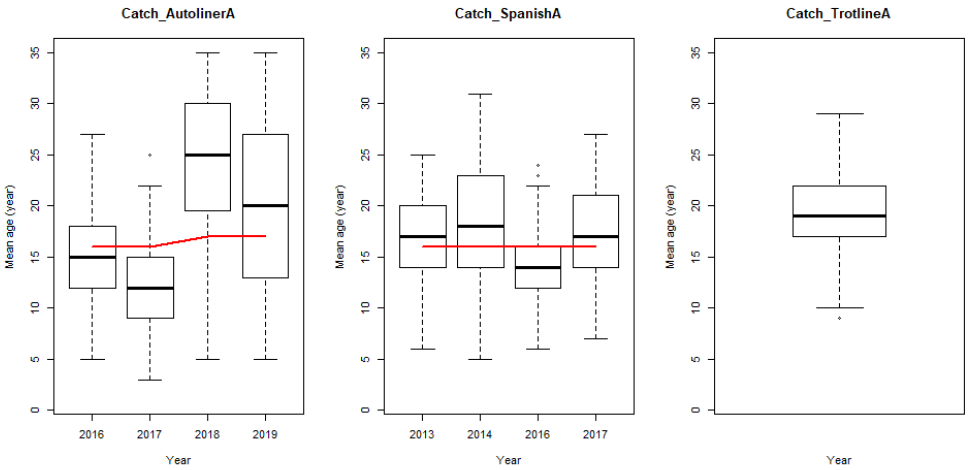



**Figure 14.13:** Boxplots of observed age by gear type and predicted median age for Model 4.

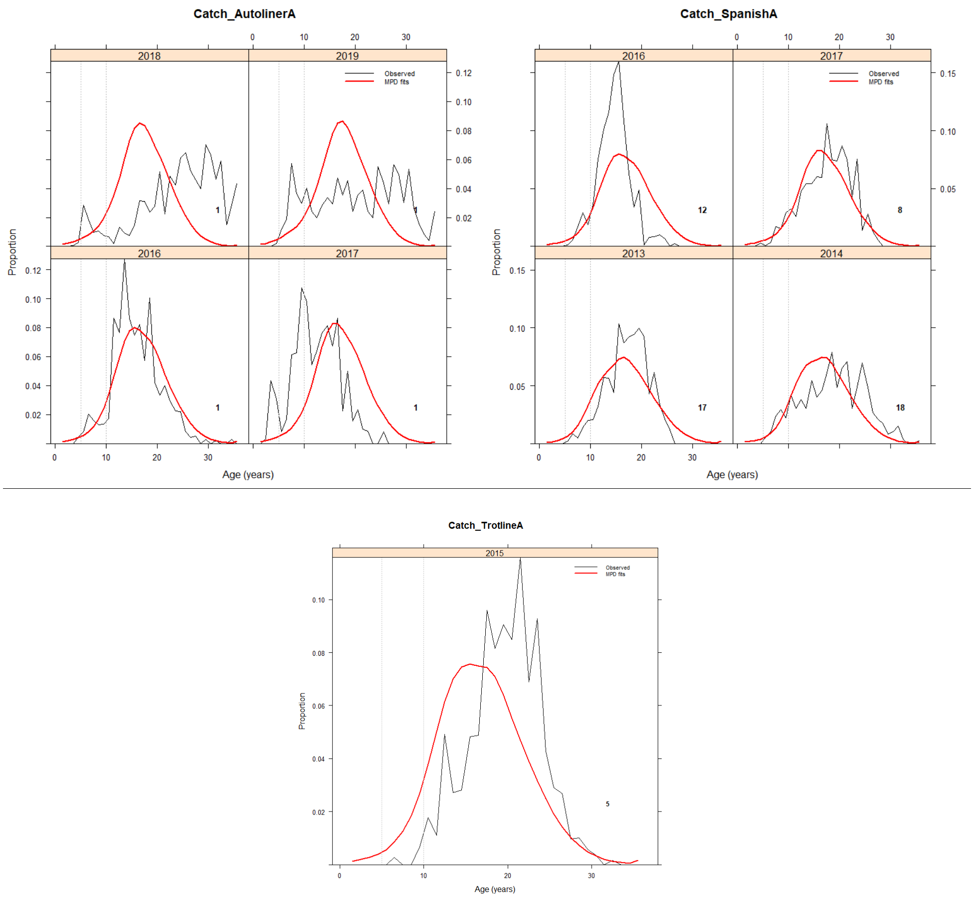



**Figure 14.14:** Observed (black) and predicted (red) proportions-at-age for autoline (left), Spanish longline (right) and trotline (bottom). Numbers are the ESS for in the final iteration of Model 4.

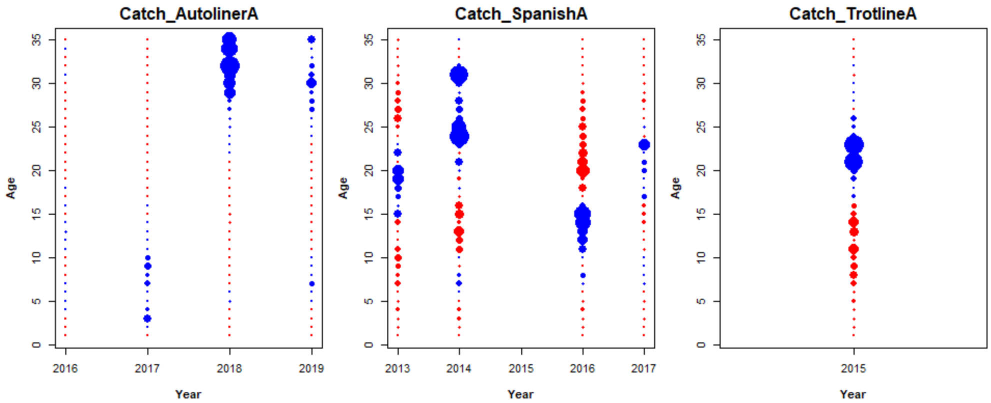



**Figure 14.15:** Pearson's residuals of MPD fits by age and year for autoline (left) and Spanish longline (right) for Model 4.

The likelihood profile for $B_0$ for Model 4 is shown in Figure 16. Most data sets contained little information with respect to the estimation of $B_0$. Tags released in 2012and 2016 indicating that a larger $B_0$ was most likely while tags released in 2013 and 2017-2019 indicated strongly that $B_0$ should be small.

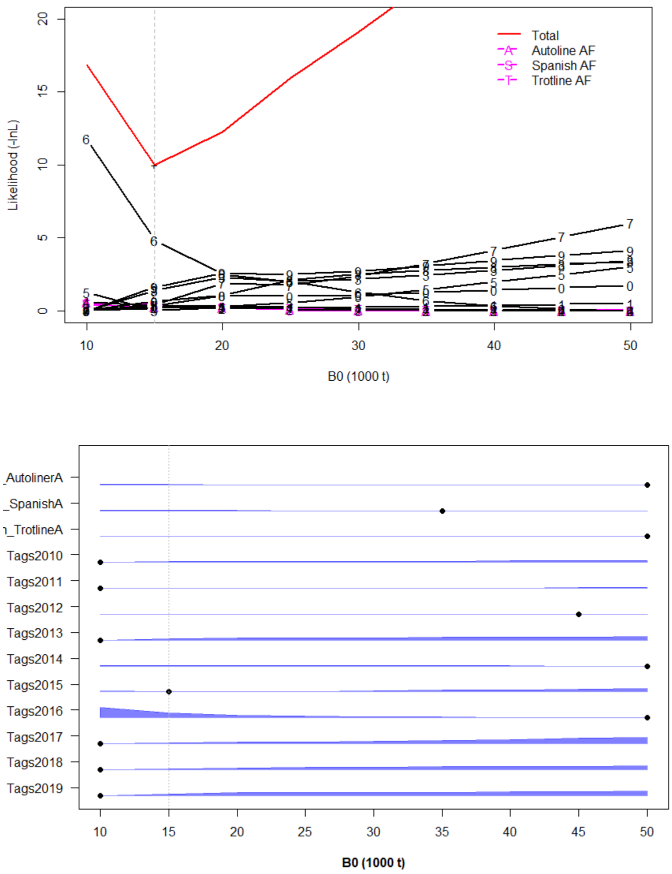



**Figure 14.16**: Likelihood profiles (-2 log-likelihood) across a range of $B_0$ values for Model 4 for all data sets together (top) and separate data sets (bottom - dots indicate the location of the minimum value). To create these profiles, $B_0$ values were fixed while only the remaining parameters were estimated. Values for each data set were rescaled to have a minimum of 0, while the total objective function was rescaled to 10. The dotted grey line indicates the MPD estimate.

**MCMC estimates**

Model 2 with an MCMC estimate of 26 609 tonnes leads to a larger estimate of the virgin spawning stock biomass $B_0$ than that obtained for Models 3 and 4 (Table 14.10). The MCMC estimate for $B_0$ in Model 4 was 15 122 tonnes, with an estimated *SSB* status at the end of 2019 of 0.75.

**Table 14.10:** MCMC results (median and 95% confidence intervals) for $B_0$ and SSB status for Models 2 to 4.

| **Model** | | $B_0$ | ***SSB* Status** |
|---|---|---|---|
| Model 2 | Equal vessel tagging performance | 26 609 (20 931 - 35 198) | 0.89 (0.79 - 0.97) |
| Model 3 | Individual vessel tagging performance | 15 122 (11 860 - 19 612) | 0.75 (0.66 - 0.85) |
| Model 4 | Individual vessel tagging performance, one selectivity | 15 122 (11 860 - 19 612) | 0.75 (0.66 - 0.85) |

The *YCS* were poorly estimated, with large uncertainties for all estimated years 1997-2014 (Figure 14.17). Similarly, the estimated selectivity functions for autoline, Spanish longline and trotline showed large uncertainties in Model 3 (Figure 14.18). The shapes of the three estimated selectivities were similar, so it was unsurprising that assuming a combined gear selectivity in Model 4 resulted in similar model estimates. All estimated selectivities showed a strong tendency to fully select older fish.

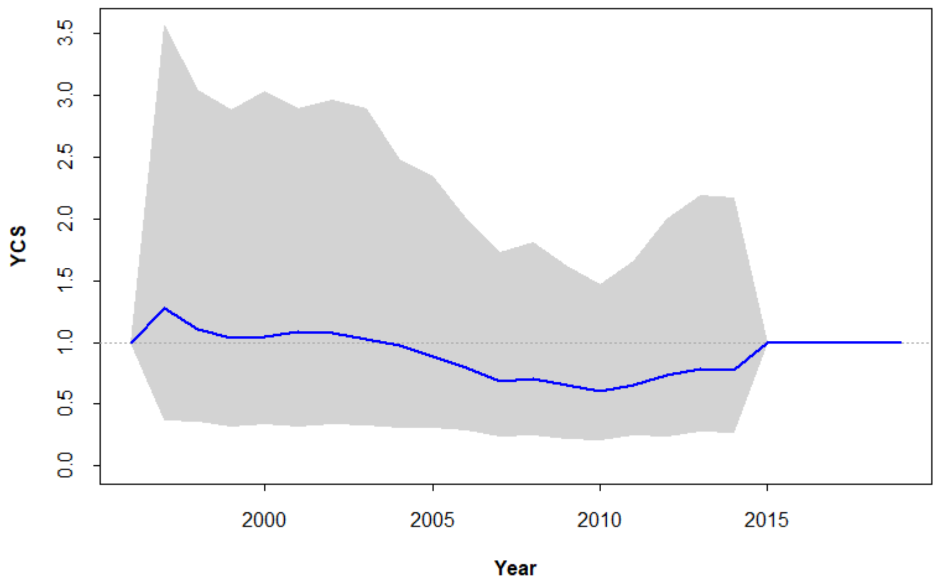
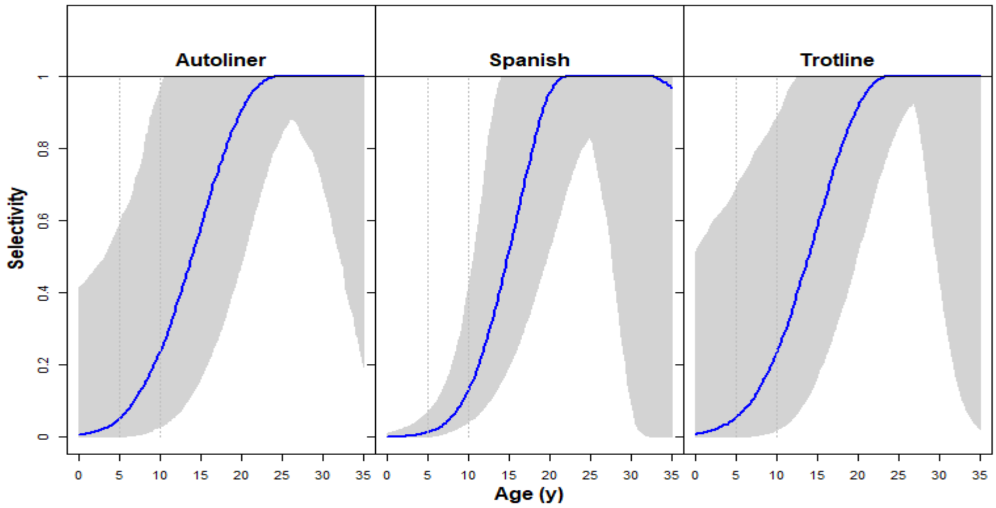



**Figure 14.17:** Estimated YCS for Model 3 showing 95% confidence bounds obtained from the MCMC sample.

(a) Model 3




(b) Model 4

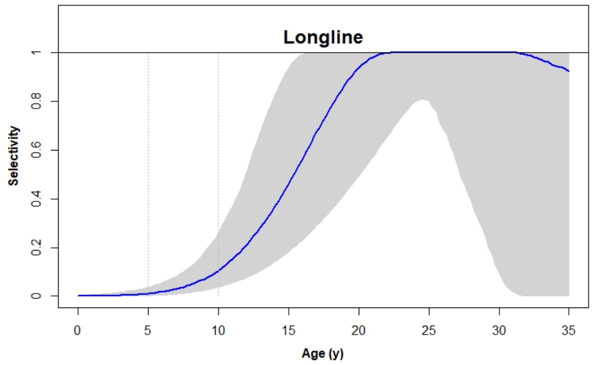



**Figure 14.18:** Estimated double-normal-plateau fishing selectivity functions for (a) autoline, Spanish longline and trotline in Model 3 and (b) all combined longline gear types in Model 4, showing 95% confidence bounds obtained from the MCMC samples. Vertical reference lines are shown at ages 5 and 10.

The trace plots of the MCMCs for Models 3 and 4 were acceptable for $B_0$ and *YCS*, however the trace plots for the selectivity parameters in Model 4 showed better properties than those in Model 3 (Figures 14.19 and 14.20).

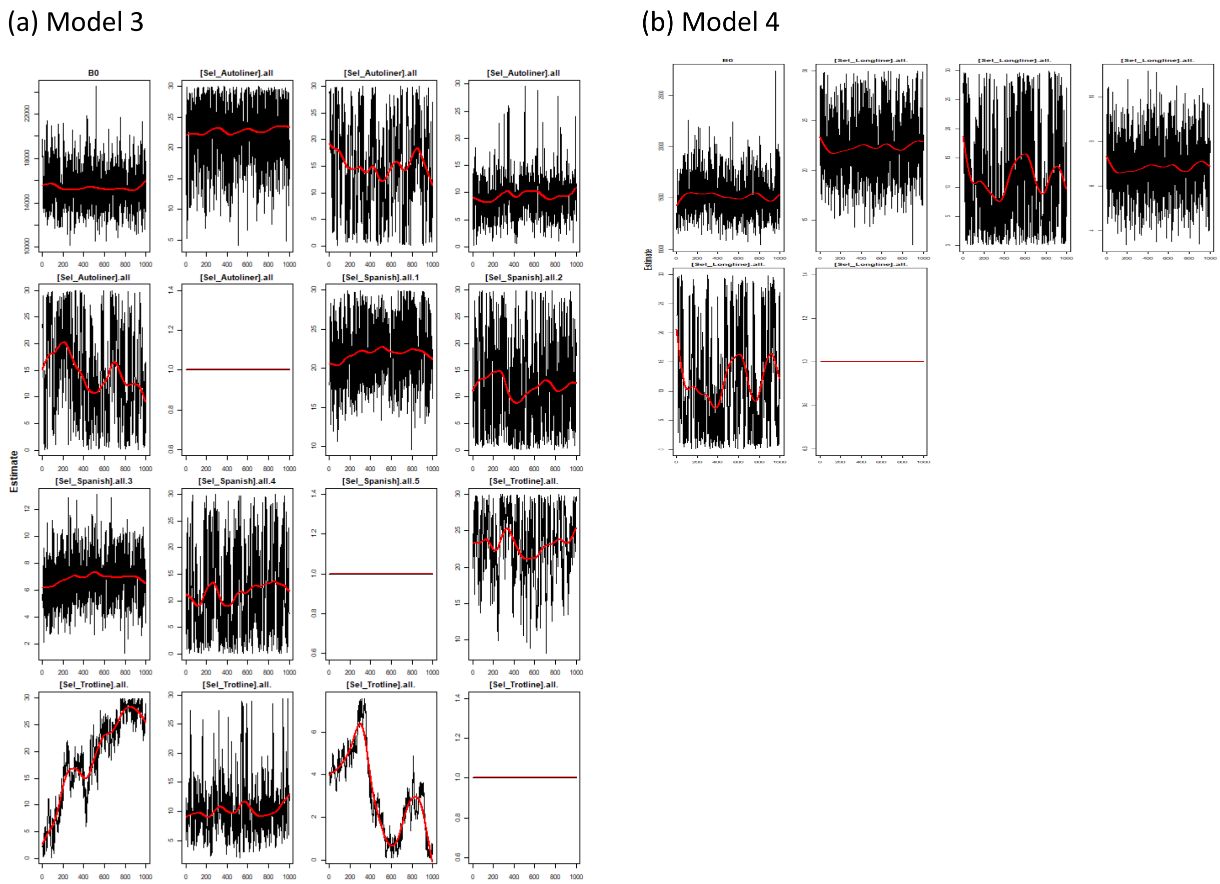



**Figure 14.19:** MCMC posterior trace plots for $B_0$ and the selectivity parameters for (a) Model 3 and (b) Model 4.

(a) Model 3 (b) Model 4

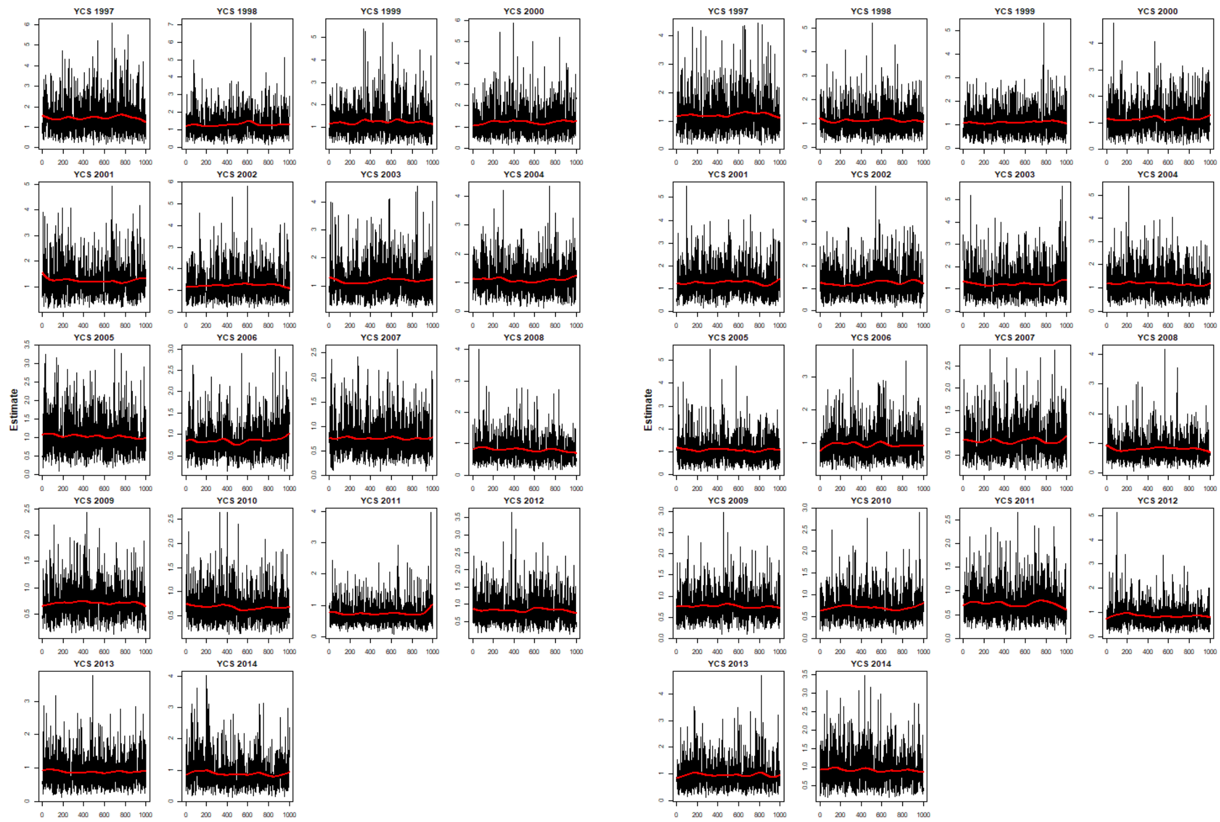



**Figure 14.20:** MCMC posterior trace plots for YCS for (a) Model 3 and (b) Model 4.

### Calculations of catch limits

The median CV estimated for the *YCS* period from 1997-2014 were used to generate the random recruitment from 2015-2020 and the 35-year projection period from 2021-2055 ($\sigma_R$ = 0.57 - 0.59 in Models 2 to 4).

Following the CCAMLR decision rules, the yield for Models 2, 3 and 4 were estimated at 1350, 760 and 770 tonnes (Table 14.11 and Figure 14.21).

**Table 14.11:** Estimates of catch limits in tonnes based on MCMC sampling that satisfy the CCAMLR harvest control rules, with (i) a median escapement of the spawning biomass at the end of the 35-year projection period of at least 50% of the median pre-exploitation level ('Target'), and (ii) a less than 10% risk of the spawning biomass dropping below 20% of its median pre-exploitation level at any time over the 35-year projection period ('Depletion').

| Model | Catch limit (t) | Target | Depletion |
|---|---|---|---|
| Model 2 | 1350 | 0.503 | 0.01 |
| Model 3 | 760 | 0.502 | 0.01 |
| Model 4 | 770 | 0.500 | 0.01 |

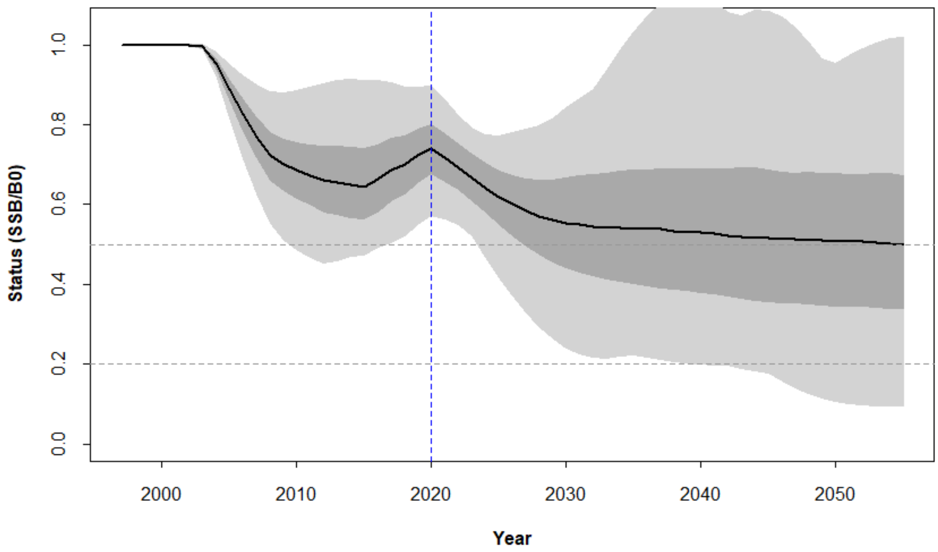



**Figure 14.21:** Projected SSB status relative to $B_0$ for the assessment Model 4 and a constant future catch of 770 tonnes using MCMC samples. The YCS period from 1997-2014 was used to generate random lognormal recruitment from 2015-2055. Shown are median (black line), 100% confidence bounds (light grey) and 80% confidence bounds (dark grey). Horizontal dotted lines show the 50% and 20% status levels used in the CCAMLR decision rules, the vertical blue line indicates the current year.

## 14.8 Discussion

Here, we present an update of ageing and estimates of biological parameters, and of the single-region integrated stock assessment for Antarctic Toothfish (*Dissostichus mawsoni*) fishery in CCAMLR Divisions 58.4.1 and 58.4.2. The update of ageing and estimates of biological parameters addresses Milestone 1.4, the update of the stock assessment addresses Milestone 1.6 of the current multi-member research plan for these Divisions (SC-CAMLR-39/BG/10).

The assessment model used all data available from the region, supplemented with parameter estimates from other Toothfish stock assessments. Compared to the previous assessment (WG-FSA-18/58 Rev.1), this model also included:

- Estimation of vessel tag performance and accounting for vessel performance in the tag-recapture data used for the assessment;
- Inclusion of more ageing data from autoline and trotline, which allowed a direct estimation of trotline selectivity;
- Update of the estimation of region-specific growth.

All evaluated assessment models indicated that the Antarctic Toothfish stock in Divisions 58.4.1 and 58.4.2 is unlikely to be depleted by the current level of fishing mortality. Accounting for vessel tagging performance was highly influential in the estimates of $B_0$ and

*SSB* status, and we recommend further work to consolidate appropriate estimates of vessel-specific tag survival and detection performance.

The model indicated unresolved issues with the tagging data, even when vessel-tagging performance was accounted for, and a systematic lack of fit to the catch-at-age data. There was little information in some tag-recapture cohorts to estimate $B_0$, while in 2018 a relatively high number of tagged fish were recaptured in a small area (research grid) in research block 5841_2 where a substantial number of tags had been released in the previous year (WG-FSA-18/58 Rev.1).

In addition, the lack of directed fishing in Division 58.4.1 resulted in spatially-restricted data collected from one single research block in Division 58.4.2 over the last two fishing season. There has been a relatively high number of recaptures in this area, and the estimates of abundance based on these tag-recapture cohorts are likely to represent the biomass at the scale of the local research block rather than the two Divisions. In addition, the catch-at-age composition for the last two years was distinctively different from other years, and is likely to reflect the particular fish population characteristics of Prydz Bay where research block 5842_1 is located.

The specification of fishing selectivity in the model, i.e. whether autoline, Spanish longline and trotline were fitted separately or by one common function, did not have an impact on the model estimates. This indicates that fishing gear has only a minor influence on catch-at-length and catch-at-age compositions and tag-recapture data in this Antarctic Toothfish fishery, particularly relative to vessel and spatial population effects. This result is consistent with the results from the Toothfish stock assessment in the Ross Sea which indicated that catch characteristics mainly vary with areas but not gear types (Dunn 2019a and 2019b).

We also calculated preliminary catch limits for the exploratory Toothfish fishery in the two Divisions based on three different models. While we consider it premature to use these biomass and catch estimates for management advice, it allows for a comparison with research block biomass estimates and catch limits using the trend analysis. Using the trend analysis, the combined vulnerable biomass in all research blocks in Divisions 58.4.1 and 58.4.2 in 2019 was estimated to be 32 454 tonnes, with a total catch limit of 643 tonnes (WG-FSA-19, Table 7). While vulnerable biomass estimates from the trend analysis were higher than from this assessment (the vulnerable biomass in this assessment is likely to be similar to the spawning biomass since the maturity selectivity functions are comparable), the lower resulting catch limits indicates that the trend analysis rule is precautionary.

We will update this assessment again in 2022 as per Milestone 1.11 of this multi-member research plan (SC-CAMLR-39/BG/10) and welcome any comments from members on possible improvements. We recommend continuing and further work on:

- Improvements in the estimation of vessel tag performance to account for vessel performance in the tag-recapture data;
- Approaches to account for spatial patterns of tag-releases and recaptures;
- Region-specific or updated estimation of key parameters such as growth and maturity, and tag-shedding rates;
- Inclusion of further ageing data;
- Sensitivity analysis for different levels of IUU catches.

The collaborative approach adopted by the research plan proponents Australia, France, Japan, Republic of Korea and Spain in Divisions 58.4.1 and 58.4.2 has worked well, with valuable on-water data collection and extensive subsequent data analyses. Based on these analyses, research has now progressed to a stock assessment, highlighting the value of the management procedures, agreed to by CCAMLR in 2011, which requires research plans in exploratory fisheries. However, an expansion of the spatial distribution of catch, tagging and data collection in Divisions 58.4.1 and 58.4.2 beyond a single research block will be required to improve estimates of stock biomass and catch limits in the future.

# Discussion and Conclusions

This project provided research between 2018 and 2020 needed for the sustainable management of the HIMI Toothfish and Icefish fisheries as well as the CCAMLR's exploratory Toothfish fishery in Divisions 58.4.1 and 58.4.2. The project covered a wide range of research topics following its main objectives.

**Objective 1. Support and improve the collection of biological, ecological and population dynamics data for key target and bycatch species in the Toothfish and Icefish fisheries at Heard Island and McDonald Islands (HIMI), in the Australian Antarctic Territory (AAT), and in the Ross & Amundsen Seas.**

1.1 Support of data collection programs

The data collection programs on Australian vessels at HIMI, MI and in CCAMLR's exploratory fisheries were supported and improved to ensure that they are of a high standard.

Data from these fisheries are reported through two processes. The fishing company is required to estimate and report all catch of target and bycatch species in their logbooks on a haul-by-haul basis. In addition, scientific observers and data collection officers have been deployed during the RSTS and commercial fishing operations, with 100% observer coverage on all vessels and fishing hauls since Australian vessels started fishing.

Sampling by observers aboard fishing vessels is designed to address the requirements prescribed by Australian legislation and CCAMLR, and to provide sufficient data to develop assessment models of the fished stocks. It is currently the most cost-effective method for monitoring Australia's Southern Ocean fisheries. Up until the disruption of the COVID-19 virus outbreak, two observers were required to be present on every vessel. The primary sampling requirements for this project were to characterise the total catch of target and bycatch species for every fishing event (i.e. each trawl or longline set), and provide biological data (total length, total weight, sex and reproductive development) from a representative fish sample in each fishing event, ensuring coverage of around 60% of a fishing event. Observers also collected otoliths from the catch of Toothfish, and tagged Toothfish at a rate of 2 Toothfish per tonne of catch landed (i.e. around 6000 tagged fish per year) and up to 2000 skates per year. Further duties included monitoring the numbers of seabirds and marine mammals around the vessels during fishing operations, and recording any interactions between the fishing gear and mammals and seabirds. Opportunistically, observers deployed underwater cameras and instruments to collect connectivity, temperature and depth (CTD) data from HIMI, MI and the AAT.

The project team continued to support these data collection programs by on-board fisheries observers on all Australian vessels fishing in the Southern Ocean, consisting of:

- The provision and installation of data collection hardware aboard fishing vessels, including ruggedised laptops, electronic fish measuring boards and scales, automatic tag detectors, and conventional tags for tagging Toothfish and skates, cameras and CTDs.

- Provision and support of data capture, quality control and data management software to enable comprehensive reporting of catch, effort and biological characteristics of catch and bycatch.
- Annually conducting joint AFMA and AAD training workshops for observers before deployment on vessels participating in these fisheries.
- Briefing before each voyage to detail any specific objectives for data collection, and changes or upgrades to hardware and software.
- Correspondence with observers and vessels during each voyage to troubleshoot gear problems and adapt sampling protocols as required.
- Debriefing and a data quality report following each voyage.

The AAD also maintains a database of all data collected from Australian vessels and has established processes for quality checking new data prior to importing them into the database. These processes enabled a consistently high-quality data set to be collected by observers for the duration of the project. Similar data were also accessible from CCAMLR for non-Australian vessels that fish in the AAT and other exploratory fisheries, and from France for their vessels fishing in the French EEZ on the northern part of the Kerguelen Plateau.

### 1.2 Review of the otolith sampling program

The sampling protocol to collect fish otoliths in the Toothfish fishery at HIMI resulted in several thousands of otoliths being collected from commercial fishing operations per fishing season, while only a subsample of around 500 otoliths are subsequently aged. An evaluation of the effects of alternative requirements for collecting fish otoliths per length bin per fishing trip indicated that the maximum number of fish sampled for otoliths per length bin could be reduced from 5 to 3 without loss of representation of the fish caught by the fishery (Chapter 1).

### 1.3 Other work

Work also started on the review of the purpose and required periodicity of the RSTS and the design of a longline survey to collect tag-recapture data for a fishery-independent estimator of fish abundance. However, this work was incomplete and will be continued as part of FRDC project 2020-095.

**Objective 2. Provide robust estimates of key population parameters (growth, reproduction, recruitment, mortality, and movement) and their uncertainty for Toothfish, Mackerel Icefish, and key bycatch species at HIMI and in the AAT.**

2.1 RSTS in 2018, 2019 and 2020

The annual random stratified trawl surveys (RSTS) in 2018, 2019 and 2020 provided robust estimates of fish abundance for the two target species Icefish and Toothfish, and for bycatch species such as skates and Macrourids (Chapter 2). The RSTS has been run annually since 1997 and their data are a critical input for the annual stock assessment for Mackerel Icefish and the biennial integrated stock assessment of Toothfish. Abundance estimates have also been used in the skate assessment presented in Chapter 11.

2.2 Toothfish ageing

Fish ages are essential to improve estimates of biological parameters and provide age-length keys. Both are important sources of data for the Toothfish stock assessments at HIMI, MI and in the AAT. As part of this project, 4670 Toothfish have been aged from these three regions. Most Toothfish samples were caught in the most recent seasons, but some tag-recaptures and fish from earlier fishing seasons, where only a relatively small number of fish had been aged previously, have also been aged:

| Area | Species | Season/Type | Number of aged fish | Totals |
|---|---|---|---|---|
| HIMI | Patagonian Toothfish | 2007/08 | 187 Commercial | |
| | | 2008/09 | 175 Commercial | |
| | | 2009/10 | 183 Commercial | |
| | | 2011/12 | 78 Commercial | |
| | | 2017/18 | 323 RSTS<br>550 Commercial | |
| | | 2018/19 | 283 RSTS<br>492 Commercial | |
| | | Various | 593 Tag-recaptures | 2864 |
| Macquarie Island | Patagonian Toothfish | 2017/18 | 312 | |
| | | 2018/19 | 281 | 593 |
| East Antarctica | Antarctic Toothfish | 2015/16 | 331 | |
| | | 2016/17 | 202 | |
| | | 2017/18 | 375 | |
| | | 2018/19 | 305 | 1213 |
| **Total** | | | | **4670** |

To estimate fish ages, all otoliths have been double-read by technicians who have been trained following the recommendation of the 2012 Toothfish ageing workshop (SC-CAMLR 2012) and the protocols for thin sectioning developed at the Australian Antarctic Division (Welsford et al. 2012, Farmer et al. 2014, Ziegler et al. 2021).

## 2.3 Estimation of biological parameters for Toothfish at HIMI and in the AAT

Estimates of biological parameters (length-weight relationship, growth and maturity) were updated as part of the 2018-2020 Icefish stock assessments (Chapters 3 to 5), the 2019 Toothfish assessment at HIMI (Chapter 8), and the Toothfish assessment for the AAT in 2020 (Chapter 14).

## 2.4 Estimation of fishing-induced mortality from longline gear loss

Fishing-induced mortality from longline gear loss at HIMI was estimated for the first time (Chapter 6). Longline gear loss has increased over time with the Toothfish fishery switching almost entirely to using longline gear and an increase in the catch limit until 2019. The estimated fishing mortality caused by gear loss was at a relative maximum of 1.5% of the total catch in 2018, and an absolute maximum of 50 t in 2019.

Fishing-induced mortality from gear loss together with fishing-induced depredation of Toothfish from fishing gear by marine mammals were the last sources of mortality components in the stock assessment which had not been estimated. Tixier et al. (2019a and 2019b) estimated the impact of odontocete whale-longline interactions across a number of Toothfish fisheries in the Southern Ocean including HIMI. Unlike in other fisheries, killer whales had not been observed to interact with the Toothfish fishery at HIMI, and interactions with sperm whales only started in 2013 and have remained at a very low level. Depredation mortality is therefore likely to be negligible in the HIMI Toothfish stock assessment at the moment, however whale interactions with longline fishing are increasing and will need to be closely monitored.

## 2.5 Estimation of vessel tagging performance

Vessel tagging performance was estimated for the Toothfish fisheries at HIMI (Chapter 7) and in the AAT (Chapter 14). At HIMI, all vessels which are currently active in the fishery and from which tagging data are used in the stock assessment, showed a high and consistent tag-release and tag-detection performance. This result is encouraging and highlight the effectiveness of the tagging protocols and practices that have been applied across the Australian fishing fleet. In the AAT, the vessel performance was good for Australian vessels but variable for vessels from other CCAMLR members who have fished in the area.

## 2.6 Development and implementation of a research plan in the AAT

Australian vessels have participated in CCAMLR’s exploratory Toothfish fisheries in the AAT and the Ross and Amundsen Seas in recent years. As part of this FRDC project, Australia led the development of a multi-member research plan in the AAT following the requirements in CCAMLR Conservation Measure CM 21-02 and in accordance with the format of CM 24-01, Annex 24-01/A Format 2. This research plan was jointly developed in 2018 and annually updated by the Delegations of Australia, France, Japan, the Republic of Korea and Spain (2018a, 2019a, 2019b, 2020). The plan had several research objectives, namely:

- Objective 1: Provide an assessment of the status and productivity of Toothfish stocks in Divisions 58.4.1 and 58.4.2.
- Objective 2: Identify the spatial distributions of Toothfish, important habitats and vulnerable marine ecosystems (VME) to inform spatial management approaches.
- Objective 3: Identify the spatial and depth distributions of bycatch species, and inform bycatch mitigation measures.
- Objective 4: Improve the understanding of trophic relationships and ecosystem function to assist the development of ecosystem-based fisheries management approaches.

With Australia as a key member of this research plan, project staff led or contributed significantly to:

- Annual fishing season reports by Delegations of Australia, France, Japan, Republic of Korea and Spain (2018a), Yates and Ziegler (2018 including the development of a standard format), and Delegation of Australia (2019, 2020d - see Chapter 13)
- Updates on Toothfish ageing and growth estimation by López-Abellán et al. (2018) and Delegations of Australia, Republic of Korea and Spain (2019)
- Exploration of catch rate standardisation variances in the Ross Sea Antarctic Toothfish longline fishery by Maschette et al. (2019) to address concerns raised by Russia on the use of multiple longline gear types (Autoline, Spanish longline and trotline) in the AAT (see Chapter 12)
- Preliminary integrated stock assessment for Toothfish in the AAT by the Delegation of Australia (2020e - see below and Chapter 14)
- Reports on fish bycatch by Péron et al. (2018) and Delegations of France and Australia (2020)

**Objective 3. Develop, implement, and improve stock assessment methods that account for species population dynamics and ecosystem linkages, and uncertainty in key parameters and processes at HIMI and in East Antarctica.**

3.1 HIMI Icefish assessments

Maschette et al. (2018) developed a standard set of assessment diagnostics which were subsequently used in the Generalised Yield Model (GYM) assessment for Mackerel Icefish at HIMI (Maschette and Welsford 2018, Maschette et al. 2019 and 2020 - see Chapters 3, 4 and 5). These stock assessments were used to provide advice on sustainable catch limits following the CCAMLR decision rules for Icefish.

Maschette et al. (2020) also rewrote the GYM as an R package Grym (Generalised R Yield Model) (Wotherspoon and Maschette 2020). Designed to work within R (R Core Team 2020), the Grym was built to provide a toolbox of functions that replicate the existing core functionality of the GYM software described by Constable and de la Mare (1996). This has provided more transparency for the Icefish assessment and increased the functionality and flexibility for any future assessments.

### 3.2 HIMI Toothfish assessment

The Patagonian Toothfish at HIMI was assessed in 2019 as part of the biennial assessment cycle for Toothfish fisheries with an established integrated stock assessment (Ziegler 2019a, see Chapter 8). The assessment estimated that the spawning stock was close to the target level of 50% $B_0$ and recommended a reduction in the catch limit from 3525 t to 3030 t.

The assessment also predicted that the median SSB status would drop well below the target level over the course of the 35-year projection period, a pattern that was driven by the switch of the fishery from trawl to longline and below-average year class strength since 1998.

While the WG-FSA noted that fluctuations around the target of 50% $B_0$ would be expected for stocks near or at the target levels (WG-FSA-19 para. 3.19), it expressed concern that the stock may continue to decline if below-average YCS continued and were not accounted for in future assessments.

In response to a recommendation by WG-FSA-19 (para. 3.90), an update on stock parameters, including recruitment indices from the trawl survey, and age-frequency data and tag-recapture data from the fishery was presented to WG-FSA-20, indicating that recruitment and the stock trajectory were consistent with those estimated by the 2019 assessment (Delegation of Australia 2020a - see Chapter 9).

### 3.3 AAT Toothfish assessment

As part of the multi-member research plan for Antarctic Toothfish in the AAT, a preliminary integrated stock assessment in Divisions 58.41 and 58.4.2 was presented to the Scientific Committee in 2020 (Delegation of Australia 2020b - see also Chapter 14). The assessment model used all data available from the region, supplemented with parameter estimates from other Toothfish stock assessments. The model indicated unresolved issues with the tagging data and a systematic lack of fit to the catch-at-age data, and ultimately was not used to provide advice on catch limits for these Divisions. However, all evaluated model scenarios indicated that the Antarctic Toothfish stock in Divisions 58.4.1 and 58.4.2 was unlikely to be depleted by the current level of fishing mortality, and that the catch limits estimated by the proxy (‘trend analysis’) method used by CCAMLR for the region, were likely to be precautionary.

## Objective 4. Evaluate environmental impacts on the HIMI fishery and develop adaptation strategies to climate change on the Kerguelen Plateau

### 4.1 Adaptation strategies to climate change

Significant research to gain a better understanding of environmental impacts on the efficiency of the fishery and stock productivity to provide avenues for a long-term adaptation of the fishery to climate change on the Kerguelen Plateau has been conducted as part of FRDC Project 2018-133 ‘Impact of environmental variability on the Patagonian Toothfish (*Dissostichus eleginoides*) fishery’.

This project complemented this work through two smaller components, namely (1) monitoring annual trends in the Toothfish fishery and providing reports to AFMA and the fishing industry, and (2) exploring options for an appropriate sampling program to collect data on sea lice.

4.2 Sea lice

Sea lice (Amphipods and Isopods) attack fishing bait and fish caught on longlines, and if they occur in large numbers they can have a significant impact on catch rates and impact on the quality of fish product. Anecdotally, sea lice abundance seems to have increased in recent years which could be linked to natural variability or long-term trends due to climate change. Traps to catch sea lice have been developed as part of this project. The sea lice traps are made out of a small section of plastic tube (up to 150 mm diameter and 500 mm length), with two internal funnels to trap sea lice. Initial trials in the AAT, where traps were baited and attached to longlines, indicated that these traps attract and retain sea lice, at times in large numbers. For FRDC Project 2020-097 'Investigating sources of variability in the Heard Island and McDonald Islands Toothfish fishery', sea lice data from traps will be used to help with the understanding of sea lice impact on the fishery and to develop mitigation measures if needed. In addition, sea lice abundance and species diversity will be estimated for the waters at HIMI.

**Objective 5. Monitor, evaluate, and mitigate fish and skate/ray bycatch, seabird bycatch and cetacean depredation in the HIMI longline fleet.**

5.1 Seabird interactions

Minimising seabird interactions with longline operations is a key objective of the management of fisheries in CCAMLR. Longline fishing for Patagonian Toothfish at HIMI started as a winter fishery to minimise seabird interactions, and has employed a wide range of seabird mitigation measures since the initial fishing season in 2003. Over the years, CCAMLR has agreed to add season extensions and season extension trials in April and September to November. Ziegler et al. (2019 - see Chapter 10) analysed the risk of seabird mortality during these trial extensions and found that the rates of seabird mortality for the pre-season and post-season extension trials were comparable to that during the existing pre-season extension.

5.2 Skate bycatch

Skates (Rajidae) represent the greatest biomass of incidental bycatch caught in the Toothfish and Icefish fisheries at HIMI. In a first species-specific bycatch assessment for the three dominant skate species (*Bathyraja eatonii, B. irrasa and B. murrayi*), plausible life-history and fishing scenarios were selected as input parameters into a population projection model using the Generalised Yield Model (GYM). Where input parameters could not be determined from available data, a qualitative stepwise approach was followed to obtain quantitative estimates from other species based on taxonomic, ecological and life-history similarities. This preliminary assessment provided the first estimates of long-term annual yield for individual skate species and a framework for setting and allocating bycatch limits for data-poor species in the Southern Ocean.

# Implications

There are a number of important implications from this project. The fishing industry, fisheries management, the Australian Government, CCAMLR and the wider public can continue to have trust that:

1. Scientific and management advice for Australia's Southern Ocean fisheries is based on reliable data and best-available science:

- The ongoing support of the data collection programs ensured that fisheries and observer data collected on Australian vessels at HIMI, MI and in CCAMLR's exploratory fisheries are of a high standard.
- The fishery-independent RSTS provides reliable biomass estimates for input to the annual stock assessment for Mackerel Icefish, the biennial integrated stock assessment of Toothfish, and the skate bycatch assessment.
- The fish ageing program has produced large numbers of reliable Toothfish ages. All these data have passed through the revised ageing program and associated quality control described by Ziegler et al. (2021), and form an important input into the stock assessments of Toothfish at HIMI, MI and in the AAT.
- Updated estimates of biological and fishery parameters and for all sources of fishing-induced mortality have been available for the 2018-2020 Icefish stock assessments, the 2019 Patagonian Toothfish assessment at HIMI, and the Antarctic Toothfish assessment for the AAT in 2020.
- The work load and time allocation of fishery observers continue to be optimised. Based on this project, the maximum number of fish sampled for otoliths per length bin was reduce from 5 to 3, without loss of representation of the fish caught by the fishery.

2. The Icefish and Toothfish harvest strategies provide sound advice on stock status and sustainable catch limits at HIMI:

- The stock assessments for Mackerel Icefish at HIMI in 2018, 2019 and 2020 were presented to SARAG and then WG-FSA. In 2018 and 2019, these stock assessments were used to provide advice on catch limits (WG-FSA-18 para. 3.10-3.15, WG-FSA-19 para. 3.6-3.9). In 2020, COVID-19 prevented in-person meetings of CCAMLR, and formal meetings of the Scientific Committee and the Commission were held virtually and in a shortened format. The Icefish assessment was considered by the Scientific Committee but Russia blocked consensus on new catch advice for any fishery. As a consequence, Conservation Measure 42-02 for Icefish at HIMI remained unchanged and the second-year catch limit from the 2019 assessment remained in place for the 2020/21 season.
- The stock assessment for Patagonian Toothfish at HIMI in 2019 was presented to SARAG and WG-FSA and used to provide advice on the 2-year catch limits for the fishery (WG-FSA-19 para. 3.85-3.93 and SC-2019 para. 3.81-3.85). WG-FSA and the Scientific Committee recommended an update on stock parameters be presented to WG-FSA in 2020 to evaluate whether recruitment and the stock trajectory were consistent with those estimated by this assessment. Without formal WG-FSA meeting

in 2020, the fishery update was submitted to the Scientific Committee as a background paper but the limited time available for the meeting prevented a discussion of the paper.

3. There is sound advice for the effective fisheries bycatch management at HIMI:

- The paper on seabird interactions during three season extension trials in the longline fishery at HIMI was presented to WG-FSA (WG-FSA-19, para. 6.18-6.21). As a result, CCAMLR added these season extension trial periods to the existing season extensions, providing more certainty for the fishing industry without any loss of mitigation measures. CCAMLR also removed the requirement for any vessel to demonstrate full compliance with Conservation Measure 25-02 in the previous season in CM 41-08 (para. 3) given the specification and application of effective seabird bycatch mitigation by fishing vessels in this fishery.
- A preliminary assessment of skates at HIMI was presented to SARAG in August 2021. The study provided first estimates of long-term annual yield for individual skate species observed in the HIMI fisheries and a framework for setting and allocating bycatch limits for data-poor species in the Southern Ocean. The assessment also indicated potential improvements in the management of skates.

4. The Antarctic Toothfish fishery in the AAT is sustainable and a program to collect crucial information for the effective management of the fishery is in place:

- The collaborative approach adopted by the research plan proponents Australia, France, Japan, the Republic of Korea and Spain in Divisions 58.4.1 and 58.4.2 has worked well, with valuable on-water data collection and extensive subsequent data analyses. Based on these analyses, research has progressed to a stock assessment, highlighting the value of the management procedures, agreed to by CCAMLR in 2011, which requires research plans in exploratory fisheries.
- Results from a number of other research topics has been submitted to CCAMLR Working Groups and has led to a greater understanding of Toothfish biology and bycatch composition and species distribution in this region.
- Directed fishing in Division 58.4.1 has not been allowed since 2018, with Russia blocking consensus based on an argument that multiple gear types should not be used in this area. CCAMLR has extensively discussed this research plan and results in Divisions 58.4.1 and 58.4.2 but so far has not been able to find a consensus way forward (e.g. WG-FSA-18 para. 4.98-4.119, SC-2018 para. 3.134-3.145, CCAMLR-2018 para. 5.35-5.40, WG-FSA-19 para. 4.89-4.114, SC-2019 para. 3.102-3.123, CCAMLR-2019 para. 5.44-5.50, SC-2020 para. 4.10-4.13, CCAMLR-2020 para. 5.40-5.45).
- The paper on catch rate standardisation (Chapter 13) was presented to WG-SAM-19 as part of a focus session on 'Research Standardisation' to discuss research standardisation, ways to control or quantify the impact of gear on conclusions drawn from research data, and best practice for developing and presenting analyses (para. 6.1-6.20). This session was set up, but failed to, overcome the disagreement on the use of multiple gear types in a Toothfish fishery.

- The lack of directed fishing in Division 58.4.1 since 2018 resulted in spatially-restricted data collected from a single research block in Division 58.4.2. An expansion of the spatial distribution of catch, tagging and data collection in Divisions 58.4.1 and 58.4.2 beyond a single research block will be required to improve estimates of stock biomass and catch limits in the future.

# Recommendations

Based on this project, we make a number of recommendations to SARAG and CCAMLR:

- Continue the support of the fisheries and observer data collection programs at HIMI, MI and in CCAMLR's exploratory fisheries at a high standard, and evaluate new approaches to data collection including electronic monitoring.
- Review the purpose and required periodicity of the random stratified trawl surveys (RSTS) which provides robust estimates of fish abundance for the two target species Icefish and Toothfish, and for bycatch species such as skates and Macrourids (see FRDC Project 2020-095).
- Continue representative Toothfish ageing, since fish age estimates are essential to improve estimates of biological parameters and provide age-length keys, both important sources of data for the Toothfish stock assessments at HIMI, MI and in the AAT (see FRDC Project 2020-095).
- Develop a structured fishing program in the Australian EEZ such as a Random Stratified Longline Survey (RSLS) for a fishery-independent tag-recapture time series to inform on population abundance without bias (see FRDC Project 2020-095).
- Evaluate appropriate approaches to adequately represent tag-recapture data in an integrated tag-based stock assessment model through e.g. spatially-explicit stock assessment approaches, and estimate and account for tag-release mortality and vessel-specific tagging performance.
- Evaluate the CCAMLR harvest strategy to investigate issues such as the behaviour of the decision rules and approaches to account for potential effects of climate change and regime shifts.
- Continue and ensure adequate monitoring of odontocete whale sightings and interactions with the Toothfish longline fishery at HIMI, as interactions are likely to increase in the future.
- Continue to monitor seabird interactions with the Toothfish fishery at HIMI and if necessary improve mitigation measures to ensure seabird mortality does not increase in the future.
- Continue the stock assessment and evaluation of appropriate mitigation measures for skates.
- Review effectiveness of current measures (mitigation measures and catch limits) for other bycatch species and update as required.
- Develop a survey program to investigate sea lice species occurrence and diversity at HIMI, and assess the potential impacts of sea lice occurrence on the HIMI Toothfish fishery (see FRDC Project 2020-097).
- Continue participation in Toothfish research fishing in the AAT to collect suitable data for the development of a representative stock assessment that can provide advice on sustainable catch limits for CCAMLR Divisions 58.4.1 and 58.4.2. Also ensure that impacts of the fishery on dependent and related species and the wider ecosystem are accounted for and consistent with Article II of the CAMLR Convention (see FRDC Project 2020-095).

# Extension and Adoption

Stakeholders and beneficiaries of this project are the resource managers, commercial fishing industry and scientists, including:

- Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR);
- Australian Fisheries Management Authority (AFMA);
- Department of Agriculture, Water and the Environment (DAWE);
- Australian Bureau of Agricultural and Resource Economics and Sciences;
- Australian fishing industry in the Southern Ocean at HIMI, MI, and in the AAT;
- International fishing industry involved in fisheries in the AAT; and
- Marine Stewardship Council (MSC);
- University and CSIRO collaborators on scientific research projects.

The findings and outputs of this project have assured national, international and non-governmental organisations such as AFMA, CCAMLR and MSC that Australia manages their resources responsibly. Our extension and adoption objectives were to achieve understanding among stakeholders of:

- The best available science has been conducted in the Toothfish fisheries at HIMI and in the AAT;
- The implemented assessment procedures account for the main sources of biases and uncertainties;
- Management advice based on these assessment procedures ensures a high likelihood that the Australian Toothfish fisheries at HIMI and the Australia's participation in CCAMLR's exploratory fisheries are ecologically sustainable.

**Extension and adoption methods**

As CCAMLR and AFMA decide on the implementation of harvest strategies for the HIMI and exploratory Toothfish fisheries, they are critical fora to ensure the relevant outputs of the project are translated into recommendations for revised management measures.

Project results have been presented to the Sub-Antarctic Research Advisory Group (SARAG) to ensure that the implications of project results are considered when AFMA develops its advice for harvest strategies.

Project staff have also attended the meetings of CCAMLR's Working Groups for Statistics, Assessment and Modelling (WG-SAM) and Fish Stock Assessment (WG-FSA) and the Scientific Committee, and have used their experience in these fora to present the information that maximized the likelihood of uptake of project results (see 'Project materials developed' for list of papers).

**Evaluation**

Success of the extension and adoption plan was demonstrated by influential discussion of key outcomes by AFMA and in CCAMLR and outcomes being used to generate management advice:

| Year | Issues | Outcomes |
|---|---|---|
| 2018 | Scientific CCAMLR meetings:<br>HIMI:<br>• RSTS results (Nowara et al. 2018)<br>• Icefish assessment (Maschette and Welsford 2018)<br>• Results of season extension (Lamb 2018)<br>Exploratory fishery in the AAT:<br>• Report on fishing season (Yates and Ziegler 2018, Delegations of Australia, France, Japan, Republic Korea and Spain 2018a)<br>• Report on Toothfish age and growth (López-Abellán et al. 2018)<br>• Report on bycatch (Péron et al. 2018)<br>• Research plan (Delegations of Australia, France, Japan, Republic Korea and Spain 2018b,c) | CCAMLR endorsement of data and HIMI Icefish catch limits<br>CCAMLR endorsement to continue HIMI season extension trials<br>CCAMLR support for new research plan in Division 58.4.1 |
| 2019 | Scientific CCAMLR meetings:<br>HIMI:<br>• RSTS results (Nowara et al. 2019)<br>• Icefish assessment (Maschette et al. 2019)<br>• Toothfish assessment (Ziegler and Dell 2019, Ziegler 2019a)<br>• Results of season extension (Ziegler et al. 2019)<br>• Estimation of mammal depredation (Tixier et al. 2019a,b)<br>Exploratory fishery in the AAT:<br>• CPUE standardisation (Maschette et al. 2019)<br>• Report on fishing season (Delegation of Australia 2019)<br>• Report on Toothfish age and growth (Delegations of Australia, Republic of Korea and Spain 2019)<br>• Research plan (Delegations of Australia, France, Japan, Republic Korea and Spain 2019a,b) | CCAMLR endorsement of data, and HIMI Icefish and Toothfish catch limits<br>CCAMLR endorsement of HIMI season extensions<br>CCAMLR support to continue research plan in Division 58.4.1 |
| 2020 | Scientific CCAMLR meetings:<br>HIMI:<br>• RSTS results (Delegation of Australia 2020a)<br>• Icefish assessment (Delegation of Australia 2020b)<br>• Update of Toothfish fishery (Delegation of Australia 2020c)<br>Exploratory fishery in the AAT:<br>• Report on fishing season (Delegation of Australia 2020d) | CCAMLR did not endorse any new advice on catch limits across the Convention area<br>CCAMLR support to continue research plan in Division 58.4.1 |

| | | |
|---|---|---|
| | • Toothfish assessment (Delegation of Australia 2020e)<br>• Report on bycatch (Delegations of France and Australia 2020)<br>• Research plan (Delegations of Australia, France, Japan, Republic Korea and Spain 2020) | |
| 2021 | SARAG:<br>• Vessel tagging performance at HIMI (Phillips and Ziegler 2021)<br>• Preliminary skate assessment (Cleeland et al. 2021) | SARAG reassured about the quality of tagging program at HIMI<br>SARAG endorses tagging box and requests to finalise skate assessment |

# Project materials developed

**Papers to CCAMLR and SARAG**

*Note - where papers were presented to SARAG and CCAMLR (e.g. stock assessments), only the CCAMLR papers are listed.*

2018


Delegations of Australia, France, Japan, Republic of Korea and Spain (2018a) Joint report on exploratory fishing in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2017/18 fishing seasons. Document WG-SAM-18/35 Rev.1, CCAMLR, Hobart, Australia

Delegations of Australia, France, Japan, Republic of Korea and Spain (2018b) Draft proposal for multi-Member research on the *Dissostichus mawsoni* exploratory fishery in East Antarctica (Divisions 58.4.1 and 58.4.2) from 2018/19 to 2021/22. Document WG-SAM-18/17, CCAMLR, Hobart, Australia

Delegations of Australia, France, Japan, Republic of Korea and Spain (2018c) Proposal for multi-Member research on the *Dissostichus mawsoni* exploratory fishery in East Antarctica (Divisions 58.4.1 and 58.4.2) from 2018/19 to 2021/22. Document WG-FSA-18/59, CCAMLR, Hobart, Australia

Lamb T. (2018) Report on fishing effort and seabird interactions during the season extension trials in the longline fishery for *Dissostichus eleginoides* in Statistical Division 58.5.2. Document WG-FSA-18/57, CCAMLR, Hobart, Australia

López-Abellán L.J., Santamaría M.T.G., Sarralde R., Barreiro S., Farmer B. and Barnes T. (2018) Update of ongoing work on age and growth of Antarctic Toothfish (*Dissostichus mawsoni*) from Division 58.4.1 by Australia and Spain. Document WG-FSA-18/54, CCAMLR, Hobart, Australia

Maschette D. and Welsford D. (2018) A preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2, based on results from the 2018 random stratified trawl survey. Document WG-FSA-18/56, CCAMLR, Hobart, Australia

Nowara G., Lamb T. and Ziegler P. (2018) Estimates of abundance of *Dissostichus eleginoides* and *Champsocephalus gunnari* from the random stratified trawl survey in the waters surrounding Heard Island in Division 58.5.2 for 2018. Document WG-FSA-18/55, CCAMLR, Hobart, Australia

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Yates P. and Ziegler P. (2018) Report on *Dissostichus mawsoni* exploratory fishery research in East Antarctica (Divisions 58.4.1 and 58.4.2) between the 2011/12 and 2017/18 fishing seasons. Document WG-FSA-18/58 Rev.1, CCAMLR, Hobart, Australia

2019

Delegation of Australia (2019) Report on joint exploratory fishing in Divisions 58.4.1 and 58.4.2 between the 2011/12 and 2018/19 fishing seasons. Document WG-SAM-2019/26, CCAMLR, Hobart, Australia

Delegations of Australia, France, Japan, Republic of Korea and Spain (2019a) Continuation of multi-Member research on the *Dissostichus mawsoni* exploratory fishery in East Antarctica (Divisions 58.4.1 and 58.4.2) from 2018/19 to 2021/22. Document WG-SAM-2019/05, CCAMLR, Hobart, Australia

Delegations of Australia, France, Japan, Republic of Korea and Spain (2019b) Continuation of multi-Member research on the *Dissostichus mawsoni* exploratory fishery in East Antarctica (Divisions 58.4.1 and 58.4.2) from 2018/19 to 2021/22. Document WG-FSA-2019/44, CCAMLR, Hobart, Australia

Delegations of Australia, Republic of Korea and Spain (2019) 2019 update of ongoing work on age and growth of Antarctic Toothfish (*Dissostichus mawsoni*) from Divisions 58.4.1 and 58.4.2. Document WG-FSA-2019/47, CCAMLR, Hobart, Australia

Maschette D., Nowara G. and Welsford D. (2019) A preliminary assessment for Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2, based on results from the 2019 random stratified trawl survey. Document WG-FSA-2019/02, CCAMLR, Hobart, Australia

Maschette D., Wotherspoon S. and Ziegler P. (2019) Exploration of CPUE standardisation variances in the Ross Sea (Subareas 88.1 and 88.2A South of 70°s) Antarctic Toothfish (*Dissostichus mawsoni*) exploratory longline fishery. Document WG-SAM-2019/06, CCAMLR, Hobart, Australia

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Ziegler P. (2019) Draft integrated stock assessment for the Heard Island and McDonald Islands Patagonian Toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2. Document WG-FSA-2019/32, CCAMLR, Hobart, Australia

Ziegler P. and Dell J. (2019) Planned updates for the integrated stock assessment for the Heard Island and McDonald Islands Patagonian Toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2. Document WG-SAM-2019/27, CCAMLR, Hobart, Australia

Ziegler P., Lamb T., Wotherspoon S. and Dell J. (2019) Report on fishing effort and seabird interactions during the season extension trials in the longline fishery for Patagonian Toothfish (*Dissostichus eleginoides*) in Statistical Division 58.5.2. Document WG-FSA-2019/31, CCAMLR, Hobart, Australia

2020

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Delegation of Australia (2020b) Assessment of Mackerel Icefish (*Champsocephalus gunnari*) in Division 58.5.2 based on results from the 2020 random stratified trawl survey. Document SC-CAMLR-2019/01 Rev.1, CCAMLR, Hobart, Australia

Delegation of Australia (2020c) Update on the Heard Island and McDonald Islands Patagonian Toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2. Document SC-CAMLR-2019/BG/36, CCAMLR, Hobart, Australia

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Delegations of France and Australia (2020) Report on fish bycatch in the exploratory Toothfish fishery in Divisions 58.4.1 and 58.4.2 between 2014 and 2020. Document SC-CAMLR-2019/BG/44, CCAMLR, Hobart, Australia

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**Model Code**

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# Appendix

**List of researchers and project staff (boat skippers, technicians, consultants)**

Philippe Ziegler - Principal Investigator (AAD)

Dirk Welsford - Co-Investigator (AAD)

Tim Lamb - Co-Investigator (AAD)

Gabrielle Nowara - Co-investigator (AAD)

Simon Wotherspoon - Co-investigator (AAD)

Jeremy Lyle - Co-investigator (IMAS)

Caleb Gardner - Co-investigator (IMAS)

Chris Carter - Co-investigator (IMAS)

Peter Yates - Co-investigator (IMAS)

Dale Maschette - Co-investigator (IMAS)

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Genevieve Phillips - Co-investigator (IMAS)

Bryn Farmer - Technical Officer (IMAS)

Tom Barnes - Technical Officer (IMAS)

Andy Nicholls - Technical Officer (IMAS)

**Intellectual Property**

No intellectual property that needs protection has been identified as likely to derive from this project. Model code such as R packages are open source and fall under the Australian Government Open Source Software Policy, to facilitate use by the broader CCAMLR and fisheries science communities.