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The Patagonian toothfish (*Dissostichus eleginoides*) fishery at Heard Island and McDonald Islands (HIMI) – population structure and history of the fishery stock assessment

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Abstract

The Australian fishery for Patagonian toothfish (*Dissostichus eleginoides*) in the Australian exclusive economic zone around Heard Island and McDonald Islands (HIMI) on the Kerguelen Plateau started in 1997. Here, we describe the population structure of Patagonian toothfish on the Kerguelen Plateau, and the HIMI fishery, data collection programs and stock assessments between 2006 and 2017. Based on evidence from genetic analyses, catch composition and tag-recapture data from survey and the commercial toothfish fishery at HIMI and the adjacent French fishery around Kerguelen Island, Patagonian toothfish are continuously distributed and populations are linked on the northern part of the Kerguelen Plateau. Since 2006, integrated stock assessments have been conducted at HIMI using a CASAL framework with data from annual trawl surveys and the commercial fishery which have deployed trawl, longline and trap gear. Over the years, extensive work has been carried out to improve modelling approaches and data on toothfish ageing, specification of fleet structure, and estimation of biological population and model parameters. Trawl survey data have recently been replaced by tag-recapture data as the main indices of abundance. A recent independent review of the stock assessment considered that the modelling approaches used in this assessment were best-practice for the assessment and precautionary management of this fish stock.

La pêcherie de légine australe (*Dissostichus eleginoides*) des îles Heard et McDonald (HIMI) – structure de la population et historique de l'évaluation du stock halieutique

Résumé

C'est en 1997 que l'Australie crée une pêcherie de légine australe (Dissostichus eleginoides) dans sa zone économique exclusive entourant les îles Heard et McDonald (HIMI) sur le plateau de Kerguelen. Cet article décrit la structure de la population de légine australe sur le plateau de Kerguelen, ainsi que la pêcherie des HIMI, les programmes de collecte des données et les évaluations de stock de 2006 à 2017. Selon les analyses génétiques, les données de composition des captures et de marquage-recapture issues de campagnes d'évaluation et de la pêcherie commerciale à la légine dans les HIMI, ainsi que la pêcherie adjacente française des îles Kerguelen, la légine australe est répartie régulièrement sur la partie nord du plateau de Kerguelen et ses populations y sont liées les unes aux autres. Depuis 2006, des évaluations intégrées du stock sont menées aux HIMI dans le cadre du modèle CASAL sur la base de données issues de campagnes d'évaluation annuelles par chalutages et des opérations de pêche commerciales au chalut, à la palangre et au casier. Des travaux importants ont été réalisés au cours des années pour améliorer les approches de modélisation et les données sur la détermination de l'âge des légines, la spécification de la structure de la flottille et l'estimation des paramètres biologiques des populations et du modèle. Les principaux indices d'abondance qui, jusqu'à récemment, étaient estimés à partir des données de campagne d'évaluation par chalutage le sont désormais à partir des données de marquage-recapture. Selon un récent examen indépendant de l'évaluation de stock, les approches de modélisation utilisées correspondaient aux meilleures pratiques possibles pour l'évaluation et la gestion de précaution de ce stock de poisson.

Introduction

Patagonian toothfish (*Dissostichus eleginoides*) is a large benthopelagic fish species with a circumpolar distribution in sub-Antarctic waters around southern Patagonian and Chilean shelves, and on banks, seamounts and submersed plateaus around islands in the Southern Ocean (Eastman, 1993; Gon and Heemstra, 1990). The species occurs over a wide depth range from around 10 m to over 2 500 m (Duhamel et al., 2005), with an ontogenetic habitat shift towards deeper waters as they grow (Péron et al., 2016). Similar to other deep-sea fish species, Patagonian toothfish shows typical K-selection life-history characteristic including slow growth, large body size (up to 2 m and 100 kg), maximum life expectancy of over 50 years (Farmer et al., 2019), and late age at maturity (Yates et al., 2018).

Targeted fisheries for Patagonian toothfish have been developed in a number of regions, initially in Chile in the 1950s, then later around the Patagonian shelf, South Georgia, the Kerguelen Plateau, Crozet Islands, Marion and Prince Edward Islands, Macquarie Island, and a number of isolated banks and seamounts (Collins et al., 2010).

In this paper, we focus on the toothfish populations and fishery at Heard Island and McDonald Islands (HIMI) on the Kerguelen Plateau. We describe the population structure of Patagonian toothfish on the Kerguelen Plateau, and the HIMI fishery, the data collection program and stock assessments between 2006 and 2017. This paper follows on from a publication by Constable and Welsford (2011) which summarised the fishery management approach at HIMI and the assessment history from the start of the commercial fishery in 1997 to 2009.

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 Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). On the northern part of the plateau (north of Fawn Trough or roughly 57°S), two fisheries for Patagonian toothfish are located in CCAMLR Division 58.5.1 which covers the French exclusive economic zones (EEZ) around Kerguelen Island, and Division 58.5.2 which covers the Australian EEZ around HIMI. On the southern part of the Kerguelen Plateau, which includes BANZARE Bank, Antarctic toothfish (*D. mawsoni*) which is distributed in the colder waters around the entire Antarctic continent, is the dominant toothfish species.

In 1979, Australia declared an Australian Fishing Zone (AFZ) around HIMI, which became an EEZ in 1994 (Welsford et al., 2011b). One year after CCAMLR was established in 1980, Australia also enacted a law by which conservation measures established under CCAMLR would be applied to all vessels operating in the HIMI AFZ (and later EEZ). As part of this process, Australia has submitted proposals to manage the HIMI fishery, including fish stock assessments for the regulation of the harvest regime, to CCAMLR for consideration.

History of the fishery

Prior to the start of the Australian commercial fishery at HIMI, three random stratified trawl surveys (RSTS) were conducted in 1990, 1992 and 1993 to estimate the abundance and size structure of *D. eleginoides* and mackerel icefish (*Champsocephalus gunnari*) (Williams and de la Mare, 1995). Commercial fishing started in 1997 by two trawlers, and trawl remained the dominant fishing gear for many years (Table 1). The use of longline was initially prohibited due to the risk of seabird by-catch, but following the development of integrated weighted longlines (IWLs), longline gear was introduced in 2003. The catch taken by longline increased steadily over the years, and longline has become the dominant gear type since 2011. By 2017, almost the entire commercial catch was taken by longline. Concurrently, the number of longliners increased from one to four vessels by 2017, one of which is a dual-purpose trawl/longline vessel. The use of pots were also trialled in 2006 and between 2009 and 2013 to prevent depredation by whales, but catches remained too small for pots to be commercial viable.

Illegal, unreported and unregulated (IUU) catches in the Australian EEZ around HIMI 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). To deter IUU fishing, joint patrols by French and Australian navy vessels were successfully instituted (Duhamel and Williams, 2011). No IUU vessel has been sighted after 2005 and it is likely that no IUU catches have been taken since then.

Table 1: Catch limits, reported catch for RSTS, trawl, longline and pot, estimated IUU catch and total removals in tonnes by fishing season in the Australian EEZ around HIMI.

Fishing season[a]	Catch limits	Reported catch					Estimated IUU catch	Total removals
		RSTS	Trawl	Longline	Pot	Total		
1996	297	0	0	0	0	0	3 000	3 000
1997	3 800	0	1 866	0	0	1 866	7 117	8 983
1998	3 700	1	3 784	0	0	3 785	4 150	7 935
1999	3 690	93	3 452	0	0	3 545	427	3 972
2000	3 585	9	3 556	0	0	3 565	1 154	4 719
2001	2 995	45	2 933	0	0	2 978	2 004	4 982
2002	2 815	35	2 717	0	0	2 752	3 489	6 241
2003	2 879	13	2 580	270	0	2 863	1 274	4 137
2004	2 873	65	2 218	566	0	2 849	531	3 380
2005	2 787	21	2 040	636	0	2 697	265	2 962
2006	2 584	12	1 785	659	72	2 528	112	2 640
2007	2 427	12	1 775	625	0	2 412	0	2 412
2008	2 500	4	1 612	825	0	2 441	0	2 441
2009	2 500	20	1 268	1 173	13	2 474	0	2 474
2010	2 550	28	1 239	1 216	32	2 515	0	2 515
2011	2 550	6	1 142	1 317	33	2 498	0	2 498
2012	2 730	41	1 322	1 356	0	2 719	0	2 719
2013	2 730	8	555	2 116	40	2 719	0	2 719
2014	2 730	13	93	2 638	0	2 744	0	2 744
2015	4 410	26	180	4 073	0	4 279	0	4 279
2016	3 405	52	107	2 640	0	2 799	0	2 799
2017	3 405	41	3	3 334	0	3 357	0	3 357

[a] Fishing seasons run from 1 December to 30 November of the following year. 1995/96 is denoted as 1996, 1996/97 as 1997 and so on.

Population structure

Based on evidence from genetic analyses, catch composition and tag-recapture data from survey and the commercial toothfish fishery, Welsford et al. (2011a) formulated a population hypothesis for Patagonian toothfish around HIMI where juveniles settle on the shallow plateau and then move to deeper areas as they grow larger and older. However, the males greater than 1 000 mm were rarely observed in the fishery around HIMI and females were over-represented in catches, particularly from the eastern but less so the western side. Welsford et al. (2011a) hypothesised that older males would move predominantly west where spawning areas had been detected and north into the French EEZ and to Crozet Islands, while maturing females would move to deeper slopes around the plateau and only some would cross over to the French EEZ.

A range of subsequent studies and approaches have helped to refine this hypothesis since 2011. Péron et al. (2016) developed spatially explicit statistical models to quantify and predict the spatial distribution of Patagonian toothfish length structure and sex ratio. These models supported the ontogenetic migration from shallow to deep waters as fish grow and the dominance of larger males in the French EEZ and larger females in the Australian EEZ.

Péron et al. (2019) analysed a large amount of tag-recapture data from trawl and longline fisheries in the French and Australian EEZs which indicated that most fish of both sexes were recaptured less than 100 km from their release location, even after over 10 years at liberty. Fish were recaptured in all directions relative to their release locations, but for distances of over 100 km there was a dominance of movement in northeast and southwest directions. The reasons for these directional preferences could be related to the distribution of available habitat and higher likelihood of recapture effort in these directions.

Estimation of the proportion of the population that moves between areas is more complex than describing patterns in movement directions and distances, as it requires an estimate of abundance in the areas between which movement is occurring (Hilborn, 1990). With abundance estimates available from integrated stock assessments in the Australian (SC-CAMLR, 2017a, Ziegler, 2017a) and French EEZs (SC-CAMLR, 2017b), Burch et al. (2017) estimated annual migration rates of adult toothfish between the two EEZs. They concluded that annual migration was low, with 0.4% of adult fish vulnerable to longlines migrating south from the French to the Australian EEZ, and 1.1% migrating north in the reverse direction.

Linkages between populations of toothfish across large geographic scale, i.e. between the Australian and French EEZs as well as Crozet Islands, were also indicated by a study on genetic differentiation. Using DNA extracts of toothfish otoliths from the three regions, Toomey et al. (2016) investigated the genetic differentiation with four mitochondrial and four nuclear markers. The authors found genetic homogeneity in nuclear markers between the Australian and French EEZs and Crozet Islands, supporting some level of gene flow attributable to active movement of post-settlement fish across the three areas. However, the differentiation in mitochondrial markers, particularly between HIMI and Crozet Islands, indicated that the level of movement was small and potentially dominated by males.

Yates et al. (2018) investigated the spatio–temporal dynamics in maturation and spawning around HIMI based on gonads and otoliths collected between 2004 and 2015. They found that the majority of mature fish were encountered in depths of 1 500–2 000 m, with the main spawning areas located in waters to the west and south of HIMI. In simulations of egg and larvae transport patterns for velocity fields derived from sea-surface altimetry (AVISO) and reanalysis products (SISO), areas to the west of the plateau were considered to be most successful to lead to consistent recruitment success (Mori et al., 2016).

As indicated in the results from these studies, Patagonian toothfish are continuously distributed on the northern part of the Kerguelen Plateau and populations are linked (Figure 1). Juveniles settle in shallow waters on the plateau around the islands with potential exchange between the two EEZs, then fish move to deeper waters as they grow larger and older, with major spawning grounds on the western and southern side of the plateau. The spatial segregation between sexes, with males dominating in the north and females in the south (Péron et al., 2016), remains unexplained and requires further investigation.

Data collection and research

Following the initial trawl surveys by the RV *Aurora Australis* in 1990, 1992 and 1993, Australia started an annual RSTS on the shallow plateau around HIMI using a commercial vessel in 1997 (Nowara et al., 2018). Up to 2005, the survey design and number of stations varied due to differing objectives (Welsford et al., 2006b). From 2006 onwards, the design of the surveys has been consistent, with a total of 163 stations and the same number of stations within each of the strata. Station locations have been selected randomly each year in all strata, although the main trawl ground was subdivided into 29 small grid cells of which 20 were randomly sampling each time. In 2015, the main fishing ground stratum was subdivided into two areas with 15 randomly allocated stations in the first area and 10 in the second (Nowara et al., 2015).

Data from the RSTS and commercial fishing are reported through two processes. The fishing company is required to estimate and report all catch of target and by-catch 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 1997. These observers are tasked with collecting biological data from regular subsamples of the catch including sex, length, weight, sex and gonad development of fish as well extracting of otoliths. Further duties include tagging toothfish and skates, identifying and quantifying all by-catch caught, 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.

Data from the RSTS and the commercial fishery are crucial inputs to the stock assessments for Patagonian toothfish and mackerel icefish. They have also been used to develop novel methods and to estimate key model parameters, such as growth rates (Candy et al., 2007), maturity (Yates et al., 2018), natural mortality (Candy, 2011a; Candy et

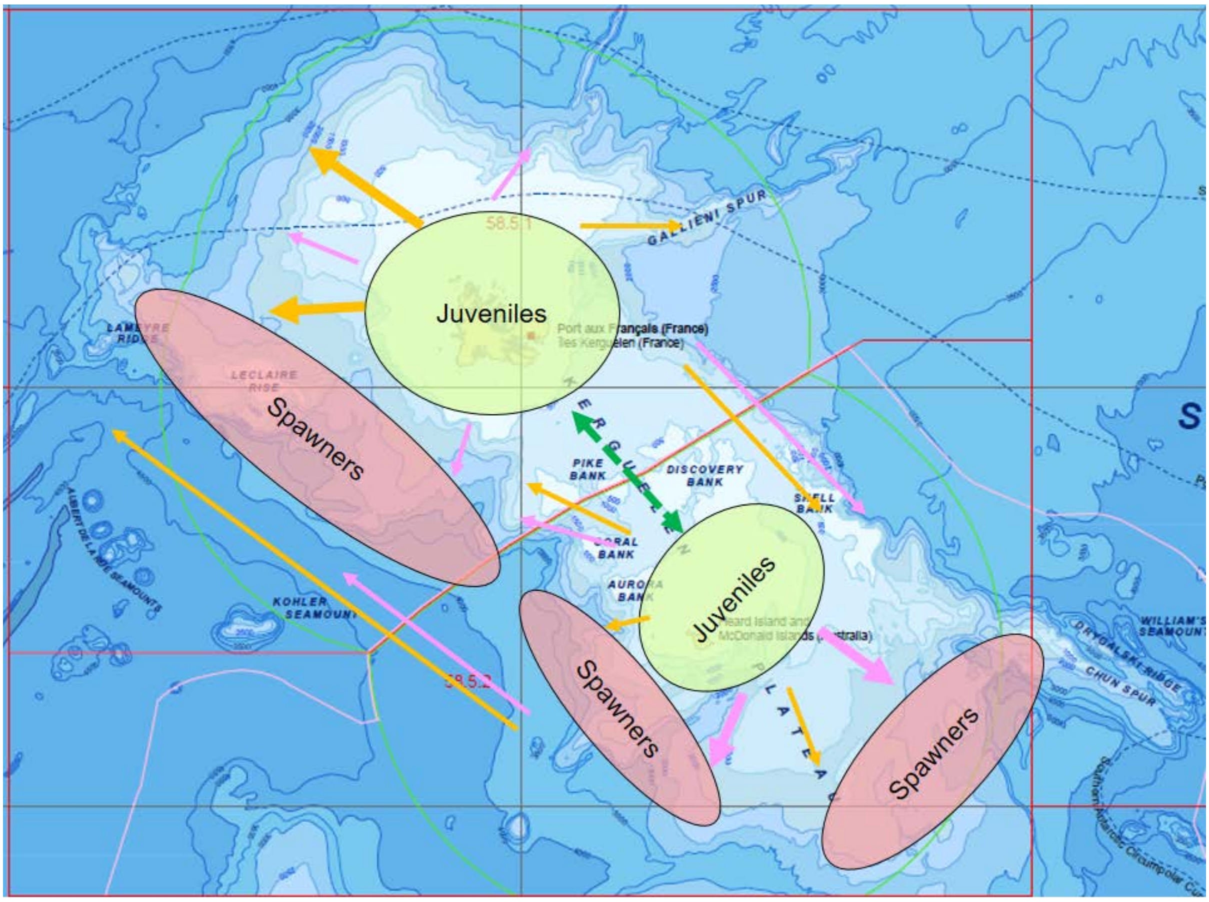

Figure 1: Schematic toothfish population structure on the Kerguelen Plateau with Kerguelen Island to the north and Heard Island and McDonald Islands to the south. Juveniles settle in shallow waters on the plateau around the islands with potential exchange between areas (dark green arrows). Males (orange 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. Long-distance movement of adult fish are rare, but occur over the entire plateau, with some level of linkages between the Australian and French EEZ (green lines). Boundaries of the CCAMLR area and divisions within are marked by red lines.

al., 2011a), standardised catch rates (Candy, 2004), catch-at-age proportions (Candy, 2008), age–length keys (ALKs) (Welsford et al., 2009) and ageing error (Candy et al., 2012; Burch et al., 2014).

History of toothfish stock assessment

The early history of stock assessment methods and models applied to the Patagonian toothfish fishery in the Australian EEZ around HIMI has been summarised by Constable and Welsford (2011). The generalised yield model (GYM; Constable and de la Mare, 1996) was used until 2005 to conduct stock assessments and provide catch advice. The GYM is a population simulation tool that combines functions of recruitment, natural mortality, growth, maturity and fishing mortality, and uncertainty in these parameters, to analyse and explore population scenarios based on historical and future harvest strategies.

In 2006, a GYM assessment (Welsford et al., 2006a) was conducted in parallel with an integrated assessment (Constable et al., 2006), and a CASAL assessment (C++ Algorithmic Stock Assessment Laboratory; Bull et al., 2012) was used for the first time to provide catch advice. In contrast to the GYM, an integrated assessment model fits the population dynamics to actual observations by either maximum likelihood or Bayes method. These observations can be derived from many different sources, including biomass indices from survey, catch rates, and tag-recapture data, and catch-at-age or catch-at-length composition data from surveys and commercial fishing.

Both assessment models provide a method for estimating fishery yield based on the precautionary approach developed by CCAMLR (Constable et al., 2000). Based on a sample of projections for spawning stock biomass, long-term catch limits are calculated following the CCAMLR decision rules for toothfish which has three components:

(1) Choose a yield gamma γ_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).

(2) Choose a yield γ_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.

(3) Select the lower of γ_1 and γ_2 as the yield.

In the following, we describe the development of the CASAL stock assessment models between 2006 and 2017. Many changes have been implemented over this time period in order to improve the assessment model structure and reflect new information that allowed parameter estimates to be updated. The main changes over this time period included the addition of new ageing data as they became available, the inclusion of externally estimated natural mortality to the model in 2011, and the replacement of survey data by tag-recapture data as the main source of information for the estimation of stock abundance in 2014.

Stock assessment 2006

The first integrated CASAL stock assessment for Patagonian toothfish at HIMI was developed in 2006 (Constable et al., 2006; Candy and Constable, 2008). The model had a basic structure consisting of a single-area, single-sex, age-structure fish population and multiple sub-fisheries, which has remained unchanged until now.

The annual cycle was split into three fishing season (1: December–April, 2: May–September, 3: October–November), with season 2 being the dominant fishing period. The sub-fisheries were defined by the two fishing methods trawling (f2 and f3) and longlining (f5 and f6) on four main fishing grounds. Each combination of gear by fishing ground was considered a separate fishery in the model to provide a proxy for spatial complexity of the region within the single-area model framework. Thus, fishing selectivities in the model represented a combination of vulnerability and gear selectivity, commonly used to model spatial structure within single area assessments (Cope and Punt, 2011; Hurtado-Ferro et al., 2014; Waterhouse et al., 2014).

Values for biological parameters were either estimated for the area, e.g. growth by Candy et al. (2006), or taken from other analogous areas. A maturity-at-length function had been estimated for toothfish at HIMI in 2001 and compared to that from South Georgia (SC-CAMLR, 2001). The two estimated functions showed little difference and subsequently, the simpler function from South Georgia had been adopted for HIMI assessments. This linear function estimated L_{m50} at 930 mm, with a range from 0 to full maturity between 780 and 1 080 mm. For the CASAL assessment in 2006, this maturity-at-length function was converted to a maturity-at-age function using the growth function. This resulted in a linearly increasing function with L_{a50} = 14 years and a range from 0 to full maturity of 11–17 years (SC-CAMLR, 2006).

Based on life-history invariant theory, natural mortality M for Patagonian toothfish was initially estimated to be within the range of 0.13–0.20 corresponding to a range of two to three times the parameter K of the von Bertalanffy growth function for Patagonian toothfish in Subarea 48.3. This range had been applied in the 2001 GYM assessment (Constable et al., 2001) and was not varied for a number of years because of the difficulties with estimating this parameter. In 2005, Agnew et al. (2005) estimated M from a range of three Beverton–Holt invariants in Subarea 48.3 with a maximum of $M = 0.165$ suggesting that the natural mortality range of 0.13–0.2 was too high, and the range of 0.13–0.165 was used for M in the GYM assessments at HIMI in 2005 (Constable et al., 2005). In 2006, natural mortality was assumed to be $M = 0.13$ as for the other toothfish assessments, with sensitivity runs for alternative values (SC-CAMLR, 2006). The same value of $M = 0.13$ was also estimated for Antarctic toothfish based on an analysis of catch-curve data from the Ross Sea fishery using the Chapman–Robson estimator (Dunn et al., 2006).

Following the review of Welsford et al. (2006b), the surveys within the assessment were split into five groups with the main group (Surv1) comprising the surveys from 2001–2002 and 2004–2006. The other surveys were treated individually because of differences in survey design, timing and type of vessel used for the survey (Surv2: 1999, Surv3: 1990, Surv5: 1993, Surv7: 2003). The surveys in 1992 and 2000 were excluded because of their unsuitable sampling design for toothfish and general poor fits to the data in early model sensitivity trials.

Time-invariant double-normal plateau selectivity functions defined by four parameters (Bull et al., 2012) were estimated for each sub-fishery and survey group. Survey group 1 was assumed to observe the juvenile stock fully and provide great accuracy on juvenile abundance, thus its catchability q was set to 1. For the other survey groups with differing design and survey vessels, values for q were estimated (with the same value for Surv3 and Surv5).

The assessment model used numbers-at-length from the survey, catch-at-length composition of the commercial catch, and standardised catch rate time series for two commercial trawl fishing grounds to estimate virgin spawning stock biomass SSB_0, year-class strength (YCS) from 1983 to 2004 and the parameters of all selectivity functions.

The inclusion of tag-recapture data from 1998 to 2006 to inform the estimation of abundance in the assessment was trialled but led to a conflict with the survey data. Since most of the tagged fish were released and recaptured on the small main trawl ground and mixing of tagged fish with other fishing grounds was incomplete, the biomass index derived from tag-recapture data was considered to represent only the local biomass rather than that of the entire fish stock. Tagging data was therefore not used in the assessment model at this time and was only included again in 2014.

Exploratory analyses were undertaken and the maximum likelihood or maximum posterior density (MPD) estimated. To better integrate across uncertainty in the model parameters, Markov Chain Monte Carlo (MCMC) sampling was then conducted based on the MPD fit and the results used in projections to estimate the long-term annual yield that satisfied the CCAMLR decision rules. The model estimated a virgin spawning biomass SSB_0 of 116 061 tonnes (95% CI: 102 675–133 602 tonnes) and an estimated spawning stock status in 2006 of 0.74 of unfished levels. The estimated long-term annual yield was 2 427 tonnes with 50% escapement after a 35-year projection period and a 0.06 probability that the stock would drop below the depletion level of 20% SSB_0.

This general model approach has been used in subsequent assessments, with updated catch and observation data as they have become available, aged fish to estimate survey and commercial catch-at-age compositions rather than catch-at-length compositions, re-estimated model parameters, and some refined modelling approaches.

Stock assessment 2007

In addition to new data, a number of small changes were made to the parameter estimation in the 2007 assessment model. The coefficient of variation (CV) of the von Bertalanffy growth function which had been estimated outside the 2006 model by Candy et al. (2007) as 0.1, was now estimated in the 2007 model together with the other model parameters.

Catch-at-length observations from the trawl fishery on the main trawl ground were estimated to have different selectivities within and between fishing seasons, i.e. separate selectivity parameters were estimated for the late season (s3) compared to the combined earlier seasons (s1 and s2), and for 2006–2007 catches (sub-fishery f2r) compared to earlier years due to the generally smaller size of fish caught in the later years (Candy and Constable, 2007; SC-CAMLR, 2007).

Where the double-normal-plateau selectivity function collapsed to a double-normal selectivity function, the simpler double-normal function was used in the assessment model to reduce the number of estimated model parameters. This was the case for some survey groups and trawl sub-fisheries, while all longline sub-fisheries were fitted with double-normal-plateau functions. This practice was maintained in all subsequent assessment models.

In addition, to estimate uncertainty in model estimates and to calculate stock projections, independent samples from the MPD distribution of the parameters were obtained using multivariate normal (MVN) sampling of the parameter vector since the MCMC samples showed a high level of autocorrelation.

While estimated SSB_0 decreased to 125 219 tonnes (SE: 5 806 tonnes), stock status in 2007 remained at 0.73 of unfished levels, and the long-term annual yield increased slightly to 2 500 tonnes.

In its 2007 meeting, the Scientific Committee of CAMLR also agreed that toothfish stock assessments which had been stable and where the current toothfish stock was estimated to be at or above target levels, could be conducted every second year instead of annually. As a consequence, the stock assessments for Patagonian toothfish at HIMI and South Georgia (Subarea 48.3), and for Antarctic toothfish in the Ross Sea region (Subareas 88.1 and 88.2) moved to a biennial cycle.

Stock assessment 2009

In 2009, the HIMI toothfish stock assessment underwent a major improvement with the inclusion of ageing data for the first time (Candy and Welsford, 2009; SC-CAMLR, 2009). For this assessment, a total of 7 412 aged fish were available to calculate annual ALKs for surveys between 2006 and 2007 and the commercial fishery between 1998 and 2008. ALKs were estimated separately for surveys and the commercial fishery, but unfortunately no fish otoliths had been collected from surveys prior to 2006, so numbers-at-length data up until 2005 were retained for the surveys. Candy et al. (2009) also estimated ageing error using a reference set of otoliths where each otolith had been aged by multiple readers, and Candy (2008) developed a method for incorporating haul-level variability in catch-at-length proportions, ALK sampling error, and random ageing error in the calculation of effective sample sizes for the CV of abundance-at-age data and the commercial catch-at-age proportions.

Three new sub-fisheries were also included in the assessment, two for trawl (f8) and longline (f9) in new fishing grounds, and one for pots (f10). Pots had been trialled in 2006 and captured comparably older fish than trawl and longline. Even though catch rate time series and single-year surveys had only minor influence on estimated parameters, they were retained in the assessment as they were considered to be useful in tracking and comparing observed and model-estimated survey and catch rate trends.

The CV of the growth function was again fixed at 0.1, the value obtained by modelling length-at-age using a von Bertalanffy model (Candy et al., 2007), since the CASAL-estimated value in 2007 had been close to 0.1 and estimating this parameter within this assessment did not improve model results.

The survey numbers-at-age data conflicted strongly with the catch-at-age data from the main trawl fishery (f2) with regard to the level of SSB_0, a conflict that could not be resolved. In the final model, the estimated SSB_0 of 116 379 tonnes (SE: 2 725 tonnes) was close to that from 2007, however with a lower stock status in 2009 of 0.63 of unfished levels. The long-term annual yield was estimated to increase slightly to 2 550 tonnes.

Stock assessment 2011

For the 2011 stock assessment, catch and ageing data were again updated and a catch rate time series for longline (f6) added. The major change in this assessment consisted of the change in the value for natural mortality M from 0.13 to 0.155 (Candy and Welsford, 2011; SC-CAMLR, 2011). This new value of 0.155 was estimated externally to CASAL from catch-at-age composition and aged mark-recapture data collected on the main trawl ground (Candy et al., 2011a).

Using a higher value for M in the integrated assessment resulted in a substantial decrease in the estimated SSB_0 and a compensatory increase in average recruitment R_0. The effect of the higher M was quite marked for the estimated values of SSB_0 and R_0 but not the stock status. When using the same data as in the 2009 assessment but with the new value for M of 0.155, SSB_0 decreased by 33% and R_0 increased by 23% compared to the 2009 assessment results. For the updated assessment model with new data in 2011, estimates of SSB_0 decreased by 26% and R_0 increased by 37% compared to the original 2009 model. Virgin spawning stock biomass SSB_0 was estimated at 86 400 tonnes (SE: 1 915 tonnes), however the estimated stock status in 2011 remained unchanged from 2009 at 0.63 of unfished levels. The long-term catch limit that satisfied the CCAMLR decision rules slightly increased to 2 730 tonnes.

Stock assessment 2013

In the 2013 assessment presented to CCAMLR, the structure of sub-fisheries was simplified and the growth model updated (Ziegler et al., 2013). The new fishery structure was based on a method by Candy et al. (2013) that suggested two depth-stratified longline sub-fisheries which were not regionally-explicit. The four trawl sub-fisheries (renamed to Trawl1, Trawl1r, Trawl2 and Trawl3) were retained, but the seasonal structure was simplified such that there was only one fishing season. Alternative trawl sub-fisheries were evaluated in different scenarios and resulted in similar spawning stock biomass patterns and estimates of current status. Since the selectivity functions for the different trawl sub-fisheries varied substantially, a separation of the trawl sub-fisheries was considered to be appropriate. Ziegler et al. (2013) recommended a model that included four separate trawl sub-fisheries, two longline sub-fisheries and one pot sub-fishery, and estimated YCS from 1992 to 2009 to be used to provide advice on catch limits. Using the CCAMLR decision rules, this model recommended a catch limit of 3 005 tonnes.

The 2013 meeting of the Working Group on Fish Stock Assessment (WG-FSA) (SC-CAMLR, 2013) made a number of recommendations about model structure and input parameters, and raised concerns about the lack of direct observations of the spawning biomass by the survey. Further, while the catch limit was consistent with the CCAMLR decision rules, WG-FSA noted that the projected spawning stock biomass status would drop below the target reference point of 50% and only increase to the target level in the last year of the projection period. This drop and subsequent recovery in SSB was the result of two factors. Firstly, the projections were run under the assumption that the future catch would be taken entirely by longline. The change from trawl to longline fishing meant that some year classes would be 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 would have a negative impact on the future SSB before the fishery would eventually benefit from the increase in yield-per-recruit through longline fishing. Secondly, YCS was estimated to be below the long-term median level R_0 in most years from 1998 to 2005, however, in the projections, future recruitment was assumed to be at R_0, subject to the stock-recruit relationship, and there were concerns whether future recruitment would in reality return to the long-term average.

In addition, an unexplained discrepancy between two different CASAL versions became also apparent during the meeting, with estimates of SSB_0 and long-term catch limits varying between the two CASAL versions used either for this or other assessments. Since CCAMLR could not resolve all these issues and not achieve consensus on the assessment, it agreed to maintain the catch limit of 2 730 tonnes for another year while the issues raised would be considered at its next meeting in 2014.

Stock assessment 2014

In response to the lack of consensus on the 2013 assessment, a number of papers were presented to CCAMLR in 2014 with information on the spatial distribution of Patagonian toothfish around HIMI (Péron and Welsford 2014), the tagging (Welsford et al., 2014) and ageing programs (Farmer et al., 2014), the revised ageing error matrix (Burch et al., 2014) and an updated stock assessment (Ziegler and Welsford, 2014; Ziegler et al., 2014; Welsford et al., 2014).

The stock assessment model was substantially revised, with a further simplification of trawl to one sub-fishery, the inclusion of a Beverton–Holt stock-recruitment relationship with steepness $h = 0.75$, the removal of survey abundance-at-length data from 1990, 1993, 2000 and 2003, the removal of all commercial catch-at-length data and catch rates time series which were uninformative in the assessment, an updated ageing error matrix and growth model, and down-weighted pot catch-at-age data. A substantial amount of new ageing data were also available, including for surveys up to 2014 and commercial longline, which substantially improved the characterisation of growth in older age classes and led to a re-estimation of the von Bertalanffy growth parameters. To integrate across uncertainty in the model parameters, MCMC sampling was again conducted and found to produce comparable results to MVN sampling.

A major change in the assessment was the replacement of the survey with tagging data as the main observation to inform the estimation of abundance (SC-CAMLR, 2014). Longline tag-release and recapture data from 2012 to 2014 were considered to be suitable for inclusion in the assessment model since longline effort and fish tagging had been initially spatially concentrated but spread out across larger parts of the fishable habitat in recent years (Welsford et al., 2014). Tag-shedding and detection rates were taken from Candy and Constable (2008) and tag-release mortality was assumed to be 0.1 based on Agnew et al. (2006).

Instead of fixing the survey catchability q to 1, Ziegler et al. (2014) estimated a prior for survey q from data of the main trawl ground by comparing survey fish abundance using the swept area method and the proportion of tag-recaptures in the survey catch. This indicated that on average only 42% of toothfish over the swept area were observed in the survey.

Including tagging data and estimating survey q in the stock assessment resulted in an estimate of SSB_0 of 108 586 tonnes (95% CI: 92 263–132 167 tonnes) with an SSB status in 2013 of 0.65 of unfished levels. The long-term catch limit that satisfied the CCAMLR decision rules also increased to substantially 4 410 tonnes.

Stock assessment 2015

With only three tag-release and recapture years in the 2015 stock assessment, the estimated SSB_0 was strongly influenced by the inclusion of new recapture data from 2014 and 2015 (Ziegler and Welsford, 2015; SC-CAMLR, 2015). In contrast, updating the growth model, changing model priors for survey catchability q, SSB_0 and YCS, and splitting the trawl fishery into two periods had relatively little effect on the estimated SSB_0.

The updated assessment model led to a lower estimate of SSB_0, with an MCMC estimate of 87 077 tonnes (95% CI: 78 500–97 547 tonnes). Although estimates of unexploited biomass had been variable over the last few years, estimates of stock status had been consistent at about 0.65 of unfished levels. The long-term catch limit that satisfied the CCAMLR decision rules was 3 405 tonnes. With a consistent stock status and a biomass estimate above the target level, CCAMLR considered that the assessment could return to the biennial cycle without incurring significant adverse risk.

Stock assessment 2017

The 2017 stock assessment (Ziegler, 2017a; SC-CAMLR, 2017a) again incorporated a number of changes, namely the inclusion of new catch, tagging and ageing data, an updated growth model, a revised maturity-at-age relationship (Yates et al., 2018), revised tag-loss estimates (Ziegler, 2017b) and estimates of emigration from the Australian to the French EEZ (Burch et al., 2017). The survey data was converted from numbers-at-age and length to a biomass index and proportions-at-age to facilitate the identification of potential signals in stock biomass and YCS. In addition, the method for data weighting described by Francis (2011a and 2011b) was applied, consistent with the approach in other toothfish stock assessments.

As in the 2015 assessment, the fishery structure was evaluated by the method developed by Candy et al. (2013) which 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 around HIMI (Figure 2). Alternative depth and regional splits of longline hauls indicated that depth splits at 1 500 m and 1 200 m provided similar results, with significantly different splines between shallow and deep hauls, and a depth split at 1 500 m was again used in the assessment. Splines from the respective depth strata on eastern and western fishing grounds were similar, indicating that separate selectivity functions for longline by fishing region were not needed in the assessment.

Based on this analysis, the commercial sub-fishery structure for the assessment remained unchanged with two trawl (Trawl1 and Trawl2), one pot (Pot), one shallow longline (LL1) and one deep longline sub-fishery (LL2). IUU catches from Table 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.

By 2017, over 17 000 individual fish from the surveys and the commercial fishery had been aged (Table 2, Figure 3). All ages had been estimated by technicians consistent with 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).

Growth estimates were updated using the approach developed by Candy et al. (2007) which accounts for variability in sampling probabilities due to length-dependent fishing selectivity and the effect of length-bin sampling. Accounting for length-bin sampling was needed because aged fish

Table 2: Number of toothfish measured for length or age and used in the assessment for the RSTS and commercial fisheries by 2017. Where numbers are in bold, the ages were used to calculate age–length keys (ALKs).

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	2 294	14 623	16 917	2	623	625
2000	2 258	20 483	22 741	20	807	827
2001	2 505	27 079	29 584	2	909	911
2002	2 965	18 476	21 441	4	829	833
2003	2 301	27 298	29 599	13	675	688
2004	2 462	33 509	35 971	4	336	340
2005	2 355	28 899	31 254	1	370	371
2006	2 081	31 427	33 508	119	1 100	1 219
2007	2 050	22 843	24 893	547	588	1 135
2008	1 281	31 475	32 756	652	107	759
2009	1 922	44 342	46 264	642	77	719
2010	5 893	30 485	36 378	918	129	1 047
2011	2 484	35 568	38 052	520	142	662
2012	6 062	37 026	43 088	549	140	689
2013	2 912	42 736	45 648	266	1 249	1 515
2014	2 769	50 417	53 186	571	526	1 099
2015	3 869	73 739	77 608	656	559	1 215
2016	5 630	57 078	62 708	315	537	852
Total	54 262	650 779	705 041	5 801	11 533	17 334

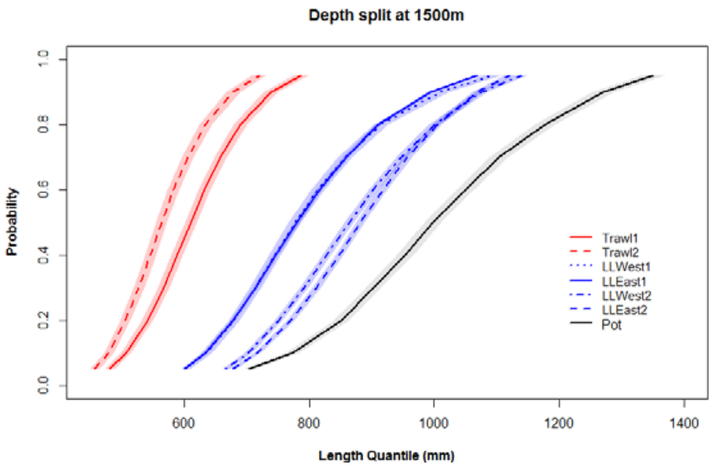

Figure 2: Predicted splines for length quantiles of trawl, longline (LL) and pot. Longline hauls were split by fishing areas (west and east of around 74°E), and 1 500 m depth, whereas '1' is shallow and '2' is deep. The shaded areas represent the 95% confidence intervals (or two standard errors) of the spline for trawl (red) and pot (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 n miles).

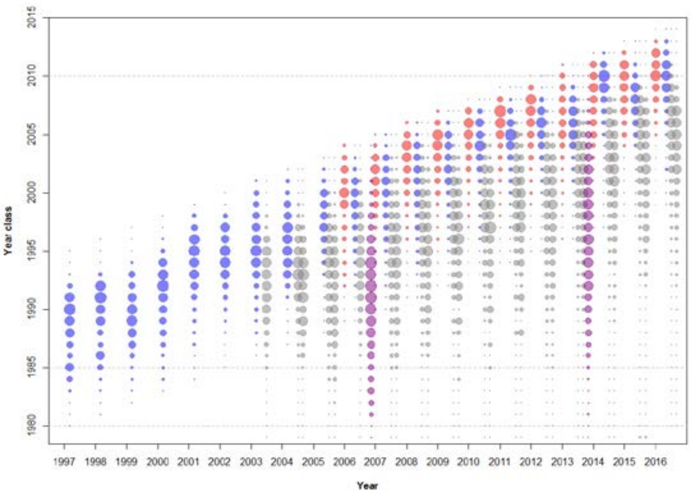

Figure 3: Bubble plot of age observations by year for the survey (red), trawl (Trawl1 and Trawl2, blue), longline (LL1 and LL2, grey) and pot (purple).

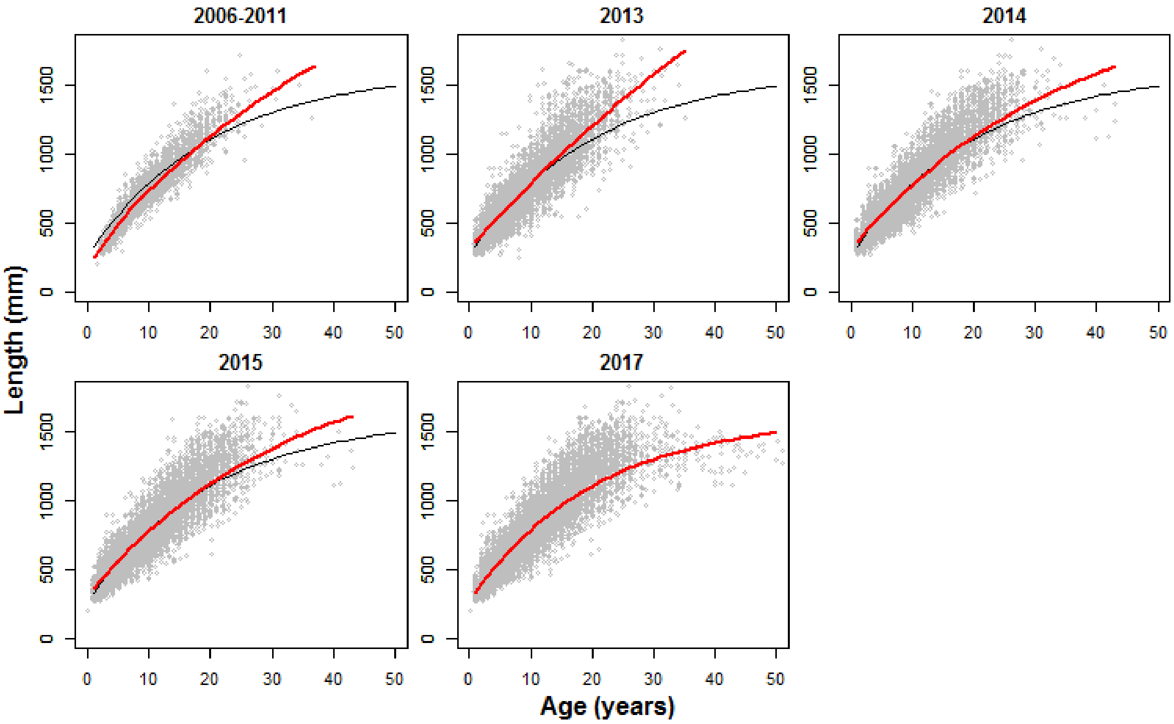

Figure 4: Growth functions used in the assessment models from 2006 to 2017 (red lines) which were estimated based on the available age-at-length data (grey dots), and the 2017 growth function (black line) as reference.

were not randomly selected from the catch, with an over-representation of age samples from fish smaller than 500 mm and fish between 1 000 and 1 500 mm compared to the catch. Over the years, the increasing proportion of old fish in the samples resulted in a decrease of the estimates for L_∞ to a more realistic value (Table 3, Figure 4).

Tagged and released fish in longline catches from 2012 to 2015 and longline tag-recaptures from 2013 to 2016 were included in the assessment because the spatial distribution of longline effort has only spread out across HIMI in more recent years (Figure 5) and tagged toothfish are unlikely to mix completely within the part of the fish population that is vulnerable to fishing (Williams et al., 2001; Welsford et al., 2007, 2014). Annual

Table 3: Model setup, input parameters, data used, and estimates of CASAL models since 2006.

Model setup	2006	2007	2009	2011	2013	2014	2015	2017
Reference	Constable et al., 2006; SC-CAMLR, 2006	Candy and Constable, 2007; SC-CAMLR, 2007	Candy and Welsford, 2009; SC-CAMLR, 2009	Candy and Welsford, 2011; SC-CAMLR, 2011	Ziegler et al., 2013; SC-CAMLR, 2013	Ziegler et al., 2014; Welsford et al., 2014; SC-CAMLR, 2014	Ziegler and Welsford, 2015; SC-CAMLR, 2015	Ziegler, 2017a; SC-CAMLR, 2017a
Assessment period	1982–2006	1982–2007	1982–2009	1982–2011	1982–2013	1982–2014	1982–2015	1982–2016
Spawning SSB_0	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated	Estimated
Mean recruitment R_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0	Derived from SSB_0
Year-class strength (YCS)	Estimated 1983–2004, lognormal with CV = 1.1	Estimated 1983–2004, uniform prior	Estimated 1983–2006, uniform prior	Estimated 1983–2007, uniform prior	Estimated 1992–2009, uniform prior	Estimated 1986–2009, uniform prior	Estimated 1986–2010, lognormal with CV = 0.6	Estimated 1986–2011, lognormal with CV = 0.6
YCS in projections	Lognormal $\sigma_R = 0.78$ (calculated from 1992 to 2004)	Lognormal $\sigma_R = 0.925$ (calculated from 1983 to 2004)	Lognormal $\sigma_R = 0.56$ (calculated from 1983 to 2006)	Lognormal $\sigma_R = 0.78$ (calculated from 1983 to 2007)	Lognormal $\sigma_R = 0.45$ (calculated from 1992 to 2009)	Lognormal $\sigma_R = 0.41$ (calculated from 1992 to 2009)	Lognormal $\sigma_R = 0.32$ (calculated from 1992 to 2010))	Lognormal $\sigma_R = 0.39$ (calculated from 1996 to 2011)
Age classes	1–35 y	1–35 y	1–35 y	1–35 y	1–35 y	1–35 y	1–35 y	1–35 y
Fishing seasons	3 (s1, s2, s3)	3 (s1, s2, s3)	3 (s1, s2, s3)	3 (s1, s2, s3)	1	1	1	1
Sub-fisheries	Surv1, Surv2, Surv3, Surv5, Surv7, f2, f3, f5, f6, IUU	Surv1, Surv2, Surv3, Surv5, Surv7, f2, f2_s3, f2r, f3, f5, f6, IUU	Surv1, Surv2, Surv3, Surv5, Surv7, f2, f2_s3, f2r, f3, f5, f6, f7, f8, f9, f10, IUU	Surv1, Surv2, Surv3, Surv5, Surv7, f2, f2_s3, f2r, f3, f5, f6, f7, f8, f9, f10, IUU	Surv1, Surv2, Surv3, Surv5, Surv7, Trawl1, Trawl1r, Trawl2, Trawl3, LL1, LL2, Trap, IUU	Survey, Trawl1, LL1, LL2, Trap, IUU	Survey, Trawl1, Trawl2, LL1, LL2, Trap, IUU	Survey, Trawl1, Trawl2, LL1, LL2, Trap, IUU
Number of estimated parameters (including q)	64	68	85	86	60	44	48	49
Sampling method	MCMC	MVN	MVN	MVN	MVN	MCMC	MCMC	MCMC

Table 3 (continued)

Model setup	2006	2007	2009	2011	2013	2014	2015	2017
Input parameters								
Size-at-age: Von Bertalanffy	Candy et al., 2006[1]	Candy et al., 2006[1]	Candy et al., 2006[1]	Candy et al., 2006[1]	Ziegler et al., 2013	Ziegler et al., 2014	Ziegler and Welsford, 2015	Ziegler, 2017a
L_∞	2870.8	2870.8	2870.8	2870.8	4509	2190	2116	1605
K	0.02056	0.02056	0.02056	0.02056	0.012	0.028	0.030	0.049
t_0	–4.2897	–4.2897	–4.2897	–4.2897	–5.96	–5.37	–5.31	–3.64
CV	0.1	Estimated (0.0977)	0.1	0.1	0.128	0.0129	0.128	0.131
Ageing error matrix	-			Candy, 2009	Candy, 2009	Burch et al., 2014	Burch et al., 2014	Burch et al., 2014
Weight at length (mm to t)	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999	Constable et al., 1999
a	2.59E-12	2.59E-12	2.59E-12	2.59E-12	2.59E-12	2.59E-12	2.59E-12	2.59E-12
b	3.2064	3.2064	3.2064	3.2064	3.2064	3.2064	3.2064	3.2064
Maturity	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	SC-CAMLR, 2006 Range 5–95%: 11–17 y	Yates et al., 2018 $a_{50} = 13.9$ $a_{to95} = 13.7$
Natural mortality M	SC-CAMLR, 2006 0.13	SC-CAMLR, 2006 0.13	SC-CAMLR, 2006 0.13	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
Stock–recruitment Steepness h	-	-	-	-	-	Dunn et al., 2006 Beverton–Holt $h = 0.75$	Dunn et al., 2006 Beverton–Holt $h = 0.75$	Dunn et al., 2006 Beverton–Holt $h = 0.75$
Survey q	Surv1: $q = 1$, Others: estimated	Surv1: $q = 1$, Others: estimated	Surv1: $q = 1$, Others: estimated	Surv1: $q = 1$, Others: estimated	Surv1: $q = 1$, Others: estimated	Survey: estimated	Survey: estimated	Survey: estimated

(continued)

Table 3 (continued)

Model setup	2006	2007	2009	2011	2013	2014	2015	2017
Tag detection	-	-	-	-	-	Candy and Constable, 2008 0.093	Candy and Constable, 2008 0.993	Ziegler, 2017a 1
Tag-release mortality	-	-	-	-	-	Agnew et al., 2006 0.1	Agnew et al., 2006 0.1	Agnew et al., 2006 0.1
No-growth period (y)	-	-	-	-	-	Agnew et al., 2005 0.5	Agnew et al., 2005 0.5	Agnew et al., 2005 0.5
Tag shedding	-	-	-	-	-	Candy and Constable, 2008 0	Candy and Constable, 2008 0	Ziegler, 2017b 0.006
Emigration correction								Burch et al., 2017 0.01
Data								
Catch (RSTS, commercial and IUU)	1997–2006	1997–2007	1997–2009	1997–2011	1997–2013	1997–2014	1997–2015	1997–2016
Survey (RSTS):								
Numbers-at-length	1990, 1993, 1999, 2001–2006	1990, 1993, 1999, 2001–2007	1990, 1993, 1999, 2001–2005, 2008–2009	1990, 1993, 1999, 2001–2005	1990, 1993, 1999, 2001–2005, 2012–2013	2001–2002, 2004–2005	2001–2002, 2004–2005	-
Numbers-at-age	-	-	2006–2007	2006–2011	2006–2011	2006–2014	2006–2015	-
Biomass index	-	-	-	-		-	-	2001–2016
Proportions-at-age	-	-	-	-		-	-	2006–2016

(continued)

Table 3 (continued)

Model setup	2006	2007	2009	2011	2013	2014	2015	2017
Commercial sub-fisheries:								
Proportions-at-length	1997–2006	1997–2007	-	2009–2011	2009–2013	-	-	-
Proportions-at-age	-	-	1997–2008	1997–2008	1997–2008	1997–2008, 2013	1997–2014	1997–2016
Estimated sample size (ESS)	Estimated using Constable et al., 2006	Estimated using Candy, 2007	Estimated using Candy, 2008	Estimated using Candy, 2008	Estimated using Candy, 2008	Estimated using Candy, 2008, Pot: ESS = 1	Estimated using Candy, 2008, Pot: ESS = 1	Estimated using Francis, 2011a, 2011b Pot: ESS = 1
Catch rates	f2, f3	f2, f3	f2, f3	f2, f3, f6	Trawl1	-	-	-
Tag-releases:	-	-	-	-	-			
Sub-fisheries						LL1, LL2	LL1, LL2	LL1, LL2
Years						2012–2013	2012–2014	2012–2015
Tag-recaptures:	-	-	-	-	-			
Sub-fisheries						LL1, LL2	LL1, LL2	LL1, LL2
Years						2013–2014	2013–2015	2013–2016
Model estimates								
Virgin spawning SSB_0 (tonnes)	116 061 (95% CI: 102 675–133 602)	125 219 (SE: 5 806)	116 379 (SE: 2 725)	86 400 (SE: 1 915)	94 794 (SE: 2 034)	108 586 (95% CI: 92 263–132 167)	87 077 (95% CI: 78 500–97 547	77 286 (95% CI: 71 492–84 210)
Spawning B status	0.74	0.73	0.63	0.63	0.63	0.65	0.65	0.61
Mean recruitment R_0 (million)	4.3	4.5	4.2	5.77	5.44	8.07	6.59	6.12
Survey q	Estimated for Surv2, Surv3, Surv5, Surv7	Estimated for Surv2, Surv3, Surv5, Surv7	Estimated for Surv2, Surv3, Surv5, Surv7	Estimated for Surv2, Surv3, Surv5, Surv7	Estimated for Surv2, Surv3, Surv5, Surv7	Estimated for Survey	Estimated for Survey	Estimated for Survey
Selectivities	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries	Estimated for all surveys and sub-fisheries
Catch limit (tonnes)	2 427	2 500	2 550	2 730	2 730[2]	4 410	3 405	3 525

[1] With linear adjustment for 1–5 year old fish.

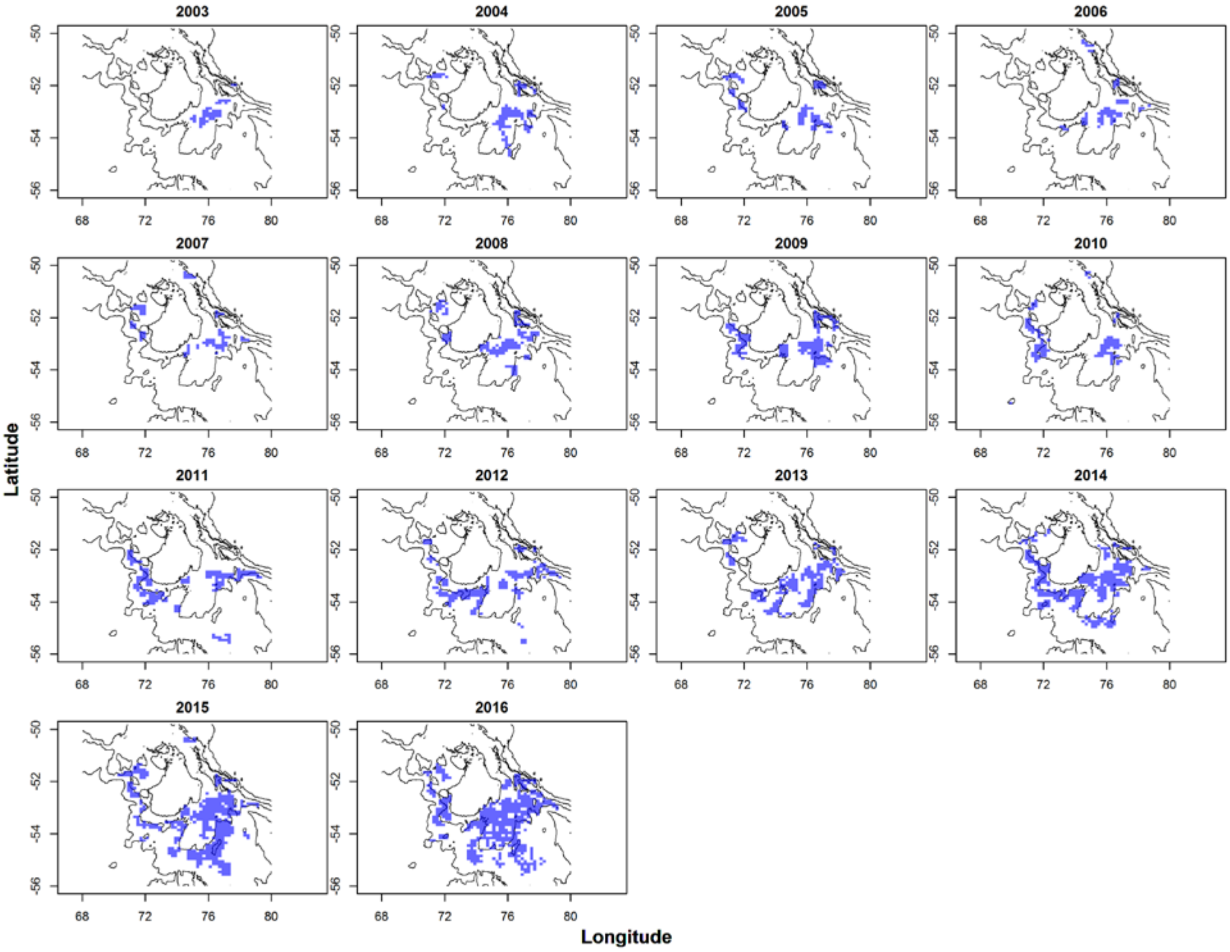

Figure 5: Annual variations in spatial distribution of longline fishing effort for Patagonian toothfish in Division 58.5.2 from 2003 to 2016. Blue cells correspond to locations where at least one longline haul event occurred.

tag-release and recapture numbers from longline have increased since 2008, particularly in 2015 due to a higher catch limit and an increase in tagging rates from two fish per three tonnes to two fish per tonne (Table 4). The numbers of longline tag-releases and tag-recaptures used were capped at six 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. Tag-detection rates during longline fishing were assumed to be 100%, and tag-shedding rates were estimated by Ziegler (2017a) following the method proposed by Adam & Kirkwood (2001). The parameter of annual tag-loss rate in CASAL's single-tag model was then approximated for a maximum time at liberty of six years as $l = 0.021$ for 2007–2011 and $l = 0.006$ for 2012–2015.

Burch et al. (2017) estimated migration rates of Patagonian toothfish between the Australian and French EEZs on the Kerguelen Plateau from longline tag-recapture data using a catch-conditioned modification of the method described by Hilborn (1990). Estimated annual migration rates were low between the two EEZs, with only 1.0% moving from the Australian EEZ north to the French EEZ and 0.4% in the reverse direction. Burch et al. (2017) also used simulations to show that such emigration can cause a bias in spawning biomass estimates of a tag-based assessment model, but that such a bias can be corrected through increasing the tag-shedding parameter by the value of the migration rate. This approach provided a simple way to correct for the effects of emigration and was considered to be appropriate for situations where the migration rates were estimated to be low (SC-CAMLR, 2018).

The model represented the trend in survey biomass and tag-recapture total numbers and numbers-by-length well (Figures 6 and 7). Generally good fits were obtained for the proportions-at-age

Table 4: Numbers of longline tag releases and tag recaptures that were used in the assessment models. Releases from 2008 to 2011 (shaded in grey) were only used the sensitivity analyses.

Releases		Recaptures								
Year	Number	2009	2010	2011	2012	2013	2014	2015	2016	Total
2008	891	25	14	3	8	23	19	24	9	125
2009	1 242	-	49	44	9	21	39	46	13	221
2010	1 214	-	-	41	5	12	52	36	9	155
2011	1 197	-	-	-	20	19	35	39	27	140
2012	1 433	-	-	-	-	22	40	39	21	122
2013	1 467	-	-	-	-	-	52	94	37	183
2014	1 799	-	-	-	-	-	-	77	58	135
2015	7 631	-	-	-	-	-	-	-	261	261
Total	16 874	25	63	88	42	97	237	355	435	1 342

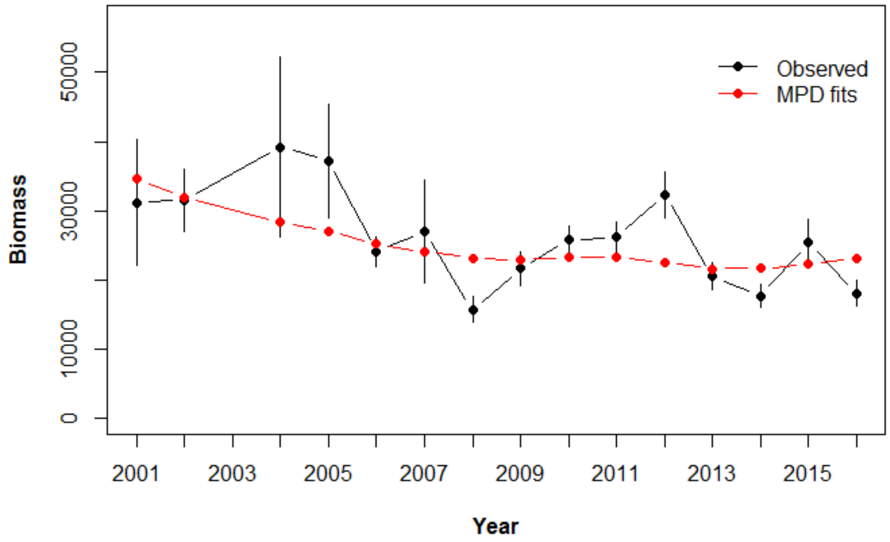

Figure 6: Observed (black line with 95% CI) and MPD-predicted (red line) survey biomass.

datasets of the survey and the longline sub-fisheries (example for the survey data in Figure 8) as indicated by the fit of the median age (Figure 9).

Even when tag releases were restricted to 2012–2015, their information about SSB_0 varied substantially as indicated by the likelihood profile (Figure 10). While tag-releases from 2014 and 2015 were in agreement and indicated that an SSB_0 of around 80 000 tonnes was most likely, tag-releases from 2012 and 2013 were in diametrical disagreement indicating that either a much larger or much smaller SSB_0 was most likely. The survey data indicated that an SSB_0 below 70 000 tonnes was most likely.

The inclusion of more years of tag-release and recapture data was evaluated in two sensitivity runs. Including all longline tag releases and recaptures from 2008 onwards or 2010 onwards resulted in spawning biomass estimates that were close to those estimated in the base-case scenario with releases only from 2012 onwards. However, the likelihood profiles indicated again strong discrepancies in the data for individual tagging release events (Figure 11). Tag releases from 2008, 2009 and 2013 indicated a smaller SSB_0, while tag releases from 2010 to 2012 and 2014 and 2015 indicated a larger SSB_0.

The updated assessment model led to a lower estimate of SSB_0 than that obtained in 2015, with an MCMC estimate of 77 286 tonnes (95% CI: 71 492–84 210 tonnes) and an estimated SSB status of 0.61 of the unfished level. Despite the smaller biomass, changes to the model compared to 2015,

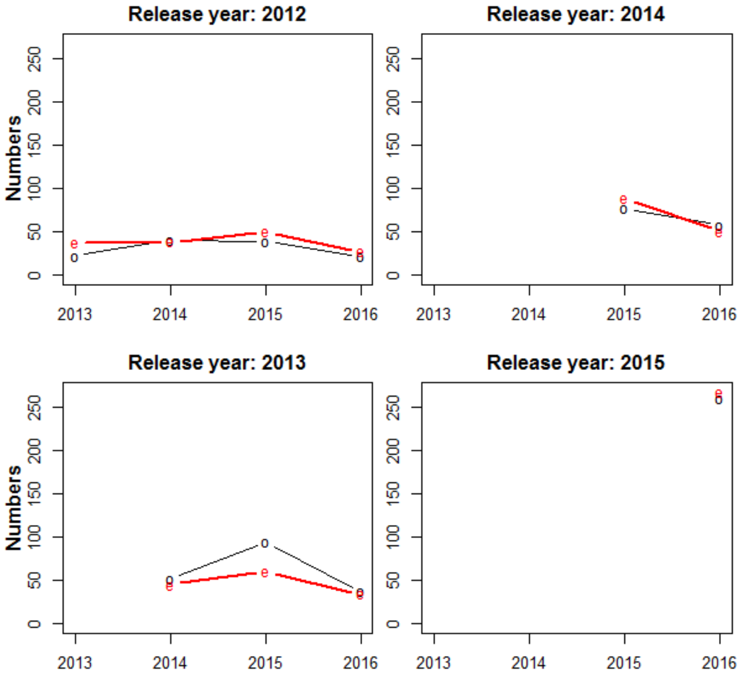

Figure 7: Numbers of observed (black) and MPD-predicted (red) tag recaptures for tag releases in 2012–2015 and tag recaptures in 2013–2016.

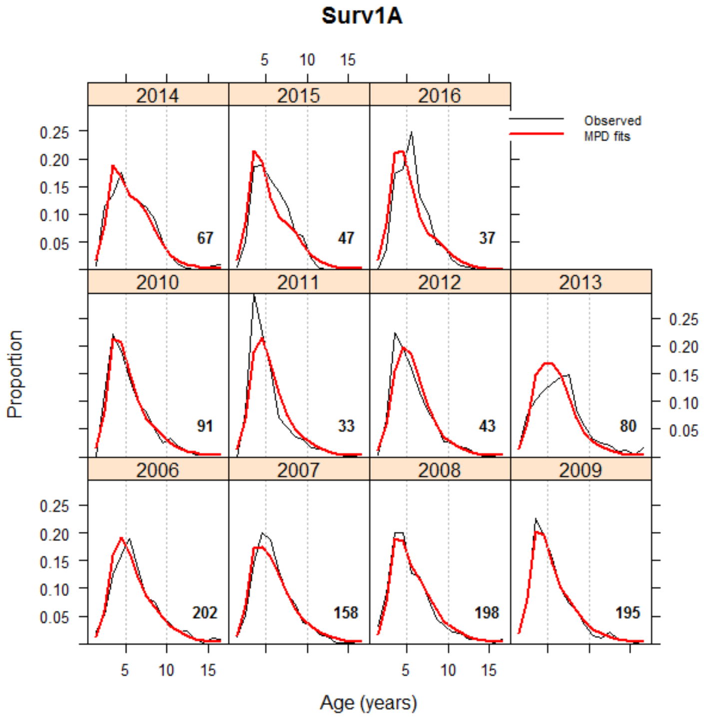

Figure 8: Observed (black) and MPD-predicted (red) proportions at age for the survey. Numbers indicate the effective sample size.

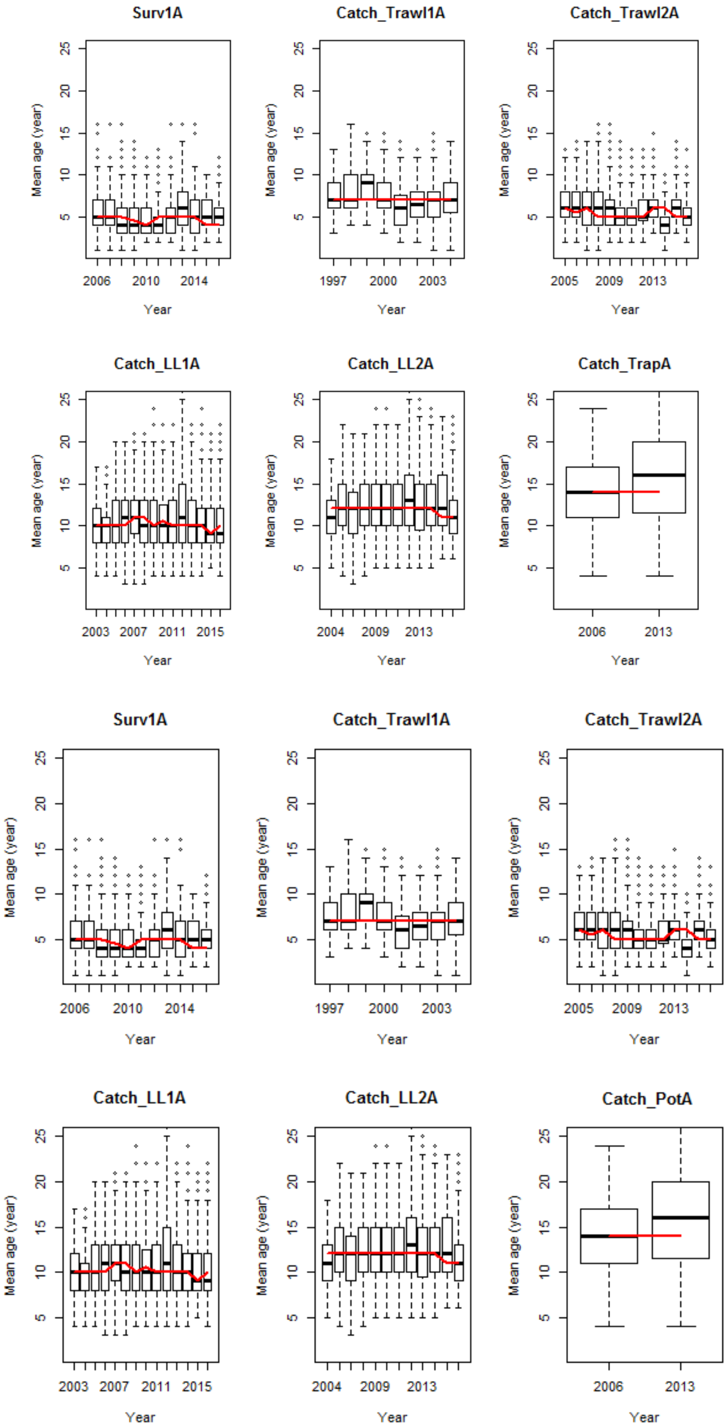

Figure 9: Boxplots of observed age by fishery and MPD-predicted median age (red line).

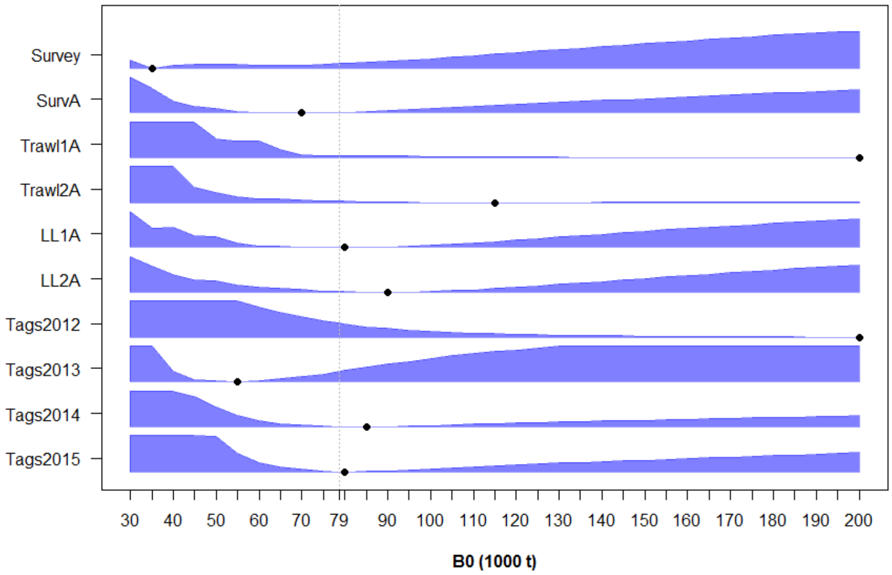

Figure 10: Likelihood profiles (–2 log-likelihood) across a range of SSB_0 values for each observation dataset (dots indicate the location of the minimum value). To create these profiles, SSB_0 values were fixed while only the remaining parameters were estimated. Values for each dataset were rescaled to have a minimum of 0, while the total objective function was rescaled to 20. The dotted grey line indicates the MPD estimate.

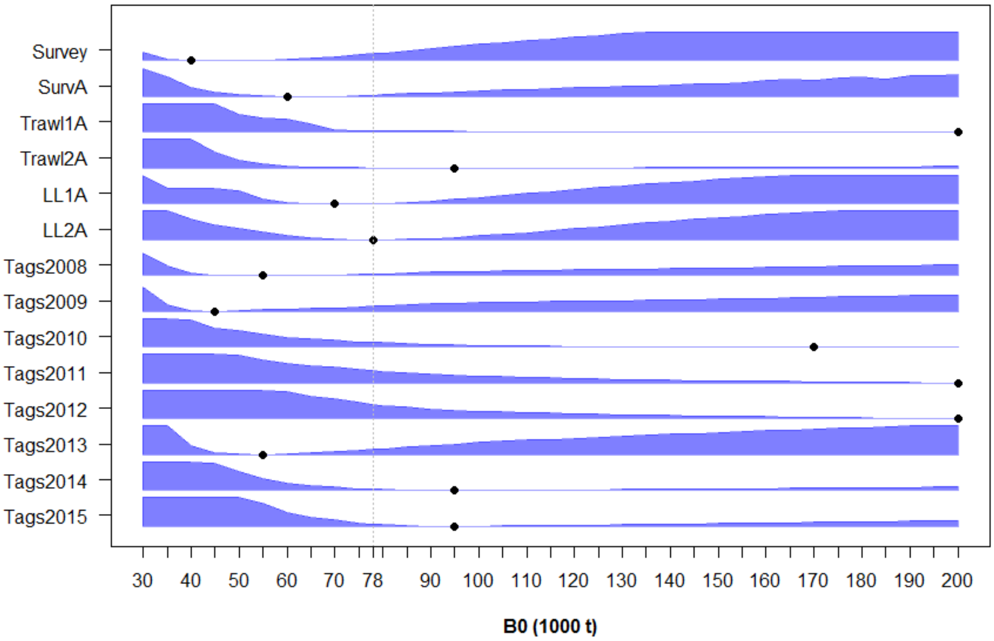

Figure 11: Likelihood profiles (–2 log-likelihood) across a range of SSB_0 values for each observation dataset (dots indicate the location of the minimum value) for sensitivity runs that included longline tagging data from 2008 onwards. To create these profiles, SSB_0 values were fixed while only the remaining parameters were estimated. Values for each dataset were rescaled to have a minimum of 0. The dotted grey line indicates the MPD estimate.

in particular the higher proportion of fish estimated to be mature, meant that the catch limit that satisfies the CCAMLR decision rules would increase from 3 405 tonnes to 3 525 tonnes (Figure 12).

The estimated YCS showed large uncertainty for the earlier years 1985–1995, with below average recruitment and higher confidence in most years since 1996 (Figure 13). The estimated selectivity functions differed distinctly between the survey and the trawl, longline and pot sub-fisheries (Figure 14). The trawl surveys and the commercial trawl sub-fisheries observed predominantly young fish, while the longline and pot sub-fisheries caught older fish, with LL2 in waters deeper than 1 500 m catching older fish compared to LL1 in waters shallower than 1 500 m. Pots were estimated to catch mainly fish older than 15 years.

Conclusions

The stock assessment for Patagonian toothfish at HIMI has developed significantly since the first CASAL model in 2006 which was a relatively simple assessment based on conservative assumptions and inferences from other fish stocks. Over the years, extensive work has been carried out to improve modelling approaches and a rich range of datasets has enabled the estimation of all key model parameters. Major uncertainties have been addressed through targeted research on e.g. the age structure, maturity, natural mortality, fish movement rates and survey catchability. While this has led to some variation in catch limits over the years, the estimated stock status has remained relatively stable and it is highly likely that the stock has been maintained above the target level.

One of the main changes in the stock assessment model was the introduction of tag-recapture data in 2014, and with it the replacement of survey data as the main observation to inform the estimated stock abundance. Survey and tag-recapture data can inform absolute indices of stock abundance, however both have limitations and rely on a number of specific assumptions. The trawl survey at HIMI targets predominantly young fish and thus does not directly observe the spawning biomass. It also requires catchability as a scaling factor between the part of the population observed by the survey and the actual fish population. Catchability has been estimated by the assessment model to be consistently lower than one, suggesting that either the survey does not cover the entire habitat of juvenile fish, or that the survey does not capture all fish in the path of a trawl net. The latter can occur when fish either swim out of the trawl net or escape from capture by being higher in the water column. Therefore, the assumption in the earlier stock assessments that catchability equals 1 was conservative.

Tag-recapture data as an index of abundance relies on many assumptions to be met, including that the population is closed, there is complete mixing of tagged fish with the part of the population that is vulnerable to fishing or recapture effort is random, and tagged fish behave in the same way as untagged fish (Pine et al., 2003). There are also a number of parameters that need to be known or at least are estimable, such as tag-shedding and tag-induced mortality rates (Agnew et al., 2006).

The population of Patagonian toothfish at HIMI is not closed, with direct observations of fish movement between the Australian and French EEZs and to Crozet Islands. As evidenced by genetic analyses, catch composition and tag-recapture data from survey and the commercial toothfish fisheries in the Australian and French EEZs, Patagonian toothfish are continuously distributed across the entire northern part of the Kerguelen Plateau and populations are linked. The fisheries in the Australian and French EEZs are assessed separately, however each has an adjustment of the tag-shedding parameter to account for the low level of adults migrating between the two areas. This approach is a simple way for dealing with emigration of tagged fish which has the potential to introduce a bias into the stock assessment (Burch et al., 2017). The key benefit of making this ad-hoc approach to increase the tag-shedding parameter is that it prevents the need to develop a new assessment framework for the fisheries in these areas, and the approach has been considered to be appropriate where movement rates are low (SC-CAMLR, 2018).

An alternative to adjusting the existing assessment would be to use a stratified assessment to model all toothfish in the Australian and French EEZs and migrations between these areas (Hampton and Fournier, 2001; Goethel et al., 2015a, 2015b). Stratified assessments have greater data requirements, can be more sensitive to model specification (Punt et al., 2015) and may require political negotiation when fish populations span jurisdictional

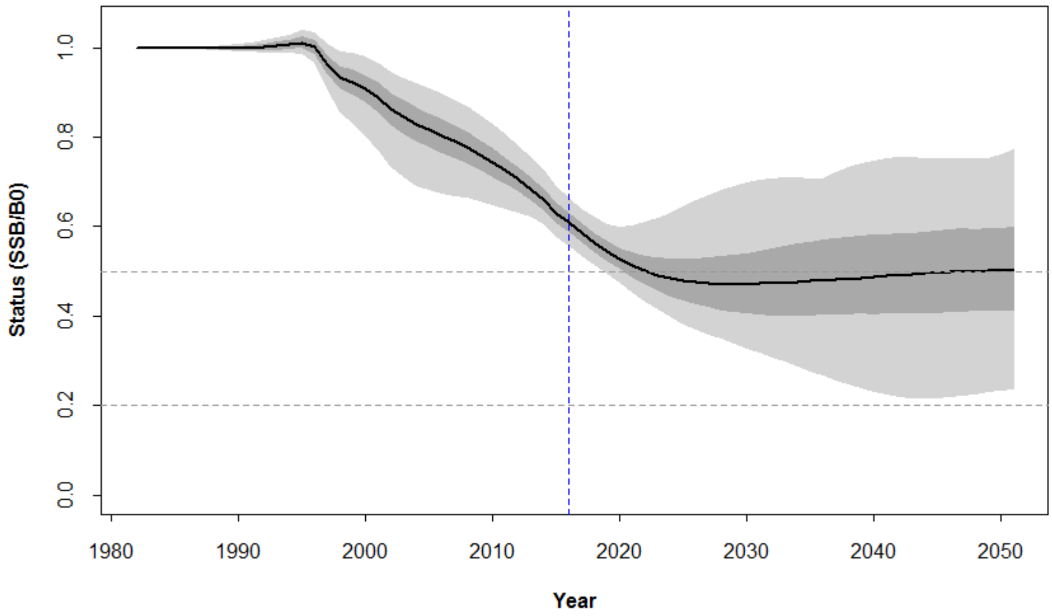

Figure 12: Historical and projected SSB status relative to SSB_0 for the assessment model and a constant future catch of 3 525 tonnes using MCMC samples. The YCS period from 1992 to 2011 was used to generate random lognormal recruitment from 2012 to 2051. Shown are median (black line), 100% confidence 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 2017.

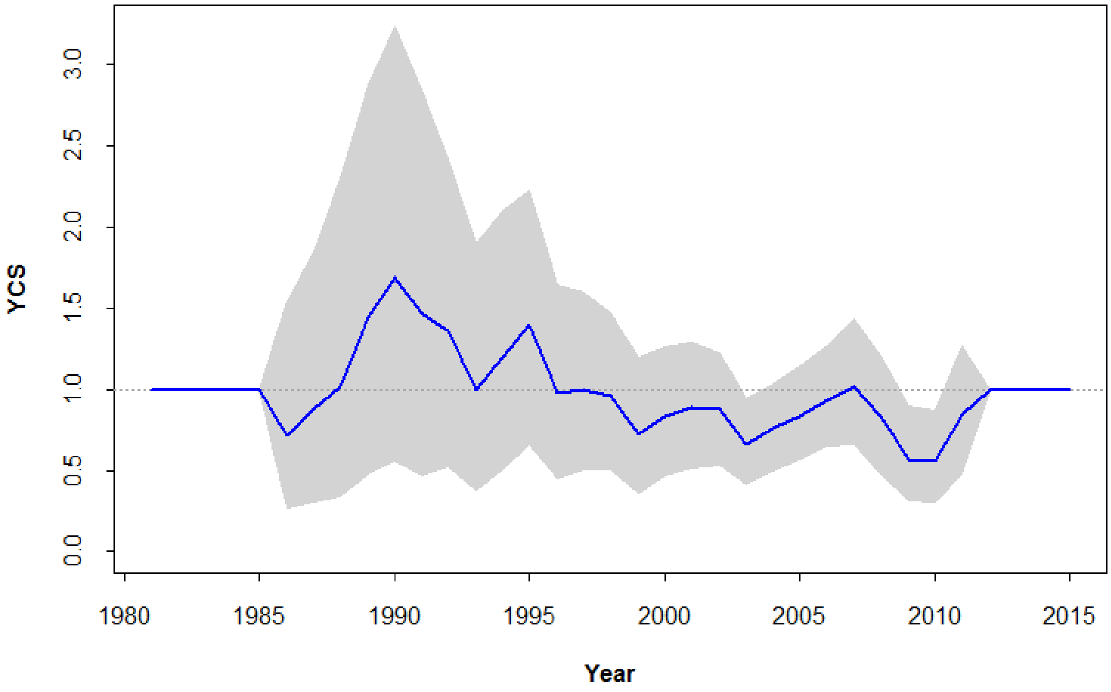

Figure 13: Estimated YCS showing 95% confidence bounds obtained from the MCMC samples.

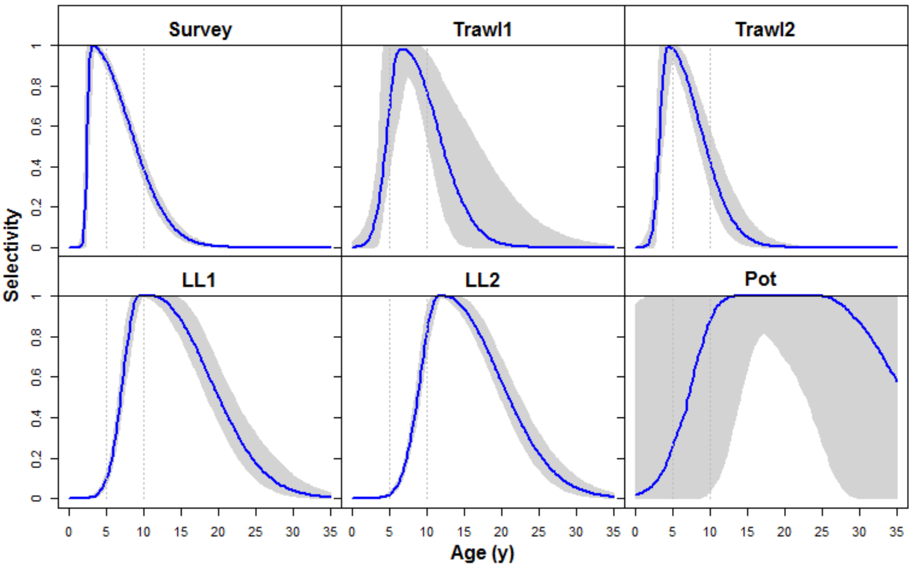

Figure 14: Estimated double-normal-plateau and double-normal fishing selectivity functions for the survey and commercial sub-fisheries, showing 95% confidence bounds obtained from the MCMC samples. Vertical reference lines are shown at ages 5 and 10.

borders as in the case here (Eide et al., 2013; Criddle and Strong, 2014). A single assessment of Patagonian toothfish in the Australian and French EEZs has been attempted by Candy et al. (2011b), however poor fits to some key datasets meant that it was not further developed and used to provide management advice.

The level of movement of younger fish as well as the level of mixing of recruits between the two areas is poorly observed and understood. In the assessment model, these processes are confounded with the estimated recruitment levels and not separated. Spawning occurs over large areas and there are spawning grounds in the Australian and French EEZs, thus recruitment in the two areas could be coupled to some degree.

The non-random distribution of fishing effort and the spatial expansion of the longline fishery has remained one of the biggest challenges for the longline tag-recapture data to be included in the HIMI stock assessment model. While the cumulative fishing effort covers large parts of the fishable habitat, fishing effort is still largely concentrated in a few locations and can vary between years. Tagged fish are approximately released in proportion to fishing effort (or indeed catch), but released fish do not mix well with the part of the population that is vulnerable to fishing. Rather most adult fish move little and only few move over substantial distances (Péron et al., 2019). More work is in progress to determine how the distribution of released fish and their subsequent movement patterns should be considered when using tag-recapture data to inform the estimation of abundance in the stock assessment.

Beside the questions about the impact of the spatial structure on the fishery and tagging data, a major focus of future work will be the evaluation of whether the stock assessment model can be significantly improved by moving from a single-sex to a sex-based model. While maturity at age appears to be similar for the two sexes, there is evidence that females grow to larger sizes than males which may affect the estimated stock productivity (Figure 15). In addition, females appear to dominate catches in deeper waters (Péron et al., 2016) which is likely to be reflected in sex-based differences of the longline selectivity functions and in turn may result in a stronger decline of female spawning stock status. Ongoing work will also include updating and improving parameter estimates, estimating whale depredation levels, investigating the cause and effects of lower than average estimated recruitment levels in recent years, and estimating the potential of long-term climate change impacts on productivity and availability. This work will contribute to the substantial research that has been conducted over the past years for this stock assessment. While biomass estimates have varied substantially since 2006, all stock assessments have estimated the stock status to be well above the target level, providing confidence that CCAMLR's long-term objectives for this toothfish stock are achieved.

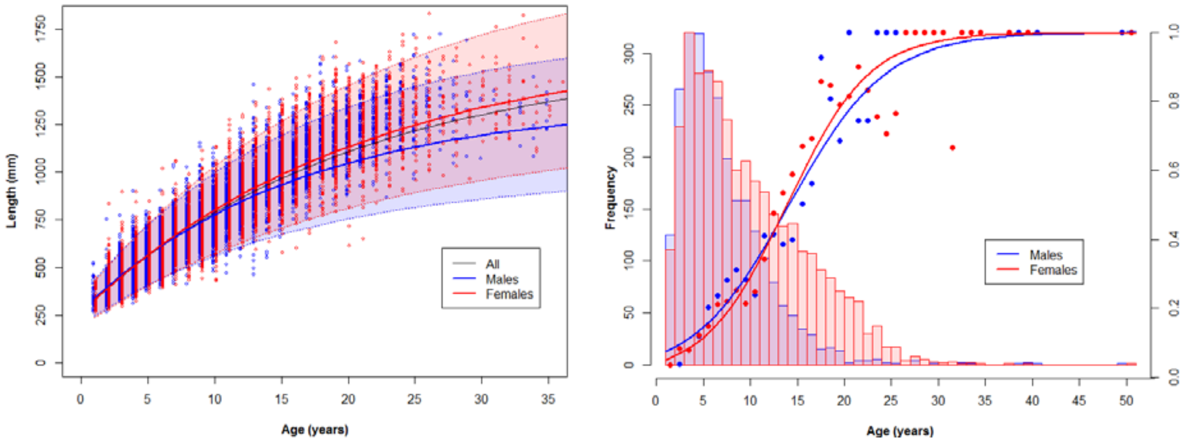

Figure 15: (a) Length-at-age for males (blue) and females (red) with observations (dots) and fitted von Bertalanffy growth models (lines) and approximate 95% confidence intervals of the data based on CV (shades) based on Candy et al. (2006); and (b) maturity at age with proportions of fish that were mature in 1-year age bins (dots), fitted values obtained by logistic regression (lines) and age-frequency histograms (shaded) (adapted from Yates et al., 2018).

This confidence was supported by the CCAMLR Independent Stock Assessment Review (SC-CAMLR, 2018) which reviewed the 2017 HIMI assessment together with those for Patagonian toothfish at South Georgia (Earl and Fischer, 2017) and for Antarctic toothfish in the Ross Sea Region (Mormede, 2017a, 2017b). All three assessment models follow similar model approaches and use tag-recapture data as the main source of information to estimate abundance. The review found that the model approaches for these assessments are appropriate for the assessment and precautionary management of these stocks. The review also highlighted the importance of the tagging data and long-term standardised surveys to index recruitment and noted that CCAMLR was world-leading in the development of tag-based integrated fish stock assessments.

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