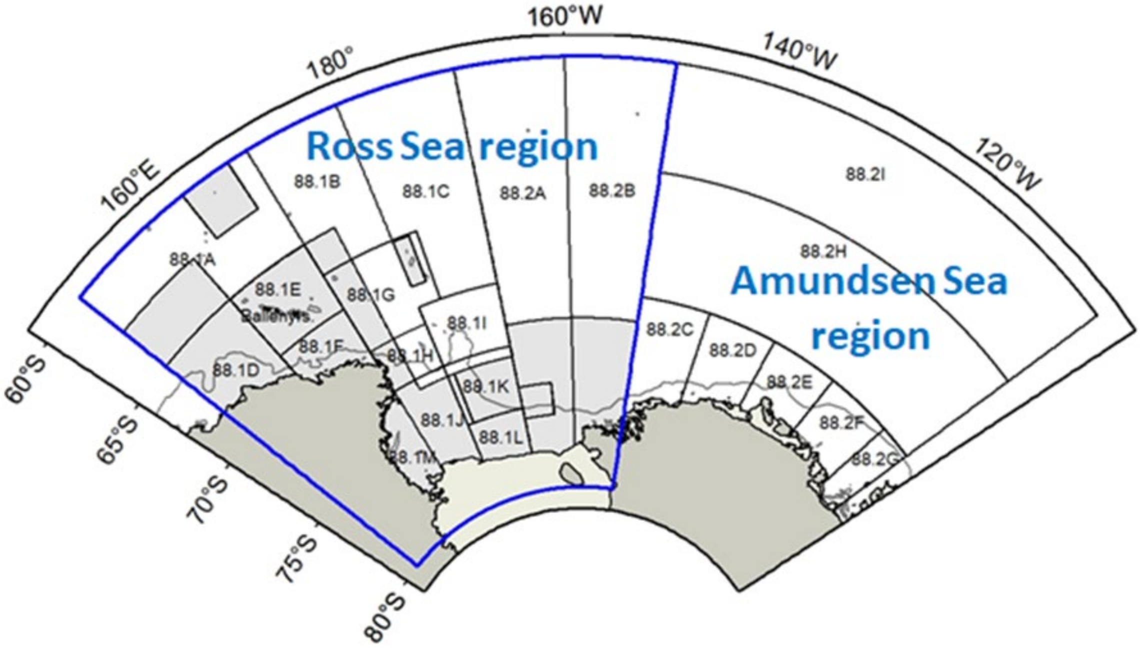
TOOTHFISH (TOT)
(outside EEZ)

(*Dissostichus mawsoni* and *Dissostichus eleginoides*[1])



The Ross Sea Region (CCAMLR Statistical Subareas 88.1 and small-scale research units (SSRUs) 88.2A and 88.2B), and the Amundsen Sea Region (SSRUs 88.2C–I) used for management and the 1000 m depth contour. Shaded regions indicate the Ross Sea region MPA boundaries and include the Special Research Zone, Krill Research Zone, and General Protected Zones (i), (ii), and (iii).

1. FISHERY SUMMARY

This working group report is a summary of the Ross Sea and Amundsen Sea toothfish fisheries in CCAMLR (Statistical Subareas 88.1 and 88.2) and includes the catches of all participating countries. These fisheries occur entirely on the high seas within the area covered by the Convention for the Conservation of Antarctic Marine Living Resources (the Convention Area). They are managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

Finfish fisheries in Antarctic waters are managed in accordance with the CAMLR Convention, in particular the objective and principles defined in Article II. The Convention Area covers the area south of the Antarctic Convergence (varying from 60° S in the Pacific Sector to 45° S in the western Indian Ocean Sector) (Figure 1). In 2016, CCAMLR adopted a Marine Protected Area in the Ross Sea Region (CCAMLR-XXXV 2016), which came into effect on 1 December 2017.

1.1 Commercial fisheries

Toothfish are large nototheniids endemic to Antarctic and Sub-Antarctic waters. There are two species: Antarctic toothfish (*Dissostichus mawsoni*) and Patagonian toothfish (*Dissostichus eleginoides*). Both have a circumpolar distribution, although *D. mawsoni* has a more southern distribution.

Commercial bottom longline fisheries targeting Patagonian toothfish occur around many of the Sub-Antarctic islands and plateaux south of the Sub-Antarctic Front[2]. To date, the main Olympic longline fishery for Antarctic toothfish outside an EEZ and within the Convention Area has taken place in Statistical Subarea 88.1, with smaller fisheries scattered around the Antarctic continental slope except

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[1] Note: this report does not cover the Patagonian toothfish (*Dissostichus eleginoides*) fishery in the New Zealand Exclusive Economic Zone.

[2] Zone found between 48° S and 58° S in the Indian and Pacific Ocean and between 42° S and 48° S in the Atlantic Ocean.

for the Weddell Sea. Statistical Subarea 88.1 is divided into three broad ecological regions: a region of northern seamounts, ridges, and banks; a region of shallow water (< 800 m) on the Ross Sea shelf in the extreme south; and a region in between covering the continental slope (800–2000 m). The main longline fishery occurs on the continental slope.

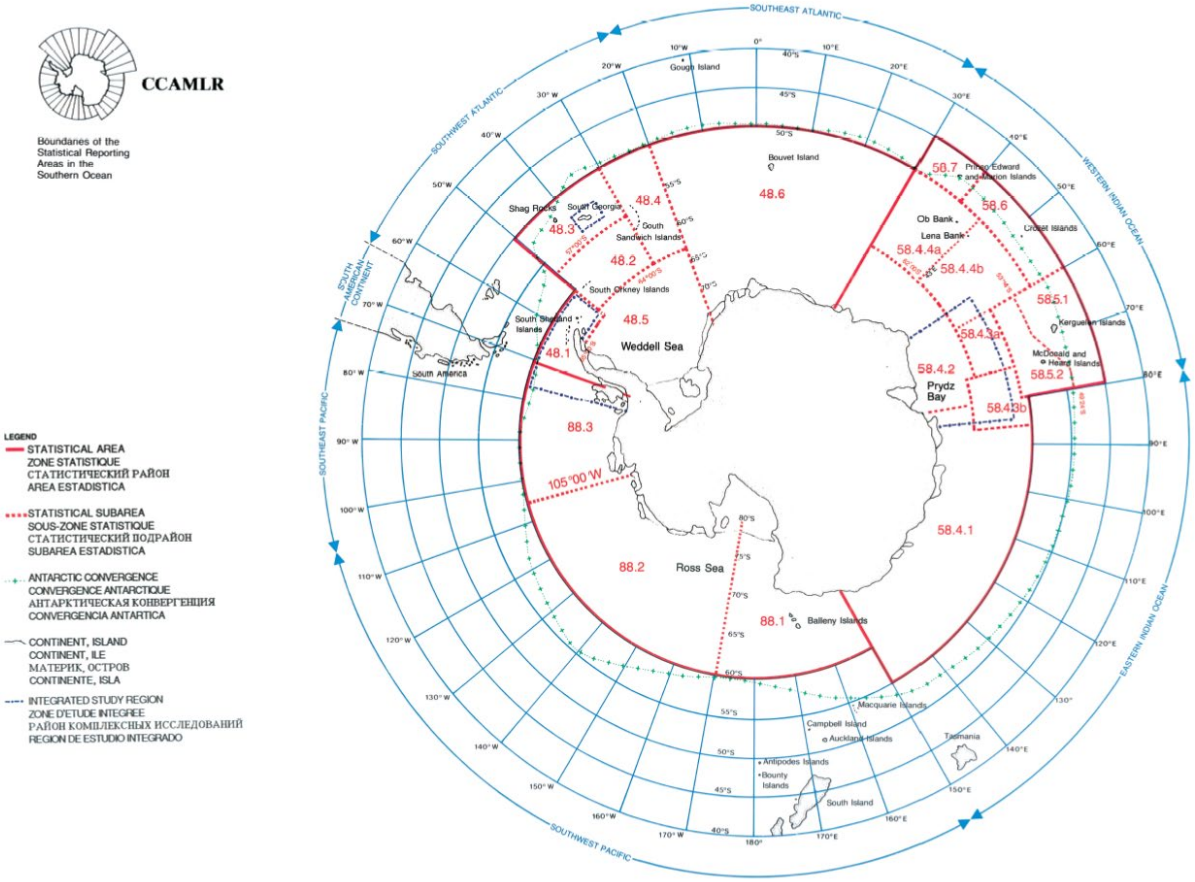


Figure 1: Map of CAMLR Convention area (https://www.ccamlr.org/en/organisation/convention-area) showing Statistical Subareas and Divisions.

The longline fishery for *Dissostichus* spp. in Statistical Subarea 88.1 was initiated as a new fishery by New Zealand in 1996–97, using a single longline vessel (Table 1). Since then, vessels from a number of countries have returned each summer to fish in this area and the adjacent Statistical Subarea 88.2 fishery. The exploratory longline fishing season in Statistical Subarea 88.1 and 88.2 begins on the 1 December and most fishing is completed by early-to-mid February.

The catch of toothfish in Statistical Subarea 88.1 and SSRUs 88.2A&B (the Ross Sea region) showed a steady increasing trend during the early period of the fishery, almost reaching the Total Allowable Catch (TAC) of about 3000 t between 2004–05 and 2006–07. In 2007–08 and 2008–09, the TAC was under-caught in Statistical Subarea 88.1 due to the severe ice conditions in 2007–08 and the early closure of the fishery by the CCAMLR Secretariat in 2008–09 because of overestimation of projected catch rates. The catches have been close to the catch limits since 2009–10, with the closure of the fishery by CCAMLR based on catch projections using daily catch reports (CCAMLR Secretariat 2016). In 2017–18 and in 2018–19, the TAC was again under-caught in the Ross Sea region due to the early closure of the fishery by the CCAMLR Secretariat, because of difficulties in projecting catch for many vessels competing for a relatively small catch limit. In the 2020–21 season, the total catch was slightly above the TAC and below the TAC in the 2021–22 and 2022–23 seasons.

The catch of toothfish in Statistical Subarea 88.2 began in 2003–04 and exceeded catch limits in 2004–05 and 2005–06. Failure to reach the catch limit in the following four years was primarily due to the low fishing effort in the southern SSRUs 88.2C–G because of the ice conditions. The catch was close to the catch limit between 2010–11 and 2017–18, with the closure of the fishery by CCAMLR based on the daily catch reports, but limits have been higher since 2018–19. Since 2022–23, spatial management within SSRU 88.2H has operated so that structured fishing on minor seamounts would precede the Olympic fishery, and the start of fishing would be delayed by two weeks to increase the likelihood that sea-ice conditions would allow vessels to access an increased number of seamounts in this region (CCAMLR 2024b). Figure 2 shows historical landings and TACs for Statistical Subareas 88.1 and 88.2.

Table 1: Estimated catches (t) of *Dissostichus* spp. by Subarea for the 1996–97 to present (Source: FAO STATLANT data; CCAMLR 2024a, 2024b). – denotes has not been estimated, but likely to be 0 t. IUU is illegal, unreported, and unregulated catch. Catch limits for Subarea 88.1 include catch set aside for research activities.

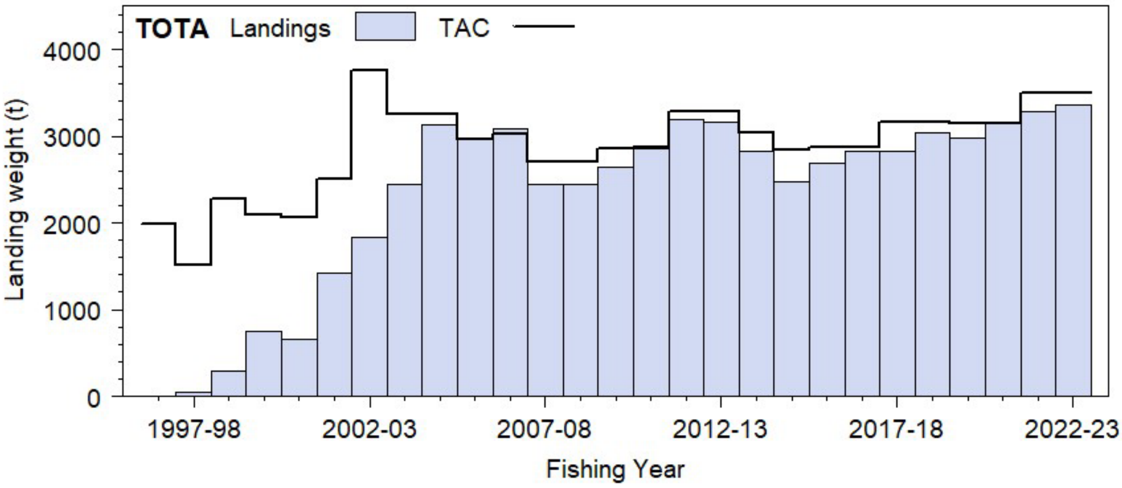
	Statistical Subarea 88.1				Statistical Subarea 88.2			
Season	**Reported catch**	**Estimated IUU catch**	**Total**	**Catch limit**	**Reported catch**	**Estimated IUU catch**	**Total**	**Catch limit**
1996–97	< 1	0	< 1	1 980*	0	0	0	1 980*
1997–98	42	0	42	1 510	0	0	0	63
1998–99	297	0	297	2 281	0	0	0	0
1999–00	751	0	751	2 090	0	0	0	250
2000–01	660	0	660	2 064	0	0	0	250
2001–02	1 325	92	1 417	2 508	41	0	41	250
2002–03	1 831	0	1 831	3 760	106	0	106	375
2003–04	2 197	240	2 437	3 250	374	0	374	375
2004–05	3 105	28	3 133	3 250	411	0	411	375
2005–06	2 969	0	2 969	2 964	514	15	529	487
2006–07	3 091	0	3 091	3 032	347	0	347	547
2007–08	2 259	272	2 531	2 700	416	0	416	567
2008–09	2 448	0	2 448	2 700	484	0	484	567
2009–10	2 869	0	2 869	2 850	314	0	314	575
2010–11	2 839	0	2 839	2 850	590	0	590	575
2011–12	3 178	–	3 178	3 282	424	–	424	530
2012–13	3 006	–	3 006	3 282	475	–	475	530
2013–14	2 823	–	2 823	3 044	426	–	426	390
2015–16	2 684	–	2 684	2 870	618	–	618	619
2016–17	2 821	–	2 821	2 870	624	–	624	619
2017–18	2 825	–	2 825	3 157	609	–	609	619
2018–19	3 047	–	3 047	3 157	753	–	753	1 000
2019–20	2 972	–	2 972	3 140	643	–	643	894
2020–21	3 146	–	3 146	3 140	530	–	530	804
2021–22	3 288	–	3 288	3 495	669	–	669	913
2022–23	3 368	–	3 368	3 495	737	–	737	1 013
2023–24**			3 499					1 116

* A single catch limit in 1996–97 applied to all of Statistical Subareas 88.1 and 88.2.
** Catches not yet reported

The toothfish catch from these areas almost entirely comprises Antarctic toothfish. Since the start of the fishery, 181 t of Patagonian toothfish have been caught in Statistical Subareas 88.1 and 88.2, almost entirely from the north of Statistical Subarea 88.1 (SSRUs 88.1A, 88.1B, and 88.1C) (CCAMLR 2024a). The data in Table 1 are collated from monthly reporting (vessel to flag state to CCAMLR) and annual reporting (FAO STATLANT reports to CCAMLR from flag state).

Spatial management of the Ross Sea region has changed multiple times since the development of the fishery (see also Delegations of New Zealand, Norway, and the United Kingdom 2014, Devine et al 2022). On 1 December 2017, three new management zones resulting from the implementation of the Ross Sea region MPA were defined: A General Protection Zone (GPZ), a Special Research Zone (SRZ on the slope area), and a Krill Research Zone (KRZ) (Figure 3). Catch limits were applied to the region outside the MPA and north of 70° S, outside the MPA and south of 70° S, and the SRZ. Spatial management, including allocation of catch among regions, will be reconsidered following evaluation of fishing effort redistribution after implementation of the MPA.

Ice conditions and bycatch limits are important factors influencing the spatial distribution of fishing effort. In 2002–03, 2003–04, 2007–08, and 2014–15 heavy ice conditions meant that little catch was taken in SSRUs 88.1J–L, SSRUs now largely within the RSrMPA. An ice index was created for the Ross Sea region, indicating the proportion of fishing grounds clear of sea ice (Fenaughty & Parker 2014), last updated in 2023 (Devine & Mormede 2023a).



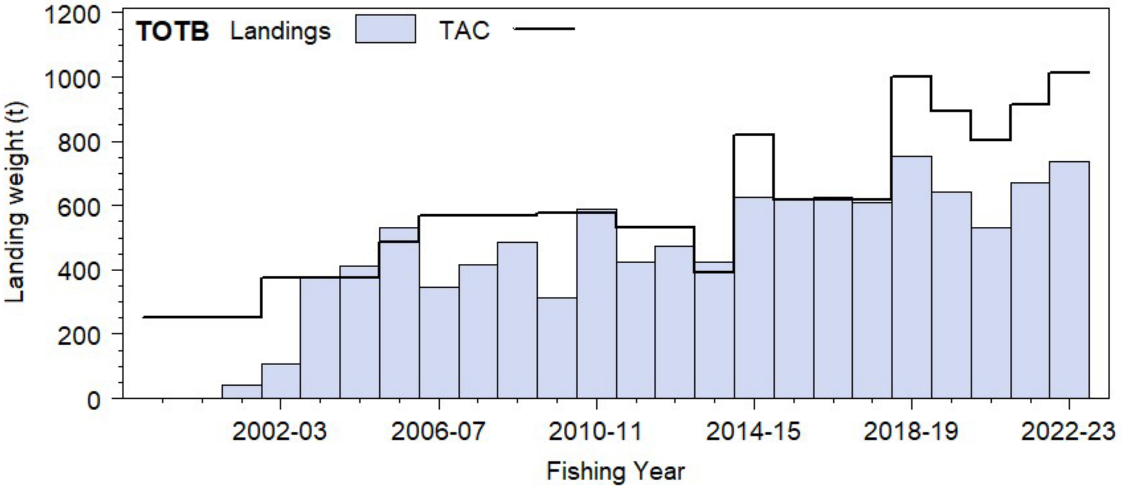


Figure 2: The landings of toothfish and catch limits (TACs) from 1997–98 to present in Statistical Subarea 88.1 and SSRUs 88.2A-B (TOTA) and 1999–00 to present in SSRUs 88.2C–H (TOTB).

The SSRUs in Statistical Subarea 88.2 were redefined for the 2011–12 season with the northern boundaries of SSRUs 88.2C–G truncated at 70º 50’ S to separate a region of seamounts in the north from the shelf/slope grounds in the south. The northern parts of those SSRUs were then amalgamated to form a new SSRU 88.2H and a separate catch limit was set for each of the northern and southern regions. The area north of 65° S (SSRU 88.2I) has always been closed to fishing.

In addition to the catch limits on the target toothfish species, other management rules have been adopted by CCAMLR via conservation measures. These include:

- gear restrictions (CCAMLR Conservation Measure (CM) 10-05 (2022));
- daily reporting requirements (CM 23-07 (2016));
- a Catch Documentation Scheme (CM 10-05 (2022));
- restrictions on bycatch (CM 33-03 (2023));
- measures to minimise local depletion of toothfish (CM 41-09 (2023) and CM 41-10 (2023));
- measures to minimise impacts to identified Vulnerable Marine Ecosystems (CM 22-07 (2013) and CM 22-09 (2012));
- non-fish bycatch mitigation measures (CM 25-02 (2023)); and
- the Ross Sea region MPA (CM 91-05 (2016)).

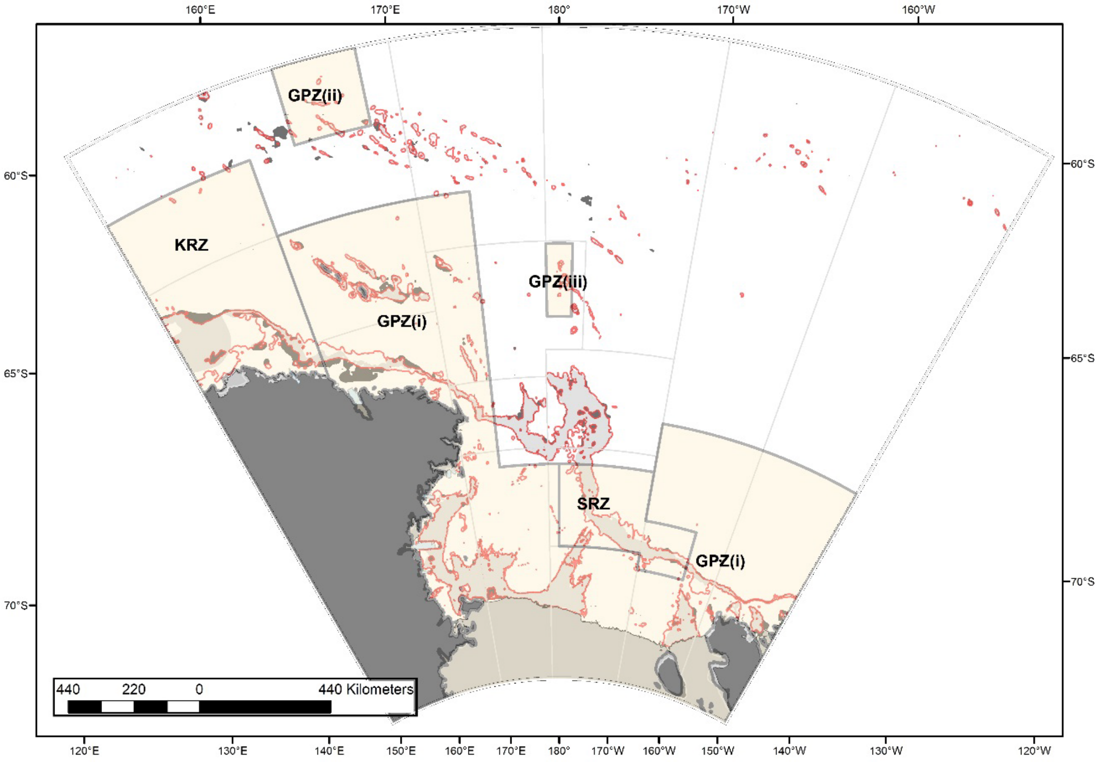


Figure 3: Ross Sea region Marine Protected Area in effect as of 1 December 2017 (CM 91-05).

In 2005–06, the macrourid (rattail) bycatch limits were exceeded for SSRUs 88.2C–G resulting in the area being closed before the toothfish catch limit was reached.

The CCAMLR Convention Area extends to 60° S in the Pacific Basin but the bathymetric features and oceanographic conditions that toothfish inhabit extend north of this boundary. The northern extent of the range of Antarctic toothfish is not well known in the area. Two research surveys in the south Pacific under the auspices of the South Pacific Regional Fisheries Management Organisation (SPRFMO) were conducted in 2016 and 2017 with catch limits of 30 t in each year and were restricted to two small research areas between near 150° W longitude and 59° S latitude (COMM-04-WP-09_rev4). Twenty-nine tonnes were landed in each year and all were Antarctic toothfish, except for two small Patagonian toothfish in 2017. This catch was included as removals from the Ross Sea region stock assessment (Mormede 2017, Dunn 2019, Grüss et al 2021, Mormede et al 2023a).

In 2018, a proposal for an exploratory longline fishery was made by New Zealand in the area to better determine the distribution and population characteristics of Antarctic toothfish on the Pacific-Antarctic Ridge system within the SPFRMO Convention Area between 140–155° W and 52–60° S over three years (SC6-DW03-Rev2-NZ, COMM7-Prop13.1, Figure 1). The total allowable catch was set at 140 t each year for 2019, 2020, and 2021 and was agreed by the Commission in 2019 (ANNEX-7l-COMM7-CMM-14a-2019-Exploratory-Toothfish-NZ). An EU proposal for a one-year exploratory fishery in the southern SPRFMO area on the South Tasman Rise (COMM7-Prop14.1-rev-1) was also approved for 2019–20 with a catch limit of 45 t of toothfish (likely to be Patagonian toothfish in that area, ANNEX -7m-COMM7-CMM-14c-2019). The exploratory fishery was extended for three more years (COMM 10-Prop 07.1) with a proposed catch limit of 240 t (SC9-DW01-rev-1). The framework for fishing, tagging, and data collection for both exploratory fisheries closely mirrors that of CCAMLR making the data comparable for analysis. A total of 77.5 t in 2020, 24.1 t in 2021, 38.7 t in 2022, and 34.4 t in 2023 were caught in the SPRFMO Convention area and were included in the 2023 stock assessment for the Ross Sea region (Mormede et al 2023b).

1.2 Recreational fisheries
There is no recreational toothfish fishery in Statistical Subareas 88.1 and 88.2.

1.3 Customary non-commercial fisheries
There is no customary toothfish fishery in Statistical Subareas 88.1 and 88.2.

1.4 Illegal catches
Based on aerial surveillance and other sources of intelligence, the level of illegal, unreported, and unregulated (IUU) catch is thought to be low (Table 1). CCAMLR stopped estimating the level of IUU catch from 2011 but estimated the level of IUU effort instead. IUU effort in recent years in the Convention Area has typically comprised vessels using gillnets, which is currently prohibited under CM 22-04, and the catch rates for this method cannot be reliably estimated. However, CCAMLR has estimated that there has been no IUU effort in Statistical Subareas 88.1 and 88.2 since 2010–11 (CCAMLR 2024a).

1.5 Other sources of mortality
Any longline gear that is baited and set, but not successfully retrieved, may result in unaccounted mortality of toothfish or other species. Bottom longline gear is most often lost due to interactions of downlines with moving sea ice, but may also result from tidal currents submerging floats, or gear failure during line retrieval.

Webber & Parker (2011) estimated line loss from 2008 to 2011 to be in the range 3–8% (expressed in terms of percent of all hooks set that are lost attached to sections of lines). Longline hooks only have the potential to catch once. Once a fish is on the hook, or the bait is gone, the hooks are effectively not able to fish anymore. Assuming that these hooks caught toothfish at the same rate as those on lines that were retrieved, and that all the toothfish caught on lost lines die as a result of being caught, then an additional 175–244 tonnes of Antarctic toothfish fishing related mortality from the commercial fishery may be unaccounted for annually.

A small quantity of toothfish is taken by other scientific research programmes in most years, typically less than 5 tonnes.

Observers monitor discards, with up to 40% of all hooks hauled being directly observed, and no discarding of dead toothfish has been reported to date. However, in 2014 it was reported that some small toothfish had been released untagged but alive by Ukrainian vessels in Statistical Subarea 88.2, as they were too small to process. Fish are occasionally lost from the line near the surface and recorded as lost.

Antarctic toothfish are occasionally caught with evidence of squid depredation (i.e., sucker marks and large flesh wounds), but the amount of depredation due to large squid is insignificant at the scale of the fishery. Until 2021, there had been no reported instances of depredation of toothfish by cetaceans or pinnipeds in the Ross Sea region; in 2021, a leopard seal was observed taking 1 toothfish and, in 2022, 3 toothfish from a longline on the Ross Sea shelf survey.

2. BIOLOGY

The Antarctic toothfish has a circumpolar distribution south of the Antarctic convergence (about 60° S). A summary of the biology of Antarctic toothfish, and related references, are given in detail by Hanchet et al (2015b). Although it is primarily a demersal species, adults can be neutrally buoyant and are known to inhabit the pelagic zone at times (Near et al 2003). Early growth has been well documented (Horn 2002, Horn et al 2003) with fish reaching about 60 cm TL after five years and about 100 cm TL after ten years. Growth slows after about 10 years as fish reach the adult stage. The maximum recorded age is 48 years and maximum length recorded is 250 cm. Ages have been validated by following modes: in juvenile fish by tetracycline marking, and lead-radium dating in adult fish (Horn et al 2003, Brooks et al 2011). There is a significant difference in growth between sexes with maximum average lengths of 170 cm and 180 cm for males and females respectively (Horn 2002).

Hanchet et al (2008a) developed a hypothetical life history of Antarctic toothfish in the Ross Sea. Fish spawn to the north of the Antarctic continental slope, mainly on the ridges and banks of the Pacific-Antarctic Ridge during winter or spring.

The first winter longline survey of Antarctic toothfish in the northern Ross Sea region was successfully completed during June and July 2016 and confirmed toothfish spawning in this region (Stevens et al 2016, Parker et al 2019). Fertilised Antarctic toothfish eggs were found to be large (greater than 3.5 mm diameter) and pelagic (found in the upper 200 m of the water column). Spawning may occur from mid-July through August (Stevens et al 2016). A second winter survey was conducted in September and October 2019 with results reported to CCAMLR in 2020 (Parker & DiBlasi 2020). Additional information on the timing, distribution, stock structure, and potentially early life history will be derived from the exploratory fishery in the SPRFMO area. The SPRFMO fishery will also have some fishing during August–October, which will greatly enhance information about spawning, which occurs in the winter and is typically inaccessible further south due to sea ice. SPRFMO samples have already shown that the fish inhabiting seamounts just north of the CCAMLR Convention Area are abundant, mostly Antarctic toothfish, all adult sizes, and in spawning or post-spawning condition during late winter. The spatial distribution of spawning has not yet been determined.

Hanchet et al (2008a) postulated that, depending on the exact location of spawning, eggs and larvae become entrained by the Ross Sea gyres (a counter-clockwise rotating western gyre located around the Balleny Islands and a larger clockwise rotating eastern gyre covering the rest of the Ross Sea region) and move either west, settling out around the Balleny Islands and adjacent Antarctic continental shelf, south onto the Ross Sea shelf, or eastwards with the eastern Ross Sea gyre settling out along the continental slope and shelf to the east of the Ross Sea in Statistical Subarea 88.2. Additional particle tracking simulations to examine the effects of sea ice and directional swimming behaviours of early pelagic juveniles by Behrens et al (2021) incorporating buoyancy measurements of eggs from Parker et al (2021) suggest differences in recruitment success from different spawning areas and the need for some directional swimming to reach the coastal current and appropriate depths for settling to a demersal lifestyle.

As the juveniles grow, it is hypothesised that they move west, back towards the Ross Sea shelf, and then move out into deeper water (greater than 1000 m). The fish gradually move northwards as they mature, feeding in the slope region in depths of 1000–1500 m, where they gain condition before moving north onto the Pacific-Antarctic ridge to start the cycle again. It is not known how long spawning fish remain in the northern area. It is currently thought that toothfish remain in the Pacific-Antarctic ridge region for up to 2–3 years (although this pattern may be different for males versus females) and then they move southwards back onto the shelf and slope where productivity is higher and food is more plentiful. A multidisciplinary approach incorporating otolith chemistry, age data, and Lagrangian particle simulations reached similar conclusions (Ashford et al 2012). The authors further postulated that the entire life cycle is structured by ocean circulation such that not just eggs and larvae, but also juvenile and adult fish, are transported downstream by ocean currents between nursery grounds, feeding grounds, and spawning grounds.

The age and length at recruitment to the Ross Sea fishery varies between areas and between years. In the northern SSRUs (88.1A–88.1G), toothfish recruit at a length of about 130 cm to the fishery. In the southern SSRUs (88.1H–88.1M), the length at recruitment depends on the depth of fishing. In some years, fish have been fully recruited at a length of about 80 cm (age 7–8), whereas in other years fish have not been fully recruited until at least 100 cm (age 10) (Devine & Mormede 2023a). In Statistical Subarea 88.2, toothfish recruit at a length of about 130 cm in the northern SSRU (88.2H) but at a length of about 60–80 cm (age 5–8) in the southern SSRUs (88.2C–G) (Devine & Mormede 2023b).

Estimates of maturity, based on hindcasting from the presence of post-ovulatory follicles in the ovaries and forecasting from the assessment of oocyte developmental stage, suggested that the mean age and length at 50% spawning for females on the Ross Sea slope were 16.6 y and 133.2 cm and the mean age and length at 50% maturity for males were 12.8 y and 120.4 cm (Parker & Grimes 2010). These estimates were updated in 2012 to 16.9 y and 135 cm for females and 12.0 y and 109 cm for males on the Ross Sea slope (Parker & Marriott 2012). Regional spawning ogives show similar relationships for the Ross Sea north and shelf areas and for Statistical Subarea 88.2.

The natural mortality rate M was estimated by Dunn et al (2006) using the methods of Chapman & Robson (1960), Hoenig (1983), and Punt et al (2005). Estimates of M derived from these methods ranged from 0.11 to 0.17 y^{-1}. After a consideration of possible biases, Dunn et al (2006) proposed that a value of 0.13 y^{-1} be used for stock modelling with a range of 0.11–0.15 y^{-1} for sensitivity analyses. They noted that further work is required on values of M and in possible changes of M with age. Biological parameters relevant to the stock assessment are shown in Table 2.

Antarctic toothfish feed on a wide range of prey but are primarily piscivorous with the observed diet varying by location (Fenaughty et al 2003, Stevens et al 2014). The most important prey species of fish caught in the main fishery are grenadiers (*Macrourus* spp.). In continental slope waters, *Macrourus* spp., the icefish *Chionobathyscus dewitti*, eel cods (*Muraenolepis* spp.), and cephalopods are predominant in the diet, whereas on oceanic seamounts *Macrourus* spp., violet cod (*Antimora rostrata*), and cephalopods are important. In the southern Ross Sea, subadult and adult toothfish feed mainly on nototheniids (*Trematomus* spp.) and icefish, whereas in McMurdo Sound, the stomachs of adult toothfish sampled through holes in the ice have been observed to contain mainly Antarctic silverfish (*Pleuragramma antarcticum*) (Eastman 1985, Parker et al 2016). In the open oceanic waters in the north of the Ross Sea region, Antarctic toothfish feed on small squid (Yukhov 1971). The diet of Antarctic toothfish also varies with their size. Crustaceans are more common prey items in smaller toothfish, whereas squid are more common in larger toothfish, likely reflecting the different spatial distributions of small versus large toothfish.

Table 2: Estimates of biological parameters for Antarctic toothfish.

Biological parameters									**Reference**
1. Natural mortality (M)									
	Males	Females							
	0.13	0.13							Dunn et al (2006)
2. Weight = a(length)^b (Weight in kg, length in cm fork length)									
	Males		Females						
	a	b	a	b					
	0.000001247	2.990	0.000007361	3.105					Dunn & Parker (2019)
3. von Bertalanffy growth parameters									
	Males				Females				
	K	t_0	L_∞	$c.v$	K	t_0	L_∞	$c.v.$	
	0.101	-0.292	164.1	0.101	0.082	-0.712	180.5	0.101	Dunn & Parker (2019)
4. Maturity									
	Males		Females						
	A_{50}	$\pm A_{to95}$	A_{50}	$\pm A_{to95}$					
	11.99	5.25	16.92	7.68					Parker & Marriott (2012)

The main predators of toothfish are likely to be odontocetes (sperm whales, historically), type C killer whales, and pinnipeds (Weddell seals) (Pinkerton et al 2010, Eisert et al 2013, Torres et al 2013, Eisert et al 2014). The scale or spatial distribution of predation is unknown.

3. STOCKS AND AREAS

The number of stocks or populations of *D. mawsoni* in the Southern Ocean is currently unknown. However, several studies looking at genetics, parasites, otolith microchemistry, stable isotopes, larval dispersal simulations, and movements of fish from tag-recapture data have produced information leading to improved knowledge of stock structure.

A genetic analysis was carried out by Parker et al (2002) using random amplified polymorphic DNA (RAPD) markers. They concluded that samples taken from McMurdo Sound (Statistical Subarea 88.1) and the Bellingshausen Sea (Statistical Subarea 88.3 (Figure 1)) were from two different genetic groups. Smith & Gaffney (2000) detected little genetic diversity in mitochondrial DNA (mtDNA) samples between the Pacific (Statistical Subarea 88.1), Indian Ocean (Division 58.4.2), and Atlantic Ocean (Statistical Subarea 48.1) sectors. One mtDNA method showed no genetic variation, and two other mtDNA methods showed only weak genetic diversity between regions. Smith & Gaffney (2000) also found only weak genetic variation using nuclear DNA introns. They concluded that despite the weak genetic diversity in Antarctic toothfish there was evidence for differentiation between the ocean sectors. Kuhn & Gaffney (2008) expanded the work of Smith & Gaffney (2000) by examining nuclear and mitochondrial single nucleotide polymorphisms (SNPs) on tissue samples collected from Statistical Subareas 48.1, 88.1, and 88.2, and Division 58.4.1. They found broadly similar results to those of the earlier studies, with some evidence for significant genetic differentiation between the three ocean sectors but limited evidence for differentiation within ocean sectors. Suggestions of weak diversity were also reported by Mugue et al (2013).

The assumption of separate stocks is supported by oceanic gyres, which may act as juvenile retention systems, and by the location of recaptures of adult tagged fish (Hanchet et al 2008a, Parker et al 2014). Most adult tagged fish have been recaptured close to where they were originally tagged, often within 100 km (Devine & Mormede 2023a). However, tagged fish have also been recaptured having moved longer distances within Statistical Subarea 88.1(Devine & Mormede 2023a). Few fish have been observed to move between Statistical Subareas 88.1 and 88.2: Ten fish have moved from Statistical Subarea 88.1 to Statistical Subarea 88.2, and nine moved from Statistical Subarea 88.2 to Statistical Subarea 88.1. Additionally, some long-distance movements of more than 2000 km been observed: one fish tagged in McMurdo Sound in SSRU 88.1M was recaptured after 18 years at liberty almost 2500 km to the northeast, in SSRU 88.2H; one fish was released in Statistical Subarea 48.4 and recaptured in Statistical Subarea 88.2, and one fish was released in Statistical Subarea 88.1 and recaptured in Statistical Subarea 58.4.1 (Devine & Mormede 2023a).

Tana et al (2014) compared otolith microchemistry signatures between the north of the Ross Sea (88.1B-C) and north of the Amundsen Sea (88.2H). Preliminary results found differences in the microchemistry of both edges and nuclei between the two areas, providing some evidence for separate Ross Sea and Amundsen Sea stocks. Pinkerton et al (2014a) compared carbon and nitrogen stable isotope values in muscle tissue samples collected from the slope and north of the Ross Sea and north of the Amundsen Sea. Carbon signatures were similar within the Ross Sea, but different between the Ross Sea and Amundsen Sea suggesting that they form separate spawning populations. Parker (2014) reviewed the stock structure of Antarctic toothfish in Statistical Area 88 including information from genetic studies, otolith microchemistry, stable isotopes, tagging, size and age structure, growth dynamics, and egg and larval dispersal simulations and concluded that there was no evidence to change existing stock boundaries.

For stock assessment purposes, all Statistical Subarea 88.1 and SSRUs 88.2A and 88.2B are treated as a single Ross Sea region stock (‘Ross Sea’ typically refers to the Ross Sea shelf area). SSRUs 88.2C–H) are treated as a second Amundsen Sea region stock. Both Statistical Subareas include closed SSRUs from which fishing has been excluded for varying numbers of years. The stock affinity of the assessed stocks with toothfish in surrounding areas is not well understood, and assessments in the medium term will consider alternative stock structures including developing a combined Statistical Subareas 88.1 and 88.2 assessment.

Information about stock structure will be collected from the exploratory fishery in the SPRFMO Area as well, including genetic samples, size and age distributions, and otoliths for microchemistry. Surveying in discrete spatial strata will enable mapping of fish density (through CPUE) and documentation of movement patterns through tagging.

4. ENVIRONMENTAL AND ECOSYSTEM CONSIDERATIONS

This section was updated for the 2024 Fisheries Assessment Plenary. Further information can be found in the Aquatic Environment and Biodiversity Annual Review 2021 (Fisheries New Zealand 2021), online at https://www.mpi.govt.nz/dmsdocument/51472-Aquatic-Environment-and-Biodiversity-Annual-Review-AEBAR-2021-A-summary-of-environmental-interactions-between-the-seafood-sector-and-the-aquatic-environment.

4.1 Incidental catch (fish and invertebrates)

The last comprehensive description of bycatch of fish species in the Statistical Subareas 88.1 and 88.2 fisheries was by Moore et al (2022a), which have been updated annually (in a modified format) by the CCAMLR Secretariat (CCAMLR 2024a, 2024b). The main bycatch species in these fisheries are macrourids, which contributed around 5% of the total catch by weight and about 30% of the total catch by number per year (Table 3, Table 4). Taxonomic studies have shown that specimens originally identified in the Ross Sea region as *Macrourus whitsoni* comprise two sympatric species: *Macrourus whitsoni* and *Macrourus caml* (McMillan et al 2012) with different biology and ecology (Pinkerton et al 2013). Work is in progress to determine the degree of overlap of these two species both within the Ross Sea region and circum-Antarctic. The other major bycatch group is skates (rajids, mainly *Amblyraja georgiana* and *Bathyraja* cf. *eatonii*). Skates made up about 10% of the total landings by weight in 1997–98 and 1998–99, but the reported catches of skates then decreased due to a tag release programme and the live release of untagged skates. In both programmes, all live skates are released and as a result are not included in catch data. Other fish bycatch species, including moray cods (*Muraenolepis* spp.), morid cods (mainly *Antimora rostrata*), icefish (mainly *Chionobathyscus dewitti*), and rock cods (*Trematomus* spp.) each contribute 1% or less of the overall catch (Moore et al 2022a).

Table 3: Catches of managed bycatch species (macrourids, rajids, and other species) in the Ross Sea region. Live rajids cut from the longlines and released are not included in estimated of catch. Numbers of rajids released include tagged and not tagged. Source: CCAMLR 2024a.

	Macrourids		Rajids			Other species	
Season	Catch limit (t)	Reported catch (t)	Catch limit (t)	Reported catch (t)	Number released	Catch limit (t)	Reported catch (t)
1996–97	–	0	–	0	–	–	0
1997–98	–	9	–	5	–	50	1
1998–99	–	22	–	39	–	50	5
1999–00	–	74	–	41	–	50	7
2000–01	–	61	–	9	–	50	11
2001–02	100	158	–	25	–	50	10
2002–03	610	65	250	11	1 932	100	12
2003–04	520	319	163	23	3 703	180	23
2004–05	520	462	163	69	5 705	180	22
2005–06	474	266	148	5	16 463	160	17
2006–07	485	153	152	38	8 786	160	41
2007–08	426	112	133	4	8 474	160	18
2008–09	430	183	135	7	9 018	160	15
2009–10	430	119	142	8	9 052	160	15
2010–11	430	190	142	4	5 456	160	8
2011–12	430	143	164	1	2 241	160	4
2012–13	430	127	164	4	5 711	160	10
2013–14	430	129	152	2	5 534	160	15
2014–15	430	92	142	6	12 981	160	26
2015–16	430	93	143	6	6 016	160	21
2016–17	430	67	143	4	3 866	160	11
2017–18	485	82	157	8	6 052	157	14
2018–19	485	147	157	9	8 885	157	25
2019–20	485	118	157	15	20 027	157	32
2020–21	485	125	157	10	9 482	157	31
2021–22	494	229	170	7	15 654	170	52
2022–23	494	139	169	27	8 461	169	23

Current catch limits for macrourids in Statistical Subarea 88.1 were derived from biomass estimates from the IPY-2008 trawl survey for the slope of the Ross Sea (Hanchet et al 2008c). This work was repeated in 2023 using data from three bottom trawl surveys carried out in the Ross Sea slope region, which were combined across years and scaled to the slope area to give a composite biomass estimate and showed that the current catch limits were precautionary (Devine et al 2023). In each of the 2003–04, 2004–05, and 2005–06 seasons, the bycatch limit for *Macrourus* spp. was exceeded in at least one of the SSRUs leading to the closure of the fishery in those areas. No bycatch limit has been exceeded since then. The catch limit for macrourids in Statistical Subarea 88.2 remains at 16% of the toothfish catch limit for each management area.

Current catch limits for rajids and other species in Statistical Subarea 88.2 are proportional to the catch limit of *Dissostichus* species in each small-scale research unit (SSRU) based on CM 33-03 (Table 4). Catch limits for rajids or for other species have never been exceeded.

Table 4: Catches of managed bycatch species (macrourids, rajids, and other species) in Statistical Subarea 88.2. Rajids cut from the longlines and released are not included in these estimates. Source: CCAMLR 2024b.

Season	Macrourids		Rajids			Other species	
	Catch limit (t)	Reported catch (t)	Catch limit (t)	Reported catch (t)	Number released	Catch limit (t)	Reported catch (t)
1996–97	–	0	–	0	–	–	0
1997–98	–	0	–	0	–	–	0
1998–99	–	0	–	0	–	–	0
1999–00	–	0	–	0	–	–	0
2000–01	–	0	–	0	–	–	0
2001–02	40	0	–	0	–	20	0
2002–03	60	18	–	0	–	140	8
2003–04	60	37	50	0	107	140	8
2004–05	60	20	50	0	–	140	3
2005–06	78	84	50	< 1	923	100	12
2006–07	88	54	50	< 1	–	100	13
2007–08	88	17	50	0	–	100	4
2008–09	90	58	50	< 1	265	100	13
2009–10	92	49	50	0	–	100	15
2010–11	92	51	50	< 1	169	100	13
2011–12	84	29	50	< 1	–	120	11
2012–13	84	25	50	0	–	120	8
2013–14	62	7	50	< 1	28	120	3
2014–15	99	19	50	1	192	120	6
2015–16	99	52	50	< 1	861	120	3
2016–17	99	22	31	1	314	99	2
2017–18	99	22	31	0	104	99	3
2018–19	143	21	45	< 1	217	143	3
2019–20	143	42	45	< 1	571	143	5
2020–21	143	16	45	< 1	194	143	3
2021–22	143	53	44	<1	1 081	143	6
2022–23	159	24	49	< 1	91	159	1

4.2 Population assessments for rajids and macrourids

Rajids

Preliminary estimates of the age and growth of *Amblyraja georgiana* in the Ross Sea suggested that these skates initially grow very rapidly for about five years, after which growth almost ceases (Francis & Ó Maolagáin 2005). However, Francis & Gallagher (2008) presented an alternative interpretation of age and growth in *A. georgiana* that is radically different from the published interpretation. By counting fine growth bands in the caudal thorns instead of broad diffuse bands, they generated growth curves that suggest much slower growth, greater ages at maturity (about 20 years compared with 6–11 years), and greater maximum ages (28–37 years compared with 14 years). Several pieces of circumstantial evidence support the new interpretation, but a validation study is required to determine which growth scenario is correct. Updated length-weight relationships for skates were provided by Francis (2010).

An experimental skate tagging programme in the Ross Sea fishery was started in 2000, and a preliminary assessment of skates completed by Dunn et al (2007). A fishery-wide tagging programme and sampling programme for skates was instituted by CCAMLR in 2008–09. It was anticipated that this initiative would lead to more Antarctic skates being tagged in Statistical Subareas 88.1 and 88.2. However, only 1907 and 99 skates were tagged in Statistical Subareas 88.1 and 88.2, respectively, in 2008–09. This programme was extended for the 2009–10 season but discontinued in 2010–11. A 2-year skate tagging and age validation programme was implemented for the 2019–20 and 2020–21 fishing seasons (SC-CAMLR XXXVII paragraph 5.7), and then extended for a third season, during which 10 137 skates were tagged and released and 186 skates have since been recaptured (Finucci 2023).

Mormede & Dunn (2010) provided a characterisation of skate catches in the Ross Sea region. The paper concluded that aspects of the catch history were very uncertain, including the species composition, the weight and number of skates caught, the proportion discarded, and the survival of those fish that were tagged. An update of the characterisation (Moore et al 2022a) found that further work was still needed on species composition of the catch and the survival of skates that were tagged. Although the size composition of the commercial catch was uncertain before 2009 because of the low numbers sampled each year, data collected in 2008–10 resulted in improved estimates of the length frequency of the catch. Tag data were also improved, with a total of about 3300 *Amblyraja georgiana* and 700 *Bathyraja* cf. *eatoni* tagged and a total of 179 skates recaptured as of 2010. A tagging programme for skates was implemented in the Ross Sea region in 2020, initially for two seasons, but extended to three seasons for some vessels (Finucci 2023), with some vessel crews volunteering to inject skates tagged and released with either strontium chloride or oxytetracycline (Francis & Parker 2019) to mark thorns to validate age estimation. At least 2408 were injected (27% of those that were tagged), of which 112 have subsequently been recaptured (Finucci 2023).

These data were subsequently used to update a risk assessment for the Antarctic starry skate (*Amblyraja georginana*) in the Ross Sea region, which included a range of possibilities for biomass and exploitation rates, as these were considered relatively uncertain (Finucci et al 2023). Current exploitation was considered sustainable if initial release mortality was <40% (where skates are cut off the line) across plausible extremes of natural mortality. If live skates are not released, then exploitation rates would be higher and would likely be inconsistent with CCAMLR decision rules.

Macrourids

In 2011, it was recognised that specimens originally identified in the Ross Sea region as *M. whitsoni* did in fact comprise two sympatric species: *M. whitsoni* and *M. caml* (Smith et al 2011, McMillan et al 2012). *M. caml* grows larger than *M. whitsoni* and is about 20% heavier for a given length (Pinkerton et al 2013). The two species can be distinguished morphologically through two main characters (number of rays in the left pelvic fin; number of rows of teeth in the lower jaw). The distribution of *M. whitsoni* and *M. caml* seems to almost completely overlap by depth and area, with both appearing to be abundant between depths of 900 and 1900 m. Catches of females of both species exceed that of males (especially for *M. caml*) and this sex-selectivity cannot be explained by size or age of fish (Pinkerton et al 2013). It is almost certain that previous work which was presumed to have been carried out on *M. whitsoni* would actually have been carried out on a mix of the two species. However, it is now possible to distinguish between the species based on their otolith morphometrics (Pinkerton et al 2014b, Moore et al 2022c), so otoliths collected in previous years of the fishery or from toothfish stomachs can be identified to species.

Otolith ageing data show that the two species have very different growth rates (Pinkerton et al 2013, Moore et al 2022b). *M. whitsoni* approaches full size at about 25–30 years of age and can live to at least 43 years, whereas *M. caml* reaches full size at about 40 years and can live for over 60 years. Sexual maturity in female *M. whitsoni* is reached at 56 cm and 23 years, but in female *M. caml* at 22 cm and 16 years. Gonad staging data imply that the spawning period of both species is protracted extending from before December to after February.

The IPY trawl survey of the Ross Sea slope was carried out in 2008 leading to a biomass estimate of macrourids for the first time (Hanchet et al 2008b). Biomass and yield estimates of *Macrourus* spp. for the Ross Sea fishery based on extrapolations under three different density assumptions from the trawl survey were given by Hanchet et al (2008c) (Table 5). The resulting biomass estimates had a CV of about 0.3.

Table 5: Biomass estimates of *Macrourus* spp. from the trawl surveys for the BioRoss 400–600 and 600–800 m and IPY-CAML 600–1200 and 1200–2000 m strata and extrapolated biomass estimates (with CVs) for the remaining strata based on three methods of extrapolation. Source: Hanchet et al (2008c).

Survey	Depth range (m)	Biomass (t)	Extrapolated biomass (t)		
			constant density	CPUE (all vessels)	CPUE (NZ vessels)
BioRoss – 88.1H	400–600	230	230 (49)	230 (49)	230 (49)
BioRoss – 88.1H	600–800	3 531	3 531 (38)	3 531 (38)	3 531 (49)
SSRU 88.1H west	800–1200		92 (50)	83 (54)	103 (55)
SSRU 88.1H west	1200–2000		713 (40)	1 114 (49)	1 038 (47)
IPY - 88.1H	600–1200	975	975 (50)	975 (50)	975 (50)
IPY - 88.1H	1200–2000	3 356	3 356 (40)	3 356 (40)	3 356 (40)
SSRU 88.1 I	600–1200		3 297 (50)	7 883 (51)	5 992 (50)
SSRU 88.1 I	1200–2000		4 670 (40)	11 168 (42)	8 576 (41)
SSRU 88.1 K	600–1200		1 539 (50)	5 027 (51)	2 774 (51)
SSRU 88.1 K	1200–2000		2 998 (40)	5 995 (45)	9 111 (43)
HIK Sub-total			21 410		
SSRU 88.2 A+B	600–1200		1 404 (50)	1 396 (58)	857 (60)
SSRU 88.2 A+B	1200–2000		4 087 (40)	525 (70)	–
88.2 A, B Sub-total			5 491		
Total			26 892 (29)	41 823 (28)	36 542 (30)

Yield estimates were calculated using the constant density assumption when extrapolating the biomass estimate across the slope region, noting that this would provide a more precautionary estimate of yield than one based on extrapolations using longline CPUE data. The resulting biomass estimate for SSRUs 88.1HIK was 21 410 t which gave a yield estimate of 388 t. This yield estimate was then apportioned across the 5 SSRUs taking into account maximum historical catches (Table 6). The catch limits per SSRU detailed in Table 6 have been used by CCAMLR since the 2009–10 season.

Additional trawl-based surveys (18 tows in 4 strata) were carried out in 2015 during TAN1502 (O'Driscoll & Double 2015) and in 2019 (TAN1901, O'Driscoll et al 2019). Composite biomass estimates for *Macrourus* spp. using these data on the Ross Sea slope indicated that the 2008 biomass estimates did not need revision (Devine et al 2023).

Table 6: Estimated yield, maximum historic catch, and revised catch limit of *Macrourus* spp. for the Ross Sea fishery.

Region	Estimated yield (t)	Maximum historic catch (t)	Revised catch limit (t)
88.1BCG	–	34	40
88.1HIK	388	390	320
88.1JL		52	70
88.1M	0	0	0
88.2AB	100	8	0
Total	488		430

The use of acoustic data to monitor trends in relative abundance of macrourids has also been explored (O'Driscoll et al 2012, Ladroit et al 2014). These studies have shown positive correlations between acoustic targets and longline catches of grenadiers, and the acoustic target strength distribution of single targets is similar to that predicted, based on the expected size range of grenadiers. However, variability in spatial coverage between years means that it is currently not possible to obtain a consistent time series of relative abundance estimates for grenadiers from acoustic data collected opportunistically by New Zealand vessels in the fishery. Recent acoustic research on toothfish suggests that the target strength of toothfish may overlap that of grenadiers (O'Driscoll et al 2018).

Identification of levels of risk from bycatch

Risk categorisation tables were prepared for rajids and macrourids by O'Driscoll (2005) based on the risk status categories of Castro et al (1999). *Amblyraja georgiana* were categorised as risk category 3, which are "species that are exploited by directed fisheries or bycatch, and have a limited reproductive potential, and/or other life history characteristics that make them especially vulnerable to overfishing, and/or that are being fished in their nursery areas". The risk to *A. georgiana* is mitigated due to the requirement to cut rajids from longlines while still in the water and release them.

Macrourus whitsoni were categorised as between risk category 2 and 3, but this analysis predates the realisation of two species of *Macrourus* in the Ross Sea. Risk category 2 includes "species pursued in directed fisheries, and/or regularly found in bycatch, whose catches have not decreased historically, probably due to their higher reproductive potential”.

Ecosystem effects associated with bycatch are thought to be less likely than those associated with predation release (see Section 4.6).

Mitigation measures

Since the start of the 2000–01 season, rajids likely to survive have been cut free and released at the surface as a measure to reduce rajid mortality. The survival of at least some of these skates has been demonstrated by the recapture of over 186 tagged skates as of 2023 (Finucci 2023), and by the results of survivorship experiment in tanks carried out by the UK (Endicott & Agnew 2004).

There is a ‘move-on’ rule in place to help prevent excessive fishing in localised areas of high abundance of bycatch species. This rule requires a vessel to move to another location at least 5 nm distant if the bycatch of any one species is equal to or greater than 1 tonne in any one set. The vessel is not allowed to return to within 5 nm of the location where the bycatch exceeded 1 tonne for a period of at least five days.

4.3 Incidental capture of protected species (seabirds and marine mammals)

Only two seabirds have ever been caught in this toothfish fishery: both were southern giant petrels (*Macronectes giganteus*). One was caught in 2003–04 and the second in 2013–14 (Table 7). None have been reported since 2014. Considerable effort has been put into mitigation of seabird captures in the fishery, through implementation of CCAMLR Conservation Measures regarding line sink rate, use of streamer lines, seasonal restrictions on fishing, prohibition of offal dumping, line weighting, and only allowing daytime setting under strict conditions.

Assessments of the potential risk of interaction between seabirds and longline fisheries (ranging from low to high) have remained unchanged since 2007. The risk levels of seabirds in the fishery in Statistical Subarea 88.1 is category 1 (low) south of 65° S, category 3 (average) north of 65° S, and overall is category 3 (SC-CAMLR-XXX, Annex 8, paragraph 8.1).

Implementation of the required CCAMLR Conservation Measures has meant that seabird captures have been successfully avoided during this toothfish longline fishery. There is a high degree of certainty in the estimates provided of seabird captures, given the high level of observer coverage (100% of vessels covered by two observers and up to 40% of all hooks hauled directly observed).

Table 7: Seabird incidental mortality limit, reported seabird incidental mortality, incidental mortality rate, and estimated incidental mortality in Statistical Subareas 88.1 and 88.2.

Season	Incidental mortality limit	Incidental mortality rate (seabirds/thousand hooks)	Estimated incidental mortality
1997–98		0	0
1998–99		0	0
1999–00		0	0
2000–01		0	0
2001–02	3*	0	0
2002–03	3*	0	0
2003–04	3*	0.0001	1
2004–05	3*	0	0
2005–06	3*	0	0
2006–07	3*	0	0
2007–08	3*	0	0
2008–09	3*	0	0
2009–10	3*	0	0
2010–11	3*	0	0
2011–12	3*	0	0
2012–13	3*	0	0
2013–14	3*	0.0001	1
2014–15	3*	0	0
2015–16	3*	0	0
2016–17	3*	0	0
2017–18	3*	0	0
2018–19	3*	0	0
2019–20	3*	0	0
2020–21	3*	0	0

* Per vessel during daytime setting.

4.4 Maintenance of ecological relationships

FEMA workshops

Developments in evaluating ecosystem effects of the Antarctic toothfish fishery were discussed at the FEMA (Fisheries and Ecosystem Models in the Antarctic) and FEMA II workshops (SC-CAMLR-XXVI/BG/6, paragraphs 45 to 48 and SC-CAMLR-XXVIII/3). The FEMA and FEMA II workshops noted that the fishery for Antarctic toothfish may affect ecological relationships in the Ross Sea region by influencing interactions between toothfish and its predators or interactions between toothfish and its prey. Effects of fishing may also 'cascade' through marine food-webs as indirect effects.

The FEMA II workshop also noted that the escapement level of 50% is the proportion of spawning biomass permitted to escape the fishery over the long term, and that, as a consequence, the sub-mature fish would have a much higher escapement (e.g., > 90% for fish < 100 cm) (SC-CAMLR-XXVIII, Annex 3, figure 1). However, the FEMA II workshop noted that the escapement level in the decision rule for the spawning biomass may need to be modified upwards if the size/age classes of *Dissostichus* spp. that are important prey for predators are reduced below the level needed to safeguard predators.

Effects on predators of toothfish

The predators of toothfish include Type C killer whales, odontocetes (sperm whales (historically)) and Weddell seals (Pinkerton et al 2010, Eisert et al 2013, Torres et al 2013, Eisert et al 2014). A mass-balance food-web model suggested that toothfish formed about 6–7% of the diet of its predators at the scale of the Ross Sea averaged over a year (Pinkerton et al 2010). The model does not exclude the possibility that the consumption of toothfish in particular locations at particular times of the year, or by particular components of predator populations may be important to some predators, even though the model suggests that the total consumption of toothfish by all individuals of a predator species is relatively low. Few data are available on consumption of toothfish by marine mammals, and results derived from this model should be treated as preliminary until better information can be obtained.

With respect to Weddell seals, Pinkerton et al (2008) and Eisert et al (2013) reviewed information on interactions with toothfish from habitat overlap estimates, diver observations, animal-mounted cameras, stomach contents, vomit and scat (faecal) analysis, and stable isotopes of carbon and nitrogen and also compared natural mortality rates of Antarctic toothfish in McMurdo Sound with potential consumption by Weddell seals. Energetic analyses of other potential Weddell seal prey in McMurdo Sound compared with Weddell seal seasonal dietary requirements suggest that toothfish are likely to be important prey during particular times of year and in particular locations but are unlikely to be a major dietary component throughout the year (Eisert et al 2013). The contribution of toothfish to Weddell seal diets is being investigated over two time scales, (1) using scat DNA analysis during the post-breeding/moult period (identified as a period potentially requiring increased food intake to recover body condition lost during lactation), and (2) using stable isotope analysis of whiskers to obtain a dietary record for an entire annual cycle. Seals have been marked by injection of ^{15}N-labelled glycine in the 2013–14 season for recapture in the 2014–15 season. The ^{15}N-label is detectable as a spike in the values for whiskers and provides a time-stamp for the stable isotope pattern preserved in whiskers (Goetz et al 2017). In addition, winter foraging areas are being investigated using satellite-linked data loggers deployed on Weddell seals to investigate potential spatial overlap with the fishery and to identify areas of particular importance to these predators.

Torres et al (2013) considered the available evidence regarding the importance of toothfish as prey for killer whales in the Ross Sea. Killer whales with toothfish in their mouths have been observed in McMurdo Sound (Eisert et al 2014), but the proportion of toothfish consumed by killer whales in the Ross Sea in general is not known. The available data—on habitat overlap, stable isotopes, and a comparison between natural mortality rates of Antarctic toothfish in McMurdo Sound and potential consumption by killer whales—were limited and inconclusive. At present, the balance of evidence suggests that toothfish are likely to be significant in the diet of type C killer whales in McMurdo Sound in summer, but it is not possible to say whether toothfish are an important prey item to type C killer whales in other locations on the Ross Sea shelf or at the scale of the whole Ross Sea shelf and slope (Torres et al 2013). An important consideration for type C killer whales, as for Weddell seals, is that toothfish, due to their large mass and high energy content, may be a unique food resource that is required to support periods of high energy demand such as lactation (Eisert et al 2014). Field work on this issue includes: (a) collecting dart (small tissue) biopsies for stable isotope analysis and (b) compiling a photo-identification catalogue of killer whales that can be used to study habitat use, migration patterns, and to estimate abundance from mark-recapture analysis.

Effects on prey of toothfish

The mass-balance food-web model suggested that toothfish consumed 64% of the annual production of demersal species as prey items (Pinkerton et al 2010), and so a reduction of the toothfish population might lead to a large reduction on the mortality of these species through a 'predation release' effect. As toothfish are large and mobile, their prey species are long-lived, and functional predator diversity seems to be low, then the potential predation release effect is likely to be high in the Ross Sea region (Pinkerton & Bradford-Grieve 2014). Mormede et al (2014d) described the development of a spatially explicit minimum realistic model of demersal fish population dynamics, predator–prey interactions, and fishery removals based on the spatial population model (SPM) for toothfish in the Ross Sea. The model includes *D. mawsoni* as well as macrourids and channichthyids, the two groups that make up about 50% of *D. mawsoni* prey. The model indicates that channichthyids, with a relatively high productivity, would be expected to substantially increase in abundance within fished locations as predation pressure by toothfish is decreased, particularly in SSRU 88.1H where historical fishery removals have been most concentrated. Macrourids would be expected to show a modest increase in biomass based on their lower productivity.

Cascading ecological effects

Changes to the abundance of toothfish prey species may have effects on other species in the food-web through second-order effects (e.g., a 'keystone' effect[3] or trophic cascades[4]); however, these are likely to be dependent on the particular ecosystem and are difficult to predict. The potential ecosystem effects of fishing in the Ross Sea region were investigated using mixed trophic impact (MTI) analysis (Pinkerton & Bradford-Grieve 2014). Overall, Antarctic toothfish had moderate trophic importance in the Ross Sea food web as a whole and the MTI analysis did not support the hypothesis that changes to toothfish will cascade through the ecosystem by simple trophic effects. Because of limitations to MTI analysis, cascading effects on the Ross Sea ecosystem due to changes in the abundance of toothfish cannot be ruled out, but, for such changes to occur, a mechanism other than simple trophic interactions is likely to be involved.

Between 2001 and 2013 the number of breeding pairs of Adélie penguins at colonies in the southwestern Ross Sea more than doubled. It has been suggested that this increase was caused by the fishery for Antarctic toothfish leading to mesopredator release of Antarctic silverfish (*Pleuragramma antarctica*), a shared prey of toothfish and Adélie penguins (Lyver et al 2014, Ainley et al 2016). The study of Pinkerton et al (2016) brought together information from multiple models to estimate the biomass of silverfish that could be released from predation through the effects of the toothfish fishery. Unpublished diet data for toothfish over the Ross Sea shelf were used. The results of the modelling were inconsistent with predation release of silverfish due to the toothfish fishery being responsible for recent increases in the number of Adélie penguins breeding in the southwestern Ross Sea (Pinkerton et al 2016). The cause of the increase in Adélie penguins breeding in the Ross Sea region remains unknown.

4.5 Effects of fishing on biogenic habitats

In 2006, the United Nations General Assembly (UNGA) agreed the Sustainable Fisheries Resolution (61/105), which calls on States and RFMOs or other arrangements to ensure fish stocks are managed sustainably and to prevent significant adverse impacts on vulnerable marine ecosystems (VMEs, UNGA Resolution 61/105, OP80–OP91). The 23 taxa included as VME indicator taxa (Parker & Bowden 2010) are defined in the CCAMLR VME taxa classification guide, which is available on the CCAMLR website (https://www.ccamlr.org/en/system/files/VME-guide.pdf).

CCAMLR has implemented several Conservation Measures pertaining to VMEs that form an approach to constrain gear types used, constrain areas fished, monitor fishing effort for evidence of VMEs, and

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[3] Keystone predators maintain biodiversity by preferentially consuming competitively dominant prey species. If keystone predators are removed or their biomass reduced, abundance of some prey species can increase to levels where they start to exclude subordinate competitors.

[4] Trophic cascade: reorganisation of the lower trophic levels of an ecosystem due to the change in abundance of a predator.

to provide information to evaluate the potential effects of fishing on VMEs.

Sharp et al (2009) developed a bottom fishing impact assessment method, which was revised by Sharp (2010), and subsequently adopted by the Commission and used to summarise the current spatially-resolved fishing footprint and potential impact (% mortality) within the fishing footprint. This assessment method has demonstrated that regardless of the distribution of VMEs within the fishing footprint, the level of impact is exceptionally low.

Parker et al (2010) analysed spatial patterns of VME taxa from fishery bycatch in the Ross Sea region. Some taxa are relatively common as bycatch (e.g., Porifera, anemones, stylasterid hydrocorals) and the detectability of habitats containing these taxa with autoline longline gear is moderate to high (e.g., 70+%), enabling the use of fishery longline bycatch as a monitoring tool. This study also showed that VME taxa distributions vary spatially within the Ross Sea, and that some areas have shown no evidence of VME taxa despite consistent fishing effort.

Following fishery impacts, the potential recovery times for the VME taxa in the Ross Sea with the lowest productivities were evaluated with a spatially explicit production model (Dunn et al 2010). This model also showed that with the current understanding of fishing gear performance, fishing effort distribution, and VME taxon life history, fishery impacts are low and recovery is likely to take place under the current management response to high bycatch levels. However, methods to determine the presence of high densities of rare taxonomic groups or unique community assemblages specific to the Ross Sea Region may need to be developed.

CCAMLR maintains a register of designated VMEs with two designated on the Admiralty seamount in the Ross Sea as well as several shallow water VMEs in Terra Nova Bay. VME Risk Areas have also been designated based on an observed fishery bycatch of over 10 kg or litres of VME taxa in a 1200-m longline segment. A total of 60 VME Risk Areas have been designated in Statistical Subarea 88.1 and 16 in Statistical Subarea 88.2, each closing a 1 nautical mile radius area surrounding the location of the bycatch observation to bottom fishing until reviewed by the Commission.

4.6 Ecosystem indicators

At present our ability to predict the effects of the toothfish fishery on ecosystem relationships in the Ross Sea region is limited. There is a need to develop and implement appropriate monitoring in the Ross Sea to ascertain how species and ecological relationships are affected by the fishery as a main objective of the Ross Sea MPA (CM 91-05). Monitoring should focus on species most likely to be affected by the toothfish fishery in the first instance. Baseline data on toothfish diet have been developed for some areas. Periodic analysis of the stomach contents of toothfish can be used to look for changes in toothfish diet that may be indicative of changes to the demersal fish community, although power analysis is needed to determine the effect size detectable. Better direct information is required on the abundance of *Macrourus* spp. and icefish on the Ross Sea slope, which will require significant trawl survey effort. Research has previously explored the extent to which acoustic methods could be used to detect changes in *Macrourus* spp. abundance at the fishery scale (O'Driscoll et al 2012, Ladroit et al 2014).

Annual surveys of toothfish abundance in the southwest Ross Sea have been carried out since the 2011–12 season and the intention is for these to continue annually. As well as providing an index of abundance of 5–10-year-old toothfish this survey provides information on changes to the availability of toothfish to predators in this region, especially in McMurdo Sound and Terra Nova Bay.

5. STOCK ASSESSMENT

Estimates of biomass and long term yield (using the CCAMLR Decision Rules) were provided in 2023 for Antarctic toothfish for the Ross Sea region stock (Statistical Subarea 88.1 and Statistical Subarea 88.2 SSRUs 88.2A and B) based on analyses using catch-at-age from the commercial fishery, tag-recapture data, and estimates of biological parameters as reported below (Mormede et al 2023a). This was the twelfth stock assessment of the Ross Sea fishery.

In 2014, the approach used in previous assessments of the Amundsen Sea stock (Statistical Subarea 88.2 SSRUs 88.2C–H) was rejected by CCAMLR because the models were unable to fit the patterns in the tag recapture data. Instead, a two-year research plan was developed by CCAMLR to collect the data required to address uncertainties in the previous assessment model. Two area models for the Amundsen Sea stock have been developed (Mormede et al 2013, Mormede et al 2014a, Mormede et al 2014b, Mormede et al 2015b, Mormede et al 2016), and the two-year research plan was extended through the 2022–23 season). The key aspects of the plan, including derivation of catch limits are discussed below under Section 5.2(ii).

5.1 Estimates of fishery parameters and abundance indices

CPUE indices

A standardised CPUE analysis of Antarctic toothfish in the Ross Sea fishery showed a gradually increasing trend through 2008 followed by a slight decline until 2012; CPUE has been relatively stable since (Devine & Mormede 2023a, Figure 4).

The patterns of increase and declines in the annual CPUE indices are thought to reflect a combination of either good or poor ice conditions, vessel crowding, increasing fisher experience, improved knowledge of optimum fishing practice, improvements in gear, and regulation changes (i.e., move-on rules and research set requirements), and will also be affected by movement patterns of toothfish rather than toothfish abundance (Maunder et al 2006).

A standardised CPUE analysis of Antarctic toothfish in SSRU 88.2H shows a steep decline at the beginning of the fishery when there had still been little fishing in the area followed by a more recent increase. Standardised CPUE in SSRUs 88.2C–G shows an increase over time with levelling off in the most recent years. In both SSRU 88.2H and SSRUs 88.2C–G the confidence bounds are very wide for the first part and later part of the time series (Large et al 2015) (Figure 5). There has been little consistent fishing effort in Statistical Subarea 88.2 until recent years and, as for the Ross Sea, the patterns of increase and declines in the CPUE indices are thought to reflect a combination of fishery and environmental factors rather than toothfish abundance (Maunder et al 2006). The CPUE analysis in 88.2H has not been updated since 2015.

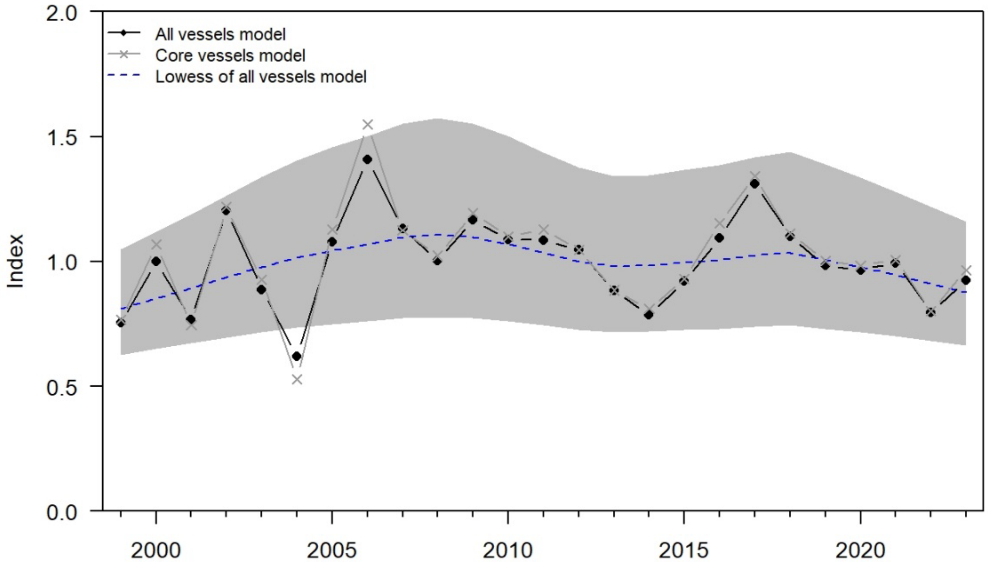


Figure 4: Relative CPUE indices (scaled to have mean of one) for the 'all vessels' model and the core vessels (involved in the fishery for at least four years) model for the Ross Sea fishery, 1999–2023. Blue dashed line shows loess fit with 95% confidence intervals (grey area).

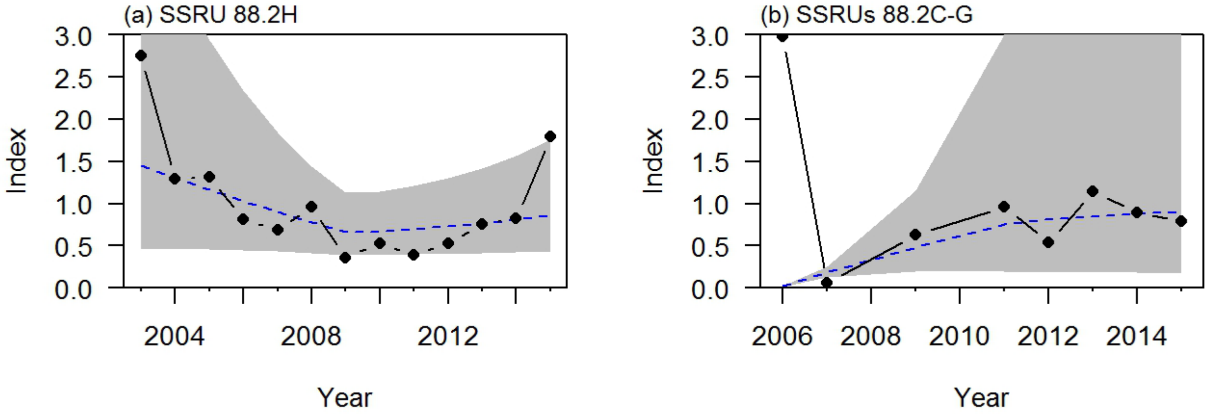


Figure 5: Relative CPUE indices (scaled to have mean of one) for (a) the SSRU 88.2H fishery, and (b) the SSRU 88.2C–G fishery, 2003–2015. Blue dashed lines show smoothed fit with 95% confidence intervals (grey area).

Mark-recapture data

The tagging programme for *Dissostichus* spp. in the Ross Sea was first initiated in the 2000–01 season in Statistical Subarea 88.1 by New Zealand vessels participating in the fishery (Devine & Mormede 2023a). Since then, the toothfish tagging programme has been made a requirement for all vessels participating in the fishery in both the Ross Sea region and Amundsen Sea region.

An index of vessel-specific tag detection performance for the Ross Sea fishery using a case-control methodology was developed by Mormede & Dunn (2013) and further refined into the calculation of effective tag release survival rate and effective tag detection rate of recaptured fish (Mormede 2014). The method controls for the inter-annual spatial and temporal variability of commercial fishing operations from which tagged fish are released and recaptured.

Between 2001 and 2022, approximately 87 000 *Dissostichus* spp. were tagged in Statistical Subareas 88.1 and 88.2, with just over 67 000 and more than 19 000 *D. mawsoni* in the Ross Sea and SSRUs 88.2C–H, respectively (Devine & Mormede 2023a, b). Recaptured fish at liberty for more than six years and within-season recaptures were not used in the assessment.

In 2022, there was a change in the management approach, such that the tagging rate and tag-overlap statistic be specified and applied at the smallest area to which a catch limit applies (CCAMLR-41 report, paragraph 4.55). For the Ross Sea, this means that these metrics are applied at management area level (N70, S70 and SRZ), rather than at the SSRU as they had been previously.

In 88.2, although more than 2500 tags had been released on the shelf and slope of Statistical Subarea 88.2 (SSRUs 88.2C–G) by 2014, few fish had been recaptured, likely reflecting the inconsistent pattern of fishing in these areas. The Scientific Committee recognised the need to develop an estimate of abundance for the south of 88.2 and recommended a two-year research plan to collect the necessary information (SC-CAMLR-XXXIII 2014, paragraph 3.168). As part of the approved research plan, fishing effort in the south was restricted to four fishing blocks for the 2014–15 and 2015–16 fishing seasons to increase the likelihood of tagged fish being recaptured. This approach has led to an increase in the tag recapture rate. The Scientific Committee considered that the research plan was providing the information necessary to develop the stock assessment and recommended that it be extended with increased tagging rate in the north to 3 fish per tonne, consistent with the rate in the south (SC-CCAMLR-XXXV 2016, paragraphs 3.215 and 3.216). At its 2018 meeting, the CCAMLR Scientific Committee recommended that the research plan in place for SSRUs 882C–H continues in the 2018–19 season following Scientific Committee advice (SC-CAMLR-XXXVII 2018, paragraphs 3.183–3.188). This arrangement was continued in the 2021–22 season with small changes in catch limit based on CCAMLR trend analysis procedures and the requirement to conduct structured fishing on minor seamounts before proceeding to the Olympic fishery in Subarea 88.2H (SC-CAMLR-41 2022, paragraphs 3.144–3.146), which was repeated for another two years, beginning with the 2023–24 season (SC-CAMLR-42 2023).

Catch-at-age data

Strata for the Antarctic toothfish length and age frequency data were determined after splitting into four strata based on area, N70, S70, SRZ, and Other (areas now part of the General Protection Zone (GPZ) or the Krill Research Zone (KRZ)). On average, about 500 Antarctic toothfish otoliths collected by observers were selected for ageing each year from each of the main fishery areas and used to construct annual area-specific age-length keys (ALKs) for the Ross Sea region. In the Ross Sea, ALKs for each sex were applied to the fisheries defined above separately. The ALKs were applied to the scaled length-frequency distributions for each year to produce annual catch-at-age distributions (Devine & Mormede 2023a). In the Amundsen Sea region (SSRU 88.2C–H) fishery, otoliths were only available from the New Zealand fleet, which did not fish there every year. Therefore, for this fishery, a single ALK for each sex using otolith ages from all available years was used to construct annual age frequencies for SSRU 88.2H, and SSRU 88.2C–G fisheries separately (Devine & Mormede 2023b).

Recruitment surveys

Thirteen years of an annual research longline survey of sub-adult (70–110 cm long) toothfish have now been carried out in the southern Ross Sea (Hanchet et al 2012, Parker et al 2013, Mormede et al 2014c, Hanchet et al 2015a, Dunn et al 2016, Large et al 2017, Stevens et al 2018, Parker & Jones 2019, Parker et al 2020b, Devine et al 2021, Devine & Prasad 2022, Devine & Péron 2023, Devine et al in prep). Catches increased between 2015 and 2020, but then declined, and the length and age structure changed. Fewer small fish and more large-sized fish have been present since 2016 in the core strata, but in 2024, there was evidence of a new cohort entering. The age distribution also showed a smaller group of fish aged 10–20 remaining in the survey area. This suggests a slower movement of fish out of the shelf area compared with the early years of the survey. The survey age structure and local biomass estimations were incorporated into the 2023 assessment (Mormede et al 2023a).

Parameter estimates

A list of parameter values used for the assessments is given in Table 8.

Table 8: Parameter values for *D. mawsoni* in Statistical Subareas 88.1 and 88.2.

Component	Parameter	Value			Units
		Male	Female	All	
Natural mortality	M	0.13	0.13		y^{-1}
VBGF	K	-0.292	-0.712		y^{-1}
	t_0	0.101	0.082		y
	L_∞	164.06	180.49		cm
	c.v.	0.101	0.101		
Length to mass	‘*a*’	0.00001247	0.00007361		cm, kg
Length to mass	‘*b*’	2.990	3.105		
Length to mass variability (CV)				0.1	
Maturity	A_{m50}	11.99	16.92		y
Range: 5% to 95% maturity		6.7–17.2	9.2–24.6		y
Recruitment variability	σ_R			0.6	
Stock recruit steepness (Beverton-Holt)	h			0.75	
Ageing error (CV)				0.1	
Initial tagging mortality				10%	
Initial tag loss (per tag)				5.7%	
Instantaneous tag loss rate (per tag)				0.033	y^{-1}
Tag detection rate				99.5%	
Tagging related growth retardation (TRGR)				0.5	y

5.2 Biomass estimates

The Ross Sea fishery (Statistical Subarea 88.1 and SSRUs 88.2A and 88.2B)

The stock assessment model

The model was sex- and age-structured, with ages from 1–50, where the last age group was a plus group (Mormede et al 2023a). The annual cycle was broken into three discrete time steps, nominally summer (November–April), winter (May–October), and end-winter (age-incrementation) (Table 9).

Table 9: Annual cycle for the Ross Sea Region Antarctic toothfish population model. AFs = catch-at-age frequencies, CPUE = catch per unit effort (not used in these models). Actual catch was calculated based on the catches from the 2018–2023 period, including SPRFMO catches (in October).

Month	Catch (%)		Biological processes						Observations				Time step
	Actual	Assumed	Ageing	Recruitment	Maturation	Growth (%)	Natural mortality (%)	Spawning	Tag release	Tag recapture	RSSS survey	AFs	
Nov	0.0	100		X			50		X	X	X	X	Summer
Dec	66.0												
Jan	33.5												
Feb	0.2												
Mar	0.0												
Apr	0.0												
May													Tag Loss
Jun	0.0	0					50	X					Winter
Jul	0.0												
Aug	0.0												
Sept	0.0												
Oct	0.4												
Year end	0.0	0	X			100							Age Increment
Total	100.0	100				100	100						

The model was run from 1995 to 2023 and was initialised assuming an equilibrium age structure at an unfished equilibrium biomass, i.e., a constant recruitment assumption. Recruitment was assumed to occur at the beginning of the first (summer) time step. Recruitment sex ratio was assumed to be 50:50 and was parameterised as a year class strength multiplier (assumed to have mean equal to one over a defined range of years), multiplied by an average (unfished) recruitment (R_0) and a spawning stock-recruitment relationship. In this model, the year class strength multipliers were assumed fixed and set equal to 1.

Fishing mortality was applied only in the first (summer) time step. The process was to remove half of the natural mortality occurring in that time step, then apply the mortality from the fisheries instantaneously, then to remove the remaining half of the natural mortality.

The population model structure includes tag-release and tag-recapture events. Each tagged fish was assigned an age-sex based on its length and the modelled population structure of fish at that age and sex. Tagging from each year was applied as a single tagging event. The usual population processes (natural mortality, fishing mortality, etc.) were then applied over the tagged and untagged components of the model simultaneously. Tagged fish were assumed to suffer a retardation of growth from the effect of tagging (TRGR), equal to 0.5 of a year for the year immediately following release.

Model estimation

The model parameters were estimated using Bayesian analysis, first by maximising an objective function (MPD), which is the combination of the likelihoods from the data, prior expectations of the values of those parameters, and penalties that constrain the parameterisations; and second, by estimating the Bayesian posterior distributions using Markov chains Monte Carlo (MCMC). Initial model fits were evaluated at the MPD, by investigating model fits and residuals. Parameter uncertainty was estimated using MCMCs. These were estimated using a burn-in length of 5×10^5 iterations; with every 1000th sample taken from the next 1×10^6 iterations (i.e. a final sample of length 1000 was taken).

Observation assumptions

The catch proportions-at-age data for 1998–2023 were fitted to the modelled proportions-at-age composition using a multinomial likelihood. Following previous recommendations of WG-SAM that

CPUE indices were not indexing changes in abundance, the CPUE indices were not used. Tag-release events were defined for the 2001–2023 years, weighted by the vessel-specific tag survival rate. Within-season recaptures were ignored. Tag-release events were assumed to have occurred at the end of the first (summer) time step, following all (summer) natural and fishing mortality.

The estimated number of scanned fish (i.e., those fish that were caught and inspected for a possible tag) was derived from the sum of the scaled length frequencies from the vessel observer records multiplied by the vessel-specific tag detection rate, plus the numbers of fish tagged and released. Tag recapture events were assumed to occur at the end of the first (summer) time step and were assumed to have a detection probability of 85% to account for unlinked tags.

For each year, the recovered tags at length for each release event were fitted, in 10 cm length classes (range 40–230 cm), using a binomial likelihood.

Process error and data weighting

Additional variance, assumed to arise from differences between model simplifications and real-world variation, was added to the sampling variance for all observations, following the methods of Francis (2011). Adding such additional errors to each observation type has two main effects: (i) it alters the relative weighting of each of the data sets (observations) used in the model, and (ii) it typically increases the overall uncertainty of the model, leading to wider credible bounds on the estimated and derived parameters. The additional variance, termed process error, was estimated for each MPD run, and the total error assumed for each observation was calculated by adding process error and observation error. A single process error was estimated for each of the observation types (i.e., one for the catch-at-age data and one for the tag-recapture data).

Penalties

Two types of penalties were included within the model. First, the penalty on the catch constrained the model from returning parameter estimates where the population biomass was such that the catch from an individual year would exceed the maximum exploitation rate. Second, a tagging penalty discouraged population estimates that were too low to allow the correct number of fish to be tagged. These penalties had no effect on the model outcome.

Priors

The parameters estimated by the models, their priors, the starting values for the minimisation, and their bounds are given in Table 10. In models presented here, priors were chosen to be relatively non-informative and this also encouraged conservative estimates of B_0.

Table 10: Starting values, priors, number of parameters (N), and bounds for the free parameters for the 2023 base case assessment model (R3) for Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*). B0 = pre-exploitation spawning stock biomass; RSSS = Ross Sea Shelf Survey.

Parameter		*N*	Start value	Transform	Prior	Prior applied to transform	Bounds	
							Lower	Upper
B_0 (t)		1	70 000	log	Uniform	yes	10	18
Fishing selectivities	a_1		8.0	-	Uniform	-	1.0	50.0
(male)	s_L		4.0	-	Uniform	-	1.0	50.0
	s_R	12	10.0	inverse	Uniform	no	0.002	1
Fishing selectivities	a_{max}		1.0	-	Uniform	-	0.01	10.0
(female)	a_1		8.0	-	Uniform	-	1.0	50.0
	s_L		4.0	-	Uniform	-	1.0	50.0
	s_R	16	10.0	inverse	Uniform	no	0.002	1
Recruitment		15	1.0	simplex	Lognormal	no	-10	10
RSSS abundance	cv	1	0.0	-	Uniform	-	0	10.0
RSSS selectivities	a_1		8.0	-	Uniform	-	1.0	50.0
(male)	s_L		4.0	-	Uniform	-	1.0	50.0
	s_R	3	10.0	inverse	Uniform	no	0.002	1
RSSS selectivities	a_{max}		1.0	-	Uniform	-	0.01	10.0
(female)	a_1		8.0	-	Uniform	-	1.0	50.0
	s_L		4.0	-	Uniform	-	1.0	50.0
	s_R	4	10.0	inverse	Uniform	no	0.002	1

Base case and sensitivity models

The estimates of B_0 and current status for the base case (R3) and a sensitivity test (R2) are described in Table 11. The base case model excluded quarantined mark-recapture and length data (but included catch removals from quarantined trips). A sensitivity model (R2) was carried out, which excluded the initial three years of tag-release data (2001–2003) and associated tag-recapture data. The initial three years of tag-release and associated tag recapture data (3.9% of all available tag data) were identified as potentially different in quality to the tag data since 2004, and this was a pilot targeting small fish to understand whether Antarctic toothfish tagging was feasible and to learn more about toothfish movement. Tagging was only introduced as a requirement in 2004 (under CM41-01/C), extending the pilot scheme to all vessels. The sensitivity evaluated the impact of removing these data on the base model.

Model estimates

MCMC samples from the posterior were estimated. MCMC diagnostics suggested no evidence of poor convergence in the key biomass parameters and between-sample autocorrelations were low.

Table 11: Median Markov chain Monte Carlo (MCMC) estimates (and 95% credible intervals) of B0, B2023, and B2023 as %B0 for the 2021 base case assessment model (2021-R1.1) and the 2023 base case assessment model (R3).

Model	B_0 (t)	B_{2023} (t)	B_{2023} (%B_0)
2021-R1.1	78 373 (71 999–85 663)		
R3	77 855 (71 954–85 115)	49 994 (44 350–57 071)	64.3 (61.4–67.3)

Key output parameters for the base case and the sensitivity are summarised in Table 12. Biomass was estimated as 63% B_0 (95% Cis 60–66%). Table 12 shows the estimated yields following the CCAMLR decision rules. The catch limit for the base case was 3495 t for the 2021–22 and 2022–23 seasons. The current stock status trajectory and uncertainty relative to the CCAMLR decision rules are shown in Figure 6.

Table 12: Estimated risks of the 2021 catch limit (3495 t) using the CCAMLR toothfish decision rules for the 2021 base case assessment model (2021-R1.1) and the estimated precautionary yield for the 2023 base case assessment model (R3).

Model	Pr(SSB < 50% B0)	Pr(SSB < 20% B0)	Catch limit (t)
2021-R1.1 estimated precautionary yield	0.50	<0.01	3 495
R3 estimated precautionary yield	0.50	<0.01	3 499

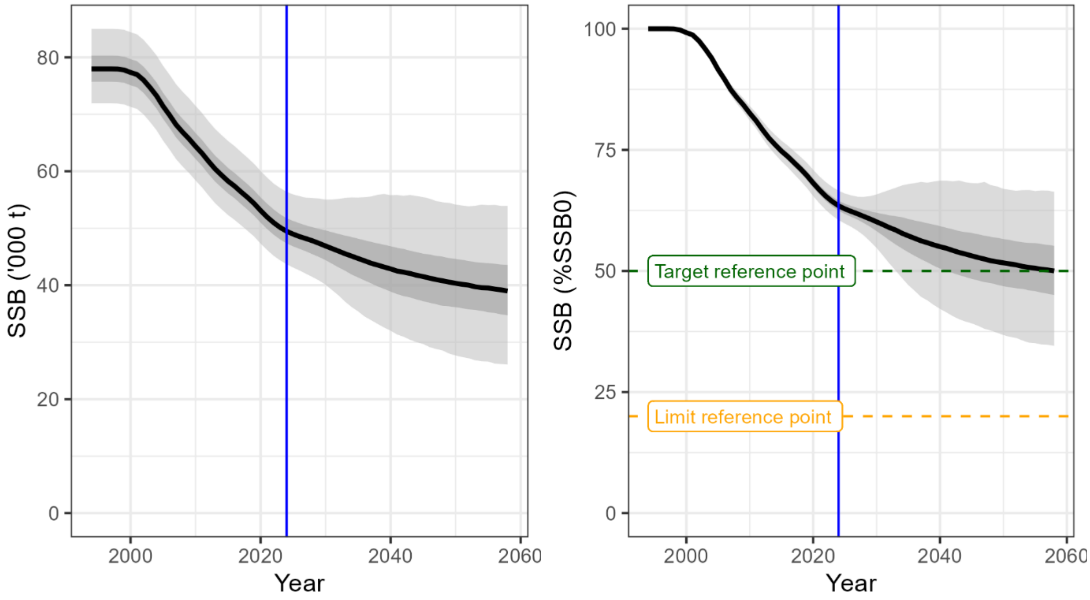


Figure 6: Markov chain Monte Carlo (MCMC) estimate of spawning stock biomass in thousands of tonnes (left) and proportion of initial spawning stock biomass (right) projected out to 2058 for the base model (R3), with the median (black line and points), interquartile range (dark grey) and 95% credible intervals (light grey).

Diagnostic plots of the observed proportions-at-age of the catch versus expected values show little evidence of inadequate model fit. Estimated selectivity curves appeared reasonable, although the right-hand limb parameters lacked convergence. Post-MCMC analyses of the non-convergence in these parameters showed no evidence that the estimates of initial biomass were unduly influenced. The tag-recapture data are well fitted and provide most of the information on abundance in the model.

Year class strengths were estimated for the years 2004 to 2018. Estimates showed that there was stronger than average recruitment in 2006, 2014, 2017 and 2018. Fits to the survey biomass indices were consistent with the patterns in the RSSS catch-at-age frequencies, suggesting that the RSSS was monitoring the relative recruitment of the population. The RSSS was noted by the 2018 independent review of the integrated modelling methods used to assess toothfish (Anon 2018) as an important index for the assessment, and as a means to employ a fishery independent method to monitor recruitment.

(ii) The Amundsen Sea region fishery (Statistical Subarea 88.2 SSRUs 88.2C–H)
There is no current stock assessment of the Amundsen Sea region fishery. A single area stock assessment model of the Amundsen Sea region was unable to fit the trends in the tag-recapture data, which came almost entirely from SSRU 88.2H (Mormede et al 2014a). Fits to the tag data from a two-area developmental model (SSRUs C-G versus SSRU H) were more encouraging but identified the need for additional recaptures of tagged fish from the southern SSRUs 88.2C–G (Mormede et al 2014b).

Fishing in the Amundsen Sea region (SSRUs 882C–H) has been managed through a research plan since the 2015 fishing season. The aim of the research plan is to collect sufficient information to carry out a reliable stock assessment of the toothfish stock in that area. The key feature of the initial two-year research plan was to restrict fishing effort to grounds in SSRUs 88.2C–G which had been fished previously to facilitate the recapture of previously tagged toothfish during year 1.

Four fishing grounds were identified in the Amundsen Sea region where fishing should take place based on an analysis by Hanchet & Parker (2014). The tagging rate was also increased from 1 tag per tonne to 3 tags per tonne so that more tagged fish would be available for recapture in year 2 and subsequent years. Analysis of ice conditions by Hanchet & Parker (2014) demonstrated that in most years one or more of the grounds were inaccessible or unfishable due to ice, and so some flexibility was necessary in prescribing areas where fishing would be allowed.

Catch limits for the Amundsen Sea region research plan were derived from Petersen biomass estimates based on recaptures of tagged fish from SSRU 88.2H. Parker & Mormede (2014) demonstrated that estimates of biomass for SSRU 88.2H were biased upwards for each successive year that the tagged fish had been at liberty, probably as a result of immigration of untagged fish from a source population (Parker 2014). Therefore, CCAMLR agreed that a catch limit for SSRU 88.2H should be based on the number of recaptures of tagged fish which had been at liberty for a single year. The resulting biomass estimate of 5000 tonnes was multiplied by an exploitation rate of 4% to give a catch limit of 200 tonnes for 88.2H.

CCAMLR also agreed that an estimate of biomass for the Amundsen Sea region based on the number of recaptures of tagged fish from SSRU 88.2H which had been at liberty for all years could apply to the entire stock in SSRUs 88.2C–H. The resulting estimate of biomass of 20 649 tonnes (Goncharov & Petrov 2014) was multiplied by an exploitation rate of 3% to give a catch limit of 619 tonnes for the entire stock. It should be noted that this latter estimate of biomass and yield did not include any tag recapture data (i.e., number of tagged fish released, tagged fish recaptured, or scanned fish) from the south and was based on the assumption that all fish tagged in the north would have been available for recapture in the south. By subtraction, the catch limit for 88.2C-G (constrained to 4 research blocks) was 419 t which had the added effect of releasing many more tagged fish in the south given the increase in TAC. This was considered a good mechanism to release many tagged fish in the southern areas in just two years to obtain a mark-recapture biomass estimate more quickly.

The final research plan for the Amundsen Sea region was approved for two years and had the following components:

(i) the catch limits were adopted for 2014–15 and 2015–16
(ii) the catch limit for SSRU 88.2H was 200 tonnes
(iii) the fishing in SSRUs 88.2C–G was restricted to four fishing areas (research blocks)
(iv) the combined catch limit for SSRUs 88.2C–G was 419 tonnes, with no more than 200 tonnes to be taken from any one of the fishing grounds in (iii)
(v) toothfish to be tagged at the rate of 3 fish per tonne in SSRUs 88.2C–G and 1 fish per tonne in SSRU 88.2H

Some preliminary model runs for the Amundsen Sea region using a two-area model were carried out to assess the utility of the results of the experiment (Mormede et al 2016) and FSA recommended that further work be undertaken on the model structure (SC-CAMLR-XXXV 2016, paragraph 3.127). The Scientific Committee considered that the research plan was providing the information necessary to develop the stock assessment and recommended it be extended by a further two years with increased tagging rate in the north to 3 fish per tonne, consistent with the rate in the south (SC-CCAMLR-XXXV 2016, paragraphs 3.215 and 3.216).

In the Amundsen Sea region in the 2016 and 2017 seasons, a total of 19 tagged fish (excluding within season recaptures) were recaptured in the research blocks in the South Amundsen Sea region, confirming the utility of the research plan to recapture tagged fish and providing key information on the size of the population in the south. Although only four tagged fish were recaptured (excluding within season recaptures) in the north (SSRU 882H) in 2017, the increase in tagging rate to 3 fish per tonne in the 2017 season has increased the number of tagged fish at liberty and therefore the number of recaptures of tagged fish was thought likely to continue to increase in the 2019 season. Estimates of local biomass based on mark-recapture data are updated annually and follow the trend analysis rules (SC-CAMLR-XXXVI 2017, Annex 7 paragraph 4.33) to set catch limits for individual fishing areas. The resulting catch limits for the 2023–24 fishing year were 184 t in research block 1, 322 t in research block 2, 242 t in research block 3, 222 t in research block 4, and 146 t in SSRU88.2H (SC-CAMLR-42 2023, table 4).

No validated age data are available since 2014 for the north of the Amundsen Sea region and exist only for 2014, 2015, and 2017 from the south of the Amundsen Sea region to support the development of a stock assessment (Devine & Mormede 2023b).

5.3 Yield estimates and projections

Yields were estimated for the Ross Sea stock using the methods described by Mormede et al (2015a). For each sample from the posterior distribution estimated for each model, the stock status was projected forward 35 years under a scenario of a constant annual catch (i.e., for the period 2023–2058). Recruitment for the 2003–2016 year classes was as estimated in the model, and was assumed to be lognormally distributed with a standard deviation of 0.6 with a Beverton-Holt stock-recruitment steepness h = 0.75 (Mormede et al 2023b). Future catch was assumed to follow the split between fisheries as defined in CM 91-05 (i.e., 19%, 66%, and 15% of the total future catch was allocated to the N70, S70, and SRZ fisheries, respectively).

The decision rules are $rule_1 = \max(Pr[SSB_i < 0.2 \times B_0]) \leq 0.10$, where I is any year in the projection period, and $rule_2 = Pr[SSB_{+35} < 0.5 \times B_0] \leq 0.50$. They were evaluated by calculating the maximum future catch that meets both decision rule criteria.

The constant catch for which there was median escapement of 50% of the median pre-exploitation spawning biomass level at the end of the 35-year projection period was 3499 t (Table 12). At this yield, there is a less than 10% chance of spawning biomass dropping to less than 20% of the initial biomass. The catch was split among the three areas using the agreed proportions. This resulted in 665 t in the N70 area (SSRUs 88.1A, B, C, part of G), 2309 t on the slope (SSRUs 88.1G, H, I, K), and 456 t in the SRZ, with 69 t taken from the predicted SRZ catch limit (525 t) for a directed research survey for sub-adult toothfish on the shelf for the 2024 survey.

6. STATUS OF THE STOCKS

Stock structure assumptions

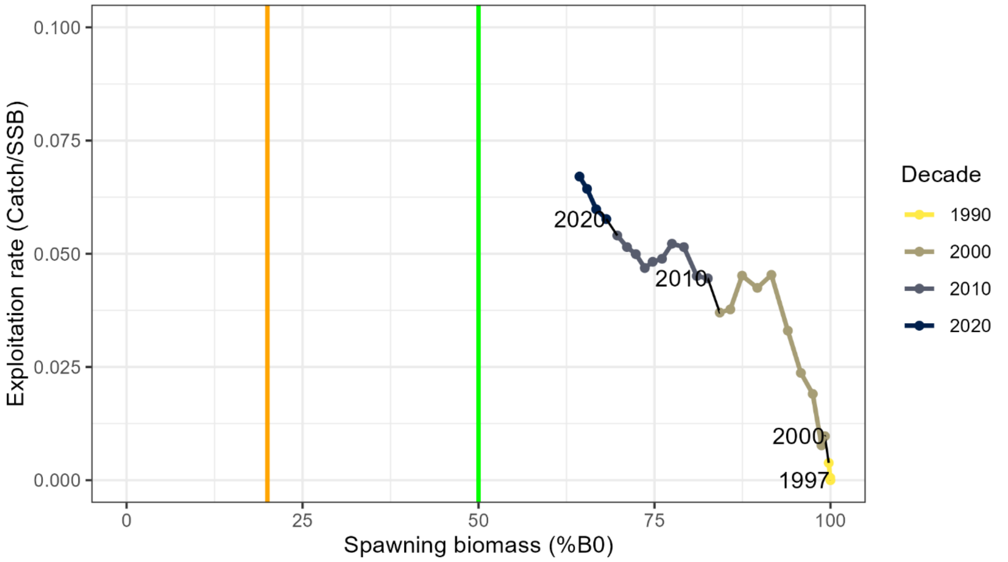
Uncertainty remains with respect to spawning dynamics and early life history of Antarctic toothfish. The present hypothesis is that Antarctic toothfish in Statistical Subareas 88.1 and 88.2 spawn to the north of the Antarctic continental slope, mainly on the ridges and banks of the Pacific-Antarctic Ridge. It has been recommended that for stock assessment purposes Statistical Subarea 88.1 and SSRUs 88.2A and 88.2B be treated as a 'Ross Sea' stock and Statistical Subarea 88.2 SSRU 88.2C–H be treated as a separate 'Amundsen Sea' stock.

In 2014, the Commission of CAMLR recognised that though there had been a large number of tagged fish recaptured in SSRU 882H, very few tags had been recaptured in 882C–G and a change in management was required to address this issue. It is also noted that the stock affinity of the toothfish in Statistical Subareas 88.1 and 88.2 with toothfish in surrounding areas is not well understood; however, the current stock structure used in the stock assessments should be continued.

- **Ross Sea stock**

Stock Status		
Most Recent Assessment Plenary Publication Year	2024	
Catch in most recent year of assessment	Year: 2023	Catch: 3 368 t
Assessment Runs Presented	A single base case model (R3) was accepted by CCAMLR	
Reference Points	Target: CCAMLR decision rule 2[4]: 50% B_0 after 35 years with Pr(SSB > 20% B_0) ≥ 0.9 for a constant catch harvest strategy (Soft) Limit: CCAMLR decision rule 1: 20% B_0 with Pr(SSB > 20% B_0) ≥ 0.9 Hard Limit: 10% B_0 Overfishing threshold: Not defined	
Status in relation to Target	B_{2023} was estimated to be 64% B_0. Virtually Certain (> 99%) to be at or above the long term target (50% B_0)	
Status in relation to Limits	B_{2023} is Exceptionally Unlikely (< 1%) to be below both soft and hard limits	
Status in relation to Overfishing	Overfishing is Very Unlikely (< 10%) to be occurring	

Historical Stock Status Trajectory and Current Status



Trends in spawning biomass and exploitation rate over time.

Fishery and Stock Trends	
Recent Trend in Biomass or Proxy	Estimates of biomass have never been below 50% B_0, and the fishery is still in a fish-down phase.
Recent Trend in Fishing Intensity or Proxy	Fishing pressure increased early in the fishery and has stabilised at about target levels.
Other Abundance Indices	-
Trends in Other Relevant Indicators or Variables	The CPUE indices are not deemed to be an index of abundance. The catch-at-age data, although a relatively short time series, is showing indication of truncation of the right-hand limb, which is captured in the stock assessment. For assessments, the tag-recapture data provide the best information on stock size, but the total number of fish recaptured is small and may introduce bias into the model. Spatial population operating models have indicated that the stock assessment is likely to be negatively biased (precautionary). Although the absolute stock size is uncertain, the available evidence (tag recapture data, catch rates, age frequency data) suggests that the stock has been lightly exploited to date.

Projections and Prognosis	
Stock Projections or Prognosis	The biomass of the stock is expected to decline slowly over the 35-year projection period to the target level under constant catch.
Probability of Current Catch or TACC causing Biomass to remain below or to decline below Limits	Exceptionally Unlikely (< 1%)
Probability of Current Catch or TACC causing Overfishing to continue or to commence	Unlikely (< 40%)

Assessment Methodology and Evaluation		
Assessment Type	Level 1– Full Quantitative Stock Assessment	
Assessment Method	Age-structured CASAL model with Bayesian estimation of posterior distributions	
Assessment Dates	Latest assessment Plenary publication year: 2024	Next assessment: 2025
Overall assessment quality rank	1 – High Quality	
Main data inputs (rank)	- Multi-year tag-recapture data - Commercial catch-at-age proportions - Sub-adult survey series (2012 onwards) to estimate annual year class strength	1 – High Quality 1 – High Quality 1 – High Quality
Data not used (rank)	Commercial CPUE	3 – Low Quality: not believed to be indexing abundance
Changes to Model Structure and Assumptions	-	
Major sources of Uncertainty	- model assumes homogenous mixing of tags within the population, which is unlikely to be true in the short term; bias was estimated to be about 30% conservative (Mormede et al 2014e) - estimates of initial mortality of tagged fish - detection rates of tagged fish	

	- natural mortality rate - stock structure and migration patterns - stock-recruit steepness - natal fidelity assumptions with respect to other areas

Qualifying Comments
For the base case and sensitivity models, current biomass is estimated to be between 61% and 67% B_0. The precautionary yield, using the CCAMLR decision rules[5] consistent with previous fishing activities and with the Ross Sea region MPA, was 3499 t. At its 2023 meeting, CCAMLR agreed to set the catch limit to 3499 t for the Ross Sea for the 2023–24 season (SC-CAMLR-42 2023).

Fishery Interactions
Main bycatch species are macrourids and rajids for which there are catch limits and move-on rules. Rajids can be released alive.

- **Amundsen Sea stock (Statistical Subarea 88.2 SSRUs 88.2C-H)**

Stock Status		
Most Recent Assessment Plenary Publication Year	2024	
Catch in most recent year of assessment	Year: 2023	Catch: 737 t
Assessment Runs Presented	An estimate of biomass for the north area (SSRU 88.2H) was available from tag recapture data. Biomass estimates and catch limit determinations were made using CCAMLR's trend analysis rules.	
Reference Points	No reference points were used for the assessment. Each of the estimates of biomass were multiplied by an exploitation rate based on a general yield model.	
Status in relation to Target	Unknown	
Status in relation to Limits	Unknown	
Status in relation to Overfishing	Unknown	

Fishery and Stock Trends	
Recent Trend in Biomass or Proxy	Biomass in the northern hills area based on tag recapture data has been trending down. No data are available for the southern area.
Recent Trend in Fishing Intensity or Proxy	Fishing pressure in the northern hills area has been increasing as seen by an increased number of tags recovered. Limited data are available for the southern area.
Other Abundance Indices	-
Trends in Other Relevant Indicators or Variables	The CPUE indices for the northern area have been declining to 2009 and increasing slightly since, but are not deemed to be an index of abundance. The catch-at-age data, when age length keys are applied annually, is showing an indication of truncation of the right-hand limb. The paucity of otoliths each year makes annual age length keys uncertain, and is seen as a

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[5] Yield estimates are calculated by projecting the estimated current status under a constant catch assumption, using the decision rules:

1. Choose a yield, 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% (the depletion probability);
2. Choose a yield, γ_2, so that the median escapement in the *SSB* at the end of a 35 year period is 50% of the median pre-exploitation level (the level of escapement); and
3. Select the lower of γ_1 and γ_2 as the yield.

In the models, the depletion probability was calculated as the proportion of samples from the Bayesian posterior where the predicted future spawning stock biomass (*SSB*) was below 20% of B_0 in that respective sample in any one year, for each year over a 35-year projected period. The level of escapement was calculated as the proportion of samples from the Bayesian posterior where the predicted future status of the *SSB* was below 50% of B_0 in that respective sample at the end of a 35-year projected period.

	priority work to improve upon. There has been no change in the sex ratio in this fishery.

Projections and Prognosis	
Stock Projections or Prognosis	-
Probability of Current Catch or TACC causing Biomass to remain below or to decline below Limits	Unknown
Probability of Current Catch or TACC causing Overfishing to continue or to commence	N/A (no defined reference level)

Assessment Methodology and Evaluation		
Assessment Type	Level 2 – Partial Quantitative Stock Assessment	
Assessment Method	Tag based or CPUE based biomass estimate multiplied by exploitation rate	
Assessment Dates	Latest assessment Plenary publication year: 2024	Next assessment: 2025
Overall assessment quality rank	2 – Medium or Mixed Quality for the north and 3 – Low Quality for the south	
Main data inputs (rank)	- Multi-year tag-recapture data (north)	1 – High Quality
	- Multi-year tag-recapture data (south)	3 – Low Quality
	- Commercial catch-at-age proportions (north)	1 – High Quality
	- Commercial catch-at-age proportions (south)	3 – Low Quality
	- Catch at age from annual age length keys where possible (north)	1 – High Quality
	- Catch at age from annual age length keys where possible (south)	3 – Low Quality
Data not used (rank)	Commercial CPUE	3 – Low Quality
Changes to Model Structure and Assumptions	- A two-area model has been developed and requires further data to index the south area biomass. - A research plan was set in place in the south to increase knowledge about the biomass in this area.	
Major Sources of Uncertainty	- the estimate of biomass for SSRUs 88.2C–H is extremely uncertain because it assumes homogenous mixing of tags within the population (i.e. fish which leave the north are available for recapture in the south) - no separate assessment or estimate of abundance currently available for the southern area (SSRUs 88.2C–G) and this is the priority for further work - estimates of initial mortality of tagged fish - detection rates of tagged fish - natural mortality rate - stock structure and migration patterns, stock-recruit steepness - natal fidelity assumptions with respect to other areas	

Qualifying Comments
At its 2023 meeting, the CCAMLR Scientific Committee recommended the catch limits that were set using CCAMLR's trend analysis rule algorithm (SC-CAMLR-42 table 4).

Fishery Interactions
Main bycatch species are macrourids and rajids for which there are catch limits and move-on rules. Rajids can be released alive.

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