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Antarctic Deepwater fisheries

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Brief overview of deep-water stocks and fisheries, fisheries description, history and development

Antarctic fisheries are limited to four species, two of which live in deep water; Patagonian toothfish and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni* respectively). The others, namely krill (*Euphausia superba*) and icefish (*Champsocephalus gunnari*), are primarily pelagic fisheries. Icefish are restricted to shelves and depths shallower than 400m, and krill are found in their highest densities over shelf breaks with significant proportions of their populations living in upper surface waters (<300m depth) waters over shelves and open ocean (Nicol and Endo 1997).

Toothfish is long-lived and slow growing, reaching 2m in length. Both species mature late (about age 10 in Patagonian toothfish, age 14 in Antarctic toothfish; CCAMLR, 2009). Toothfish are mostly piscivorous, although squid and deepwater shrimp may also be eaten (Permitin and Tarverdiyeva 1972). They shows strong depth stratification, with larger animals occurring at deeper depths (Agnew 1999), and are typically found between 200 and 2000m on continental shelf slopes around South America and the sub-Antarctic Islands (although toothfish do occur and have been caught at depths of up to 3000m (SC-CAMLR 1995)). Young animals may be found as shallow as 50m on the continental shelf itself. *Dissostichus mawsoni* (Antarctic toothfish) occurs further south than *D. eleginoides*, being generally restricted to Antarctic waters south of 65°S.

Toothfish are found throughout the CCAMLR Convention Area (Figure 1) on continental shelves, sub-Antarctic Islands or seamounts. The number of self-contained stocks/populations is not known, although genetic studies suggest some distinct major stocks (Smith and McVeagh 2000; Smith and Gaffney 2000; Appleyard, Ward, and Williams 2002; Shaw, Arkhipkin, and Al-Khairulla 2004): 1) Patagonian toothfish on the Patagonian shelf; 2) Patagonian toothfish around South Georgia (Subarea 48.3) and the northern South Sandwich islands (Subarea 48.4); 3) Patagonian toothfish at Prince Edward and Marion Islands (Subarea 58.6/7); 4) Patagonian toothfish on the Kerguelen/Heard island plateau (Subarea 58.5); 5) Antarctic toothfish in the Ross Sea (Subarea 88.1/2).

The status or existence of other stocks is not clear, but there are small populations of Patagonian toothfish on Ob and Lena banks (Subarea 58.4.4), Crozet island (Subarea 58.6), south of Heard Island, north of the Ross Sea, and in the SEAFO area; and small populations of Antarctic toothfish in the south of the South Sandwich Islands and along the coastline of East Antarctica (Subarea 58.4.1/2), which are probably distinct stocks (Agnew et al. 2009; Roberts and Agnew 2009).

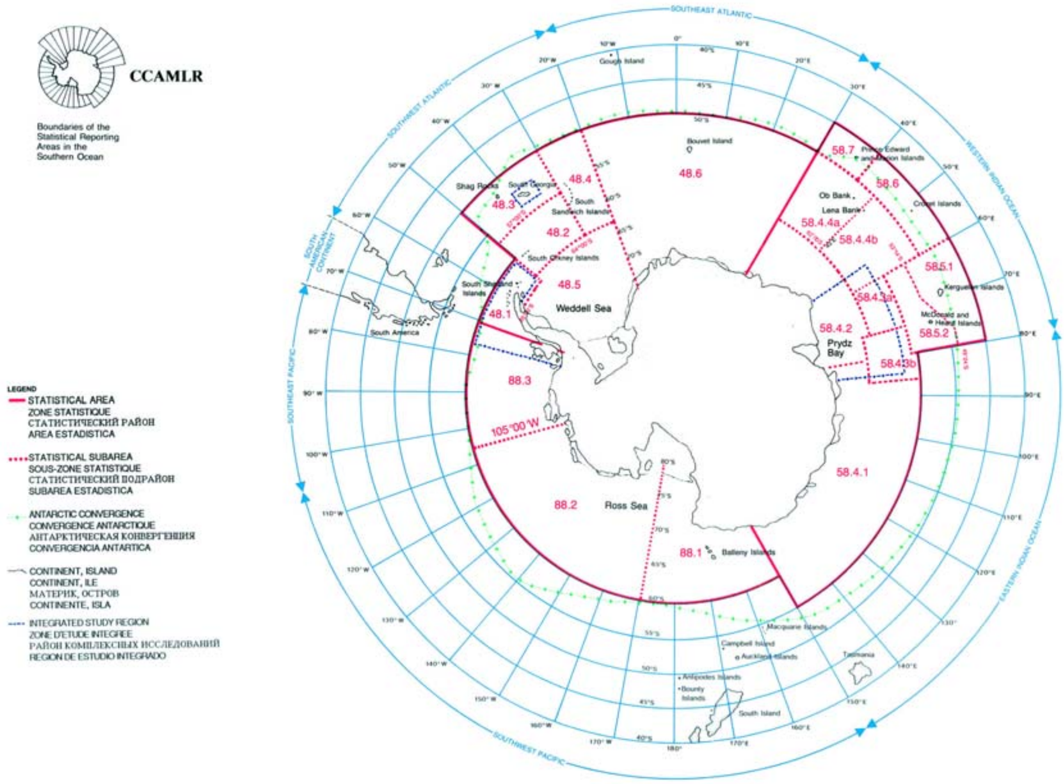

Figure 1. Map of CCAMLR convention area, with Subareas delineated in Red (CCAMLR).

The two principal methods of catching Patagonian toothfish are trawling and longlining. The methods differ in the size and quantity of fish caught. Trawlers are confined to fishing at relatively shallow depths and on fairly smooth grounds, and currently only operate around Heard Island catching primarily juvenile fish. Longliners operate in deeper water, 550m – 2000m (there is a general prohibition on fishing shallower than 550m in most areas of the Antarctic) targeting adults. Different gear configurations are used – Spanish system longlines, autolines and trot lines (Agnew 2004). Longliners tend to catch the larger fish in deeper waters - 1000 to 1500m. Bait is either squid or horse mackerel. Traps (pots) are also used occasionally, though with limited success.

Patagonian toothfish have been caught in the CCAMLR area, sometimes as bycatch, since the beginning of finfish harvesting in the 1970s. However large quantities were only taken with the development of longlining in the late 1980s. Exploitation developed serially around the Antarctic, being initiated in the late 1980s around South Georgia (Subarea 48.3) and shortly afterwards around Kerguelen Island (58.5.1). Toothfish stocks around these islands were plagued for much of the 1990s by illegal, unregulated and unreported (IUU) fishing. IUU fishing was a major problem at South Georgia until 1996, when within a period of about 3 months the IUU fishery transferred to the Southern Indian Ocean – most strongly around the sparsely patrolled Prince Edward and Crozet islands (Agnew and Kirkwood 2005; Green and Agnew 2002). Fishing on Antarctic toothfish in the Ross Sea (Subareas 88.1 and 88.2) did not start until the late 1990s, and remains an exploratory fishery in CCAMLR nomenclature. A designation as “exploratory” comes with requirement for prior notification and the undertaking of research/observer activities (although for most other fisheries vessels are also required to undertake research and have observers).

To the end of the 2008/09 fishing season a total of 400,000 t had been taken from CCAMLR waters, 33% by IUU fishing. The annual licensed catch from assessed fisheries (i.e. all non-exploratory fisheries plus the Ross Sea) is about 14,000 t.

Table 1. Reported (licensed) and IUU catch (tonnes) from the three major ocean sectors of the Antarctic (SC-CAMLR 2009).

	Atlantic sector (Area 48)		Indian Ocean sector (Area 58)		Pacific sector (Area 88)		Total	
	Licensed	IUU	Licensed	IUU	Licensed	IUU	Licensed	IUU
1985	521	0	0	0	0	0	521	0
1986	733	0	0	0	0	0	733	0
1987	1954	0	488	0	0	0	2442	0
1988	876	0	913	0	0	0	1789	0
1989	7060	144	1311	0	0	0	8371	144
1990	6785	437	1243	0	0	0	8028	437
1991	1756	1775	3008	0	0	0	4764	1775
1992	3839	3066	7759	0	0	0	11598	3066
1993	3030	4019	3597	0	0	0	6627	4019
1994	658	4780	5437	0	0	0	6095	4780
1995	3371	1674	5711	0	0	0	9082	1674
1996	3602	0	5655	13666	0	0	9257	13666
1997	3812	0	8645	32673	0	0	12457	32673
1998	3201	146	10169	14960	42	0	13412	15106
1999	3627	667	9730	5201	297	0	13654	5868
2000	4904	1015	11972	6629	751	0	17627	7644
2001	4047	196	9097	8606	660	0	13804	8802
2002	5742	3	8233	11467	1366	92	15341	11562
2003	7528	0	9087	7422	1937	0	18552	7422
2004	4504	0	8836	1938	2572	240	15912	2178
2005	3112	23	9658	2024	3516	23	16286	2070
2006	3717	0	9666	3069	3483	15	16866	3084
2007	3705	0	9227	3615	3438	0	16370	3615
2008	3986	0	8953	982	2675	186	15614	1168
2009	3798	0	6458	938	2918	0	13174	938

Management of CCAMLR fisheries also involves the mitigation of detrimental ecosystem interactions. Restrictions on fishing that limit the interaction with seabirds provides a good example of how this has been achieved (Kock 2001). Setting of fast-sinking lines at night, seabird scaring devices, restrictions on offal discharge and avoidance of areas where seabird interactions are high, have essentially eliminated seabird bycatch in the regulated fishery. The CCAMLR convention has also ensured measures exist to limit damage to the benthic ecosystem (CCAMLR 2009). Bottom trawling is prohibited in the high seas of the CCAMLR convention area (and currently only takes place around Heard Island), as is all bottom fishing in waters shallower than 550 m around the entire Antarctic continent. Protected areas also exist. For example, fishing for all finfish is prohibited around the Antarctic Peninsula and the South Orkney Islands to protect finfish stocks that were depleted prior to the establishment of CCAMLR. In addition to these restrictions, a trigger mechanism is imposed on bottom fishing vessels: if the catch rate of benthic organisms exceeds the threshold, the vessel is required to complete its fishing operation and move to another area. The location of regions where the trigger has been activated can then be used to inform future spatial management measures designed to protect the most vulnerable benthic regions.

Monitoring and assessment methods

A fairly standard suite of monitoring methods – demersal trawl surveys, commercial CPUE, scientific observer data – are augmented with mark-recapture data from tagging. Only recently have tagging data become available, and prior to this the assessment of toothfish, as for any deep water species, was difficult.

Early attempts at assessments of toothfish used local depletions of CPUE (i.e. local deLury methods) to arrive at estimates of local density. They also used literature-based estimates of attraction distance to estimate densities based on the catch rate of the baited commercial longlines. The first comprehensive attempt to estimate toothfish stock size and sustainable exploitable biomass was made in 1992 (SC-CAMLR 1992) for the South Georgia stock. The estimates of growth rate at this time were similar to current estimates of growth rate, except for L^{inf}, which was estimated to be much higher (210cm) than it is today (135cm). Natural mortality was estimated at 0.13, the same as it is today. However the estimates of biomass were very uncertain, and a depletion experiment conducted in 1994 demonstrated that this method was not reliable (Parkes et al. 1996). For this year, and all subsequent years, international scientific observers were required on all vessels, an aspect of this fishery which has considerably improved data quality and availability.

A special workshop on toothfish assessment methods was held in 1995, and recommended two major developments: 1) standardisation of CPUE series using generalised linear models to account for depth and month, as well as other less important factors such as bait type and soak time; 2) demersal trawl surveys of shelf areas to estimate the abundance of pre-recruits. The latter takes advantage of the life history of toothfish, which includes pelagic egg and larval stages (that are rarely observed (Evseenko, Kock, and Nevinsky 1995)). After hatching, the larvae appear to move inshore over the shelf, grow rapidly, moving closer inshore until as juveniles they leave the surface waters and become demersal (North 2002).

From 1995 to 2003 assessments of toothfish at South Georgia and Heard Island incorporated their respective shelf surveys of juvenile toothfish and calculated constant future yields that satisfied the CCAMLR decision rules (see later) using a stochastic projection methodology incorporating uncertainty in natural mortality (Constable et al. 2000). Developments during this period were focussed on refining the estimates of recruitment; because reliable methods of determining age of toothfish from otoliths had not yet been developed, recruitment estimates were dependent upon use of a mixture analysis of length density data (De la Mare 1994).

The essential problem with using survey data for juvenile abundance estimation is the very high variability of the estimates, caused by the highly patchy distribution of juvenile toothfish. Moreover even adult toothfish appear to have a bentho-pelagic lifestyle (Yukhov 1982; Williams et al. 2002), so that bottom trawl surveys are very inefficient at sampling them. Furthermore, these methods required the ability to undertake bottom trawl surveys on shelf distributions of juvenile toothfish, which was possible in only a very few areas where toothfish populations were being fished (South Georgia, Kerguelen and Heard islands). In other areas, including the Ross Sea, the pre-recruits are inaccessible to trawl surveys.

Although the method of assessing toothfish based on survey estimates of recruitment abundance continued to be used for several years, for instance at Heard Island, in the mid-2000s there was a move away from this method, because of its high levels of uncertainty and inapplicability for some stocks of toothfish, towards the use of tagging data. Experiments on tagging toothfish had started in 2000, and with some surprise it was discovered that toothfish are relatively robust to tagging. Even though they are often recovered for tagging from 1500m depth, their lack of a swim bladder and their apparently regular vertical migrations means that they do not suffer serious traumatic shock, and though they may be effectively blind for a few weeks their survival is estimated at greater than 90% (Agnew et al. 2006). Since this discovery mark-recapture programmes have become the mainstay of the observations used in assessments, although because toothfish appear to move very little (Marlow et al. 2003) mixing must be undertaken physically by vessels. Tagging is eased in CCAMLR because of the presence on board each vessel of one scientific observer, and in exploratory high latitude fisheries of two observers.

Current assessment methods for the well-studied stocks – South Georgia, Heard Island and the Ross Sea - use an integrated age-structured model (CASAL (Bull et al. 2005)) that are based on data on catches at length and age, survey catches at length and age, standardised CPUE trends and mark-recapture data to estimate stock size with Bayesian estimation of parameter uncertainty (Hillary, Kirkwood, and Agnew 2006). These methods produce consistent, relatively robust estimates of stock size, although the complexity of the estimation model may be large (Candy and Constable 2008). Difficulties with these assessments remain in a number of areas, for instance the correct estimation of natural mortality, and the difficulty of integrating tag-recapture data from widely different fleets in an international mixed fishery, but the essential method appears to be quite reliable given a good understanding of the required model structure.

There remain a number of fishing areas, however, where "mature" assessments of the type described above are not yet possible. In these, a range of different approaches are used. For instance, in Kerguelen the assessment is based on simple monitoring of biomass trends from a deep water survey, made possible by the relatively fishable grounds around that island (SC-CAMLR 2007). On the coast of East Antarctica the mark-recapture experiment appears to be failing, for reasons that are not known, and CCAMLR has resorted to estimates based on local depletions and the comparison of CPUE from vessels fishing in this area and the well-assessed Ross Sea

(Agnew et al. 2009). On Banzare bank (the Southern Indian Ocean sector) local depletion methods have been used (McKinlay et al. 2008). Although these methods are acknowledged to be inaccurate, and to have failed in some areas in the past, these important fishing areas lack either juvenile trawl surveys, or reliable mark-recapture data from which to make alternative stock estimates. Furthermore, CCAMLR generally applies a very high level of precaution to interpreting the results of these alternative assessment methods and determining sustainable yields.

The apparently successful methods of assessment of toothfish used by CCAMLR may not be easily transferable to other deep water stocks. CCAMLR is fortunate that toothfish survive tagging so well; that all vessels have well trained scientific observers on board; and that juvenile toothfish live on continental shelves accessible to demersal research surveys (although not all toothfish stocks appear to have easily accessible shelf recruitment areas, and as noted above juveniles are not necessarily obligate demersals).

Review of management methods (include HCRs and BRPs): a brief description of each, information required, strengths and weaknesses.

The foundation of the harvest control rules used by CCAMLR is set within Article II (3) of the convention:

> Article II (3). Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provisions of this Convention and with the following principles of conservation:
> (a) prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size should not be allowed to fall below a level close to that which ensures the greatest net annual increment;
> (b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and (c) prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of the introduction of alien species, the effects of associated activities on the marine ecosystem and of the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine living resources.

Discussions on how to embrace the objectives set out in Article II arose during early meetings of the Scientific Committee (about 1985; (Constable et al. 2000)) but it was not until 1991 that a framework expressed explicitly in terms of precaution and uncertainty were accepted, initially for managing the krill fishery. The harvest control rule was expressed, for krill, as a three part rule based on a constant harvest rate γ, determined as a proportion of an estimate of the pre-exploitation biomass (B^0):

(i) choose γ_1 so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period is 10%;
(ii) choose γ_2 so that the median krill escapement in the spawning biomass over a 20-year period is 75% of the pre-exploitation median level; and
(iii) select the lower of γ_1 and γ_2 as the level for calculation of krill yield.

The first part is thought of in CCAMLR as a "recruitment criterion" corresponding to the requirements of Article II (3) (a), and the 20% B^0 level as an effective limit reference point. The second part is thought of in CCAMLR as a "predator criterion", corresponding to the requirements of Article II (3) (b), and the 75% B^0 level as an effective target reference point. CCAMLR chose 75% as a compromise point, between what would be considered appropriate in a single-species context (taken, with precaution, by CCAMLR to be 50% B^0) and what would be the case in the absence of fishing (i.e. 100% B^0). The time period over which evaluation is undertaken (20 years for krill) corresponds to the requirements of Article II (3) (c).

In the early 1990s, when standard stock assessment approaches were being applied to toothfish, standard calculations of yield were also made, using $F_{0.1}$ as the target reference point. In 1995, when for the first time the assessment was conducted using the general yield model, a harvest control rule based on the CCAMLR decision rules (above) was applied, although at that time only part (i) was used. In 1996 and subsequent years parts (ii) and (iii) were also applied, but with a modification to ensure that escapement was 50% of the pre-exploitation median level, appropriate to a single species context with precaution. This was considered to be relevant for toothfish because the species has relatively few predators (Agnew, 2004). Adherence to the CCAMLR criteria was ensured through a process of simulation, whereby the stock is projected forward under constant values of γ_1 and γ_2.

Application of the same harvest control rule for the main assessed stocks (South Georgia; Heard Island; Ross Sea) has been continuous from 1996, even though the underlying assessment methodology has changed. From 1996 to 2007 assessments were conducted annually, thereafter only every two years. A different harvest control rule is applied to the Prince Edward Islands (South Africa), which has nevertheless been evaluated by extensive simulation in light of its performance against the CCAMLR criteria (Brandao and Butterworth 2009). Management of Kerguelen and Crozet Islands (France) remains opaque.

For each stock where the harvest control rule is applied, the TAC is allocated to vessels either licensed with the sovereign state or registered directly with CCAMLR (when fishing in international waters). It is only when the stock lies with the exclusive economic zone of a particular state that enforcement is possible, making illegal activity a continual threat. Indeed, this unregulated fishing has likely contributed to failure of tagging experiments in exploratory fisheries on the Eastern shelf of Antarctica (Agnew et al. 2009), where the IUU catch is equivalent to that taken by the legal fishery.

Most assessed stocks are above their target reference points (50% B^0 – Table 2), with the exception of Prince Edward Islands, which have been subjected to heavy illegal fishing. The applied management framework can thus far be considered successful. However there is still potential for improvement. Recent developments of the assessment to include survey data as indices of recruitment at age, and the incorporation of catch at age rather than catch at length data in the CASAL model (Agnew and Belchier 2009; Agnew and Peatman 2009), allow for relatively accurate estimation of cohort strength. This suggests the possibility of deviation from the constant-catch methodology to account for variations in the size of cohorts as they enter the fishery.

Table 2. Summary of the status of stocks in CCAMLR waters (SC-CAMLR 2009). ICAA: Integrated catch at age model; ICAL: Integrated catch at length model. In all cases these were implemented using CASAL (Bull et al. 2005). SPM: surplus production model.

Stock	Location	Species	Assessment	Depletion (B/B^0)
48.3	South Georgia	*D. eleginoides*	ICAA/L	0.61
48.4	South Sandwich Islands	*Dissostichus spp.*	ICAL	1.09
58.5.1	Kerguelen	*D. eleginoides*	None	-
58.5.2	Heard Island	*D. eleginoides*	ICAA/L	0.63
58.6	Crozet Islands	*D. eleginoides*	None	-
58.6/7	Prince Edward Islands	*D. eleginoides*	ICAL	0.37
Exploratory fisheries				
48.6	-	*Dissostichus spp.*	None	-
58.4.1/2	-	*Dissostichus spp.*	Preliminary	None
58.4.3a	Elan Bank	*Dissostichus spp.*	SPM	0.95
58.4.3b	Banzare Bank	*Dissostichus spp.*	None	-
88.1/88.2	Ross Sea	*Dissostichus spp.*	ICAL	0.80

The success of CCAMLR's approach can perhaps be measured by the number of fisheries that have been assessed and certified as sustainable by the Marine Stewardship Council. Certified deepwater fisheries include South Georgia Toothfish (certified 2004, recertified with no conditions 2009) and Ross Sea Toothfish (under recommendation for certification, as of February 2010).

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