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Title **Medium-term research plan for the Ross Sea toothfish fishery**

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Abstract

The aim of this paper is to review the management of the Ross Sea toothfish fishery and to identify key research objectives for the fishery over the next 3–5 years in relation to Article II of the Convention. The paper focuses primarily on Antarctic toothfish, as catches of Patagonian toothfish are negligible, and covers Subarea 88.1 and Subarea 88.2 SSRUs 88.2A and B. We begin by briefly summarising the management and operation of the fishery up to and including the 2012/13 fishing year. This includes the 3-year experiment from 2005/06 to 2007/08, the further development of the CCAMLR tagging programme and associated requirements, and other changes to the management of the fishery. We then identify uncertainties in our current knowledge that need to be addressed to fulfil the requirements of Article II. These include, for example, uncertainty in the biological parameters and stock assessment of Antarctic toothfish, uncertainty in its ecological relationships with predators and prey, and uncertainty over other ecosystem effects of fishing which can be addressed over the short to medium term. However, the need to further develop Management Strategy Evaluation and Management Procedures for the toothfish fishery in the medium-long term is also recognised. The purpose of this paper is to begin the discussion on medium-term research objectives for the Ross Sea fishery and the development of a medium-term research plan which could be adopted by the Scientific Committee.

Medium-term research plan for the Ross Sea toothfish fishery

EXECUTIVE SUMMARY

The following is a summary of the research objectives identified in this medium-term research plan for the Ross Sea toothfish fishery.

Maintenance of the Antarctic toothfish population in the Ross Sea region above target levels

(a) Reduce uncertainty in toothfish model parameters

(i) To spatially and temporally delineate toothfish spawning grounds.
(ii) To delineate stock structure – especially in relation to SSRUs 88.2C-I.
(iii) To define and quantify fine-scale movement patterns, including by size and sex.
(iv) To improve estimates of initial (and longer-term tagging) mortality, and tag detection.
(v) To continue monitoring the relative abundance of sub-adults and to estimate recruitment variability and autocorrelation.
(vi) To monitor key population-level parameters (e.g., growth, age/length at maturity, sex ratio) which could potentially be affected by fishing.

(b) Reduce management uncertainty

(i) To continue to improve the stock assessment (e.g., improve diagnostics, estimation of year class strength etc).
(ii) To develop simple stock performance indicators / dashboard.
(iii) To develop prioritised list of MSE scenarios and begin MSE testing of high priority issues (e.g., alternative model parameters, spatial management, movement and stock assumptions etc).
(iv) To continue development of operating models as additional tag and fishery data are collected, through improved predictive layers (e.g., ice coverage), and better knowledge of life cycle.

Maintenance of ecosystem structure and function

(i) To determine the temporal and spatial extent of the overlap in the distribution of toothfish and its key predators (in particular killer whales and Weddell seals).
(ii) To investigate the abundance, foraging ecology, habitat use, functional importance and resilience of key toothfish predators (in particular killer whales and Weddell seals).
(iii) To develop methods of monitoring changes in relative abundance of key prey / bycatch species (in particular macrourids and icefish) on the Ross Sea slope and hence assess the potential impact of the toothfish fishery on these species.
(iv) To monitor diet of toothfish in key areas, especially on the Ross Sea slope.
(v) To simulate the effect of the fishery on populations of toothfish, its predators, and its prey (using Minimum Realistic Models or similar).
(vi) To develop quantitative and testable hypotheses as to the "second-order" effects (such as trophic cascades, regime shift) and ensure data collection is adequate to monitor for any risks deemed reasonable.
(vii) To assess the impact of the toothfish fishery on Patagonian toothfish.
(viii) To estimate survivorship of released skates.
(ix) To develop semi-quantitative and spatially explicit risk assessments for macrourids and Antarctic skates (*A. georgiana*), especially in the slope fishery of the Ross Sea.
(x) To develop methods to assess whether the potential impacts of the toothfish fishery on the ecosystem are likely to be reversible in two to three decades.

1. INTRODUCTION

The exploratory toothfish longline fishery in the Ross Sea region was started in 1996/97. The fishery initially developed slowly, but there was a doubling of effort, in terms of numbers of vessels and sets, in 2000/01 and again in 2003/04. The catch limit was reached for the first time in 2004/05, which also coincided with the year of the first independent assessment of the Antarctic toothfish (*D. mawsoni*) stock based on tag-recapture data. In response to difficulties experienced in the day-to-day management of the fishery by the Secretariat and in the prosecution of the fishery by fishers, and to improve the usefulness of the information coming from the fishery, a number of changes in the management of the fishery were proposed at the 2005 CCAMLR meeting. These changes, which included amalgamation of catch limits across Small Scale Research Units (SSRUs), the introduction of open/closed SSRUs, the removal of the requirement for prescribed geographical separations and minimum and maximum hook numbers for research sets, and research allocations for closed SSRUs, were agreed on the basis that they would form the basis of an experiment which would run for a period of three years until the end of the 2007/08 fishing year. The Scientific Committee considered that after this time, there would be better understanding of how to gain the information necessary to establish catch limits in other areas of the Ross Sea (SC-CAMLR XXIV para. 4.163)

At the end of its three year period, the NZ Delegation (2008) and SC-CAMLR-XXVII reviewed the results of the experiment with respect to the fishing activity, the day-to-day management of the fishery, and the reduction of uncertainties in the stock assessment. As a result of that review, many of the management changes which had been implemented for the three-year experiment were retained, and several new ones introduced. The spatial management of the Ross Sea fishery has remained largely unchanged since the 2009 season (Figure 1).

At its 2010 meeting, the Scientific Committee noted that the research and assessment work in Subarea 88.1 on the distribution, abundance and demography of Antarctic toothfish resulted in an estimate of the fisheries potential yield, and allowed the CCAMLR Scientific Committee to formulate and provide advice to the Commission on appropriate harvest levels and other aspects of conservation over the last eight years (SC-CAMLR-XXIX, para. 3.129). Although robust stock assessments are now available, there is still some uncertainty over aspects of Antarctic toothfish biology and ecology including early life history, spawning dynamics, distribution and abundance of Antarctic toothfish in areas within the Ross Sea region which have not been fished, as well as regarding potential effects of fishing on the ecosystem (Abrams 2014, Mormede et al. 2013b, Parker & Marriott 2012, Pinkerton & Bradford-Grieve 2014).

An important aspect of the management of the Ross Sea fishery has been its spatial management, and in particular areas closed to fishing. An integral part of the 3-year experiment was the establishment of open and closed SSRUs that allowed two things: (i) the concentration of fishing effort so that the tagging programme was more effective and (ii) unfished 'control' areas where the effects of fishing could be investigated (SC-CAMLR-XXVII). There has been ongoing concern expressed by some members over the continued closure of these SSRUs because of the lack of information on Antarctic toothfish biology and ecology coming from these areas (e.g., SC-CAMLR-XXXII, para 3.154). During the 2013 meeting of WG-FSA, there was a proposal to open SSRU 88.2A as part of an experiment to better understand movement of toothfish between the Ross Sea fishery and the rest of Subarea 88.2 (SC-CAMLR-XXXII, para 3.154). At the same time, WG-FSA noted that catch limits for the Ross Sea fishery are managed under two conservation measures (CMs 41-09 and 41-10) and recommended that the boundary between Subareas 88.1 and 88.2 be revised or that the scope of CMs 41-09 and 41-10 be revised such that the Ross Sea Region (Subarea 88.1 and SSRU 882A–B) is managed within a single conservation measure (SC-CAMLR-XXXII, Annex 6, para 4.80). Although both of these proposals were generally supported by the

Scientific Committee (SC-CAMLR-XXXII paras 3.155–3.160), the Commission was unable to reach consensus on the boundary change between these two CMs, and so the current catch limit for SSRU 88.2A remained at 0 tonnes.

Discussions pertaining to the spatial management of the Ross Sea fishery are also particularly relevant in the context of recent proposals for a Marine Protected Area in the Ross Sea region (most recently CCAMLR-XXXIII/21). In developing this paper, we have not considered explicitly the MPA proposal for the Ross Sea region.

In considering the future management of the fishery, it is important to consider the long-term goals of the fishery management in relation to Article II of the Convention. To address those long-term goals, we identify key medium-term research objectives that need to be achieved over the next 3–5 years. To achieve these objectives and long-term goals will require a detailed research plan and associated data collection plans. The purpose of this paper is to begin discussion of medium-term research objectives for the Ross Sea fishery and the development of a medium-term research plan for this fishery that could be formally adopted by the Scientific Committee. The paper focuses primarily on Antarctic toothfish (as catches of Patagonian toothfish are negligible) and covers Subarea 88.1 and Subarea 88.2 SSRUs 88.2A and B.

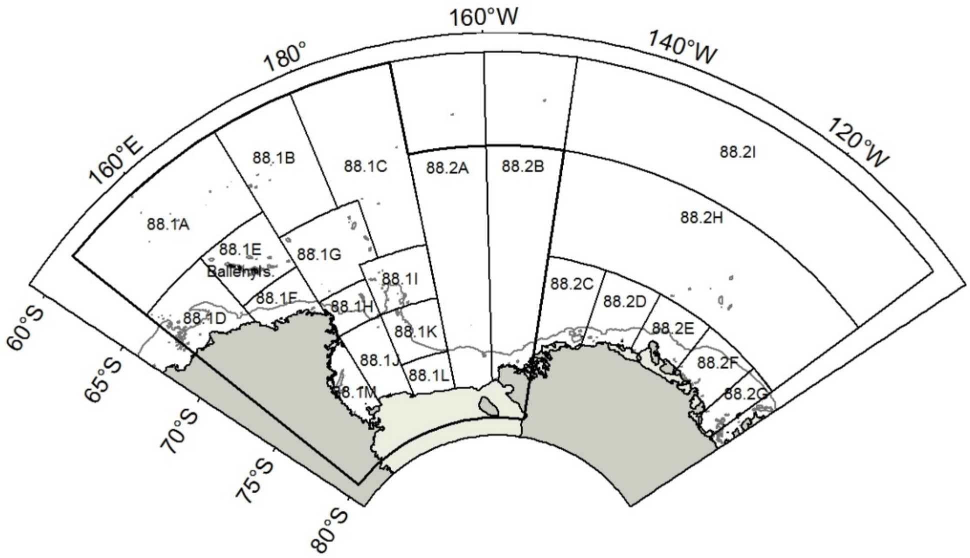

Figure 1: CCAMLR Subareas 88.1 and 88.2, and the small scale research units (SSRUs) used since 2012. Depth contour plotted at 1000 m.

2. HISTORY OF THE TOOTHFISH FISHERY UP TO 2012/13

2.1 Operational management of the fishery

2.1.1 Spatial management of the fishery

An annual catch limit has been set for *Dissostichus* spp. in Subareas 88.1 and 88.2 since 1997. In the first three years of the fishery, separate limits for *Dissostichus* spp. were set for north and south of 65ºS. Since 2000, the catches in the Ross Sea fishery have been managed and reported by small scale research units (SSRUs), but the number and location of these SSRUs have changed considerably over time. For the 2000 to 2003 seasons, the area south of 65ºS was divided into four SSRUs and the catch limit divided equally amongst them (Figure 2a). To ensure a reasonable spread of effort within SSRUs, vessels were required to carry out a requisite number of research hauls each separated by a minimum distance, and were restricted to a maximum catch of 100 t in any Fine Scale Rectangle (FSR, an area of 0.5º latitude by 1º longitude). For the 2004 and 2005 seasons, Subarea 88.1 was divided into twelve SSRUs based on similarities in bathymetry and ecology (Figure 2b), and the total catch limit subdivided amongst SSRUs based on fishable seabed area and historical CPUE (Figure 2b). For these two seasons SSRUs 88.1A, 88.1D, and 88.1F had zero catch limits and the catch limit on FSRs was removed.

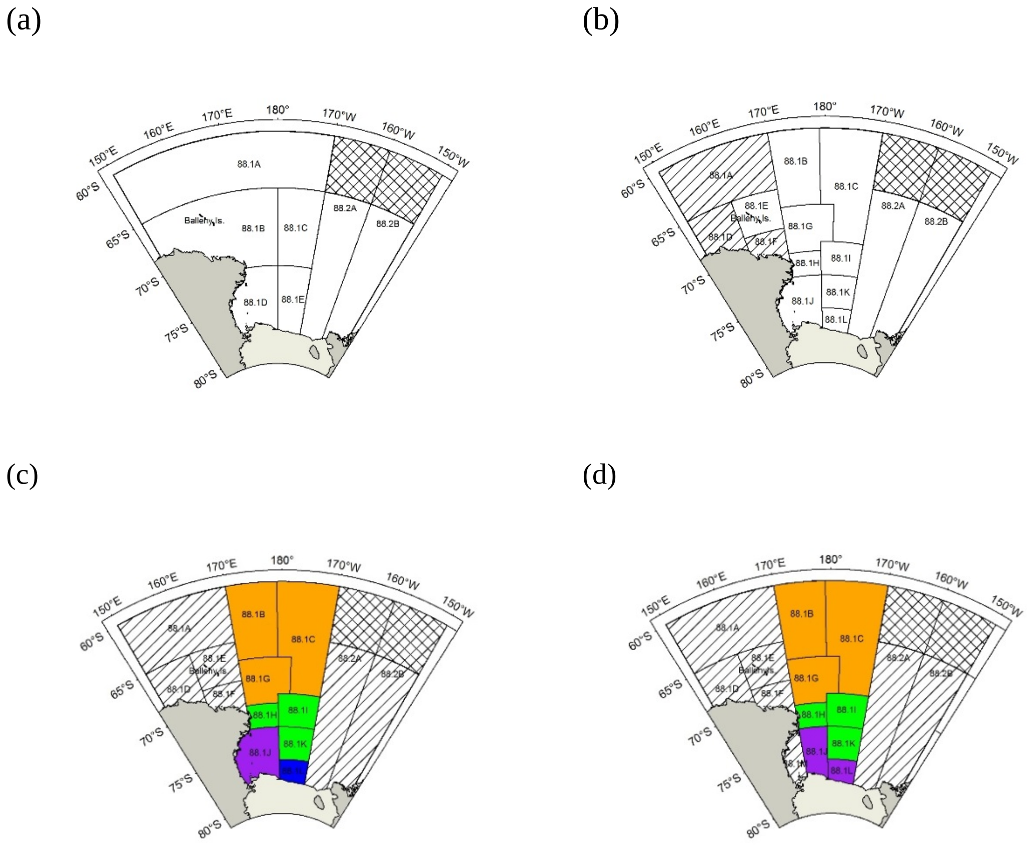

Figure 2: SSRU boundaries used for managing the exploratory toothfish fishery in Subareas 88.1 and 88.2 for (a) 2000 to 2003, (b) 2004 to 2005, and (c) 2006 to 2008, and (d) 2009 to 2013. Dashed hatching represents areas where fishing is prohibited by CM32-15), solid hatching represents SSRUs with zero catch limits (these were subject to a research exemption of 10 t from 2006 to 2008 (CM41/09), and colour shading represents SSRUs amalgamated for management. The area defined and assessed as the Ross Sea fishery since 2006 is bounded in bold.

The management of the SSRUs within the two subareas was changed as part of a 3-year experiment starting with the 2006 season (SC-CAMLR-XXIV) and the Ross Sea fishery was defined as the whole of Subarea 88.1 as well as Subarea 88.2 SSRUs 88.2A and 88.2B. As part of the experiment, the TACs for SSRUs 88.1A, 88.1D, 88.1E, 88.1F, 88.2A, and 88.2B were set to zero to ensure that effort was retained in the area of the experiment (Figure 2c). To improve administration of the SSRUs, the catch limits for SSRUs 88.1B, 88.1C, and 88.1G were amalgamated into a 'north' region and those for SSRUs 88.1H, 88.1I, and 88.1K were amalgamated into a 'slope' region. Despite A nominal research catch of up to 10 t was allowed in each SSRU with a zero TAC, in addition to the other research catch limits under the research fishing exemption. The 3-year experiment was reviewed in 2008 (New Zealand Delegation, 2008) and several new management measures were implemented for the 2009 season (SC-CAMLR-XXVII, para. 4.160) including: (i) the provision for a nominal catch of 10 t for the SSRUs with zero TACs was removed and the 60 t research catch was absorbed back into the total catch limit; (ii) a new SSRU was created in the western Ross Sea (SSRU 88.1M) for which the TAC was set at zero to protect an important corridor for movement of sub-adult toothfish moving between the shelf and north to spawn, and (iii) catch limits for SSRUs 88.1J and 88.1L were amalgamated into a 'shelf' region (Figure 2d). Since 2006, about 75% of the catch limit has been allocated to the Slope and the remaining 25% split equally between the North and Shelf.

2.1.2 Management of bycatch

Bycatch limits for *Macrourus* spp (macrourids) were introduced to all the exploratory fisheries in the 2002 season and bycatch limits for skates and rays (rajids), and for 'other species' were introduced in the 2003 season and are covered under CM 33-03. In the absence of other information, these catch limits were based on analogy to fisheries in other areas of the Southern Ocean and were usually a fixed proportion of the toothfish catch limit. The catch limits were originally applied at the SSRU level but as part of the 3-year experiment, they were amalgamated in the same way as the toothfish catch limits (see Section 2.1.1). The catch limit for macrourids on the slope was later refined based on the results of a trawl survey. Bycatch limits for macrourids were exceeded in a number of SSRUs during the early period of the fishery but since 2007 the total macrourid catch has always been less than 50% of the total macrourid catch limit. Rajids are required to be brought on board or alongside the hauler to be checked for tags and for their condition to be assessed. All rajids which are caught alive and with a high probability for survival are released alive at the surface, and any dead or injured skates are retained. The retained catch of rajids is very low and has never exceeded the catch limit but the survival of released skates is unknown (see also Section 3.4.1). The catch of other species is usually very low and has also never exceeded the catch limit.

To help prevent localised depletion of macrourids and rajids, "move-on" rules were introduced for all the exploratory fisheries in the 2001/02 season (CM 33-03). These rules require a vessel to move to another location at least 5 n. miles distant if the bycatch of any one species is equal to or greater than 1 tonne in any one set. An additional measure in CM 33-03 makes vessels responsible for managing their individual macrourid bycatch by penalising vessels exceeding a proportion of 16% of the macrourid catch to the catch of *Dissostichus* spp. Under this conservation measure, vessels are also requested to cut-off live skates at the surface as it has been shown through recoveries of tagged skates and skate survivorship experiments that many skates survive the capture event.

2.1.3 Other management measures

CCAMLR has a large number of other measures in place for managing the Ross Sea toothfish fishery. It is beyond the scope of this paper to document these measures, but they include a range of data collection and reporting requirements, move-on rules to avoid areas of high bycatch of invertebrates (CMs 22-06, 22-07), mitigation measures for seabirds (CMs 24-02, 25-02), Catch Documentation and Vessel Monitoring Schemes, and measures for Environmental Protection (see also CM 41-09 for further details).

2.2 Catch and effort in the fishery

Details of the exploratory toothfish fishery in the Ross Sea were characterised most recently by Hanchet et al. (2013a) and are summarised in Table 1 and Figures 3–4. The fishery saw a relatively steady expansion of effort from 1997 through to 2003, followed by a large increase to a peak of more than 2000 sets in 2004. Since then, effort has been slightly more stable ranging from 1000 to 1500 sets per year. The total catch of *D. mawsoni* has shown a steadier increasing trend, peaking at about 3000 tonnes between 2005 and 2007, before dropping to about 2 300 tonnes in 2008, and increasing again to about 3 200 tonnes in 2012 and 2013. These trends in catch have been driven largely by changes in the catch limit over this time consistent with scientific advice (Table 1). The number of vessels in the Ross Sea fishery peaked at 21 in 2004, was reasonably stable at 10–15 over the next eight years but then increased to 18 in 2013.

The spatial distribution of Antarctic toothfish catch summed across all years from 1997 to 2013 in Subareas 88.1 and 88.2 is shown in Figure 3. The location of toothfish catch in the Ross Sea fishery by SSRU over time is illustrated in Figure 4. The majority of the toothfish catch was taken in most years from SSRUs 88.1C, 88.1H, and 88.1I. However, in some years, when sea-ice conditions were favourable to fishing operations, a significant amount of the catch was also taken from SSRU 88.1K.

Table 1: Details of the toothfish fishery in the Ross Sea, which includes Subarea 88.1 and SSRUs 882A and 882B.

Year	Ross Sea			88.1
	No. of vessels	Number of sets	Catch (tonnes)	Catch limit (tonnes)
1997	1	2	<1	1 980
1998	1	82	41	1 980
1999	2	252	296	1 510
2000	3	480	752	2 281
2001	7	683	592	2 090
2002	2	432	1 355	2 064
2003	9	794	1 769	2 508
2004	21	2 160	2 178	3 760
2005	10	1 529	3 210	3 250
2006	13	1 040	2 967	2 964
2007	15	1 395	3 079	3 032
2008	15	1 012	2 250	2 660
2009	13	966	2 432	2 700
2010	12	1 068	2 868	2 850
2011	15	977	2 847	2 850
2012	15	1 092	3 199	3 282
2013	18	1 369	3 121	3 282

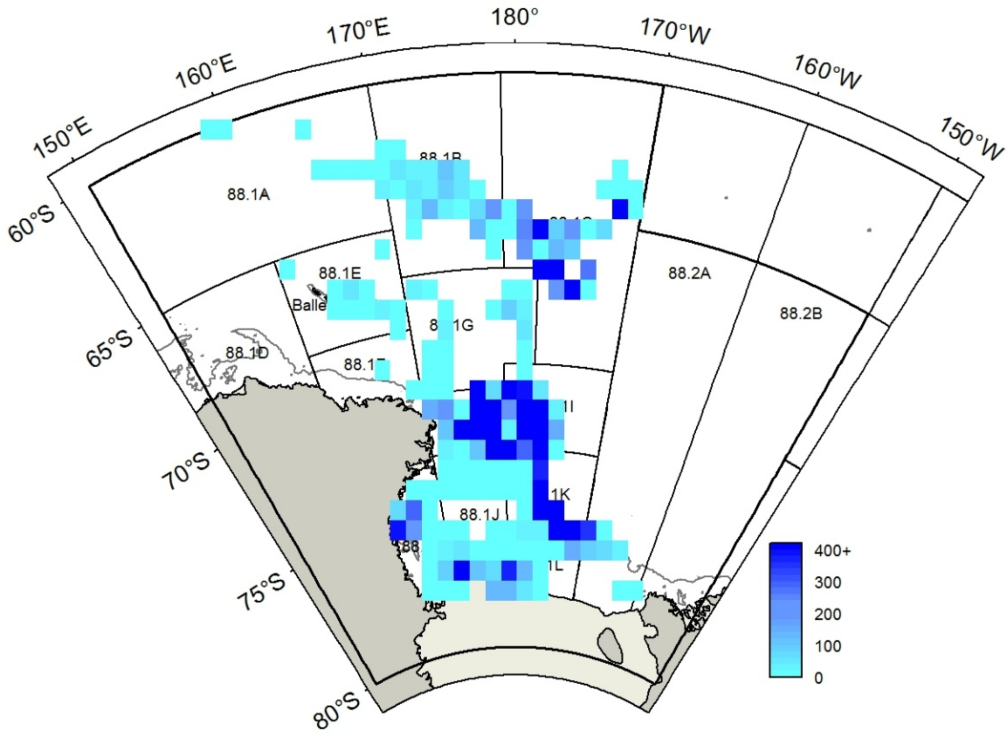

Figure 3: Spatial distribution of the cumulative historical catch (in tonnes) of *D. mawsoni* in 0.75° latitude by 1.5° longitude grid cells in the Ross Sea region.

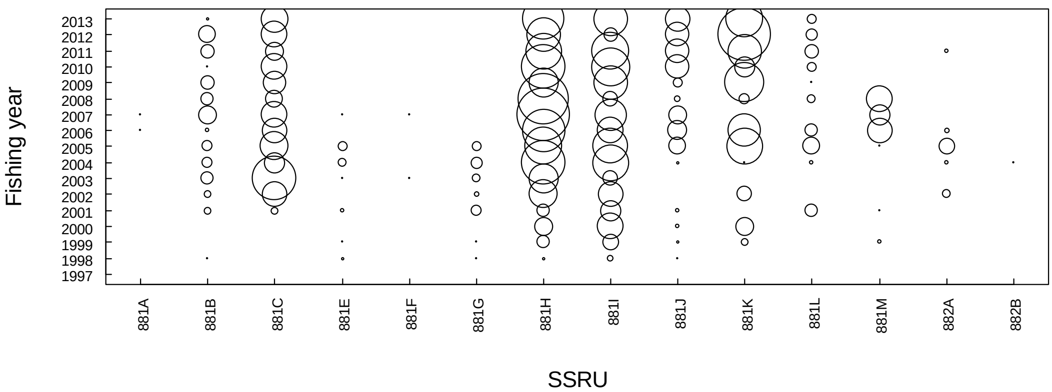

Figure 4: Annual pattern of catches for *D. mawsoni* by SSRU since 1997. The area of the circles is proportional to the maximum value which equals 1509 t. (Source Hanchet et al. 2013a)

3. DEVELOPMENT OF MEDIUM-TERM OBJECTIVES

In developing medium-term (5–7 year) objectives for the Ross Sea toothfish fishery the following questions were considered:

1. What are the long-term management goals for the fishery based on the requirements of Article II of the Convention?
2. Are we currently achieving those goals? If not, then what are the key areas of uncertainty which still need to be addressed?
3. What are the key research objectives that address those areas of uncertainty?

3.1 CCAMLR goals

The CCAMLR goals for all Antarctic fisheries are detailed in Article II of the Convention.

The three key goals are summarised below:

1. The size of the target fished population should not be decreased below a level which ensures 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.
2. The ecological relationships between harvested, dependent, and related populations are maintained.
3. Prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, including the direct and indirect impacts of harvesting, alien species, associated activities, and environmental change, with the aim of making possible the sustained conservation of Antarctic marine living resources

The management of the Ross Sea fishery was last reviewed in 2008 (NZ Delegation 2008, SC-CAMLR-XXVII). This paper reviewed progress to date which had been made towards achieving those goals, identified key sources of uncertainty, and the medium-term research required to address those uncertainties.

Over the past few years a number of papers have criticised the management of the Ross Sea fishery (e.g., Ainley et al. 2012, Abrams 2014). The Scientific Committee noted that although some of this criticism was due to a lack of understanding of CCAMLR science, there is always a need to continue to identify and address genuine concerns (SC-CAMLR-XXXII, paras 3.56–3.69). One of the main criticisms expressed in these papers is that lack of knowledge of toothfish population and ecosystem dynamics limit our ability to predict with any confidence the likely responses of the toothfish population and Ross Sea ecosystem to the harvesting of toothfish.

Hanchet et al. (in press) prepared a response to these papers from the wider CCAMLR community where they acknowledged that scientists will never understand ‘everything about everything’ related to marine ecosystem dynamics, but noted that this does not imply that successful, precautionary, well informed and science-based management systems cannot be, or have not been, developed. CCAMLR scientists have developed a range of approaches for considering uncertainty in stock assessments including sensitivity analyses, simulation studies, and precautionary decision rules. Since the adoption of the Precautionary Principle in Rio de Janeiro in 1992, Management Strategy Evaluation (MSE), also known as the Management Procedure (MP) approach when applied tactically to specific fisheries, has been acknowledged as best practice to test the robustness of existing or alternate management systems in the context of unavoidable uncertainties (Butterworth & Punt 1999, Butterworth 2007, De Oliveira et al. 2008). The MP approach involves simulation testing to ensure that the management processes being applied will achieve fishery sustainability despite the uncertainties, and as a part of this provide an appropriate trade-off between catches from, and conservation risk to, the resource under consideration. This robustness must hold not only for present best perceptions of the resource's dynamics and those of the associated ecosystem, but also for alternative scenarios that cover the range of uncertainties that are plausible and compatible with existing information.

Bearing this in mind, we have reviewed progress made on addressing uncertainties over the past five years and have identified medium-term research objectives required to achieve each of CCAMLR's goals. In general, we have focused on a limited number of tangible and achievable research objectives which will reduce uncertainty in key parameters and improve understanding of ecological relationships with predators and prey. However, we also recognise the need for further developing the MSE and MP approaches in the medium-term.

3.2 Maintenance of the Antarctic toothfish population in the Ross Sea region above target levels

This particular goal is ensured by regularly assessing the stock status of Antarctic toothfish, and then determining an appropriate level of catch consistent with the CCAMLR Decision Rules. An integrated stock assessment using CASAL was first endorsed by the Scientific Committee and the Commission in 2005. The most recent integrated stock assessment of Antarctic toothfish in the Ross Sea region was based on information from a mark-recapture program, which has been underway since 2003, and catch-at-age data. A spatially and temporally explicit algorithm has been developed to ensure that tag data from vessels reporting low recapture rates of other vessels' tags, or for which their released tags are rarely recaptured by other vessels (presumably reflecting variable tagging performance) are excluded from (Mormede & Dunn 2013a) or proportionally down-weighted (Mormede 2014) in the assessment. This resulted in an assessment based on the release of 24 000 tagged toothfish and 1200 recaptures (Mormede et al. 2013a). Current spawning stock biomass is estimated to be at 75% of the pre-exploitation level (95% Bayesian probability interval 71% – 78%), which is still well above the target reference point of 50% of the pre-exploitation level defined in the CCAMLR Decision Rules. This range reflects statistical rather than structural uncertainty; other analyses conducted outside the stock assessment model (i.e. using spatial population models, see below) suggest that structural biases in the current model are precautionary, such that actual stock status is likely to be higher than indicated by this range. So the management of the fishery is clearly meeting its goals with respect to the target levels.

To ensure that there was a high degree of certainty that the toothfish population was maintained at or above the target levels, the following research priorities were recommended in 2008 (NZ Delegation 2008):

(i) Reduce uncertainty in life history and stock structure
(ii) Reduce uncertainty in biological and model parameters
(iii) Reduce bias in stock assessment due to non-mixing of tags
(iv) Develop a Management Strategy Evaluation (MSE) for toothfish

We now review progress against each of these research priorities and update the proposed medium-term research objectives in light of developments since 2008.

3.2.1 Reduce uncertainty in life history, movement patterns, and stock structure

Some of the key uncertainties in life history identified in 2008 still exist, including for example the precise location and timing of spawning, subsequent dispersal of eggs and larvae, and the location of post-larval and juvenile fish (Hanchet et al. 2008, Ashford et al. 2012, Parker & Marriott 2012). Although some aspects of spawning behaviour indicative of likely spawning locations and associated migrations can be inferred from spatial and temporal trends in the gonadosomatic index (GSI) (Parker & Marriott 2012), uncertainty remains regarding aspects of life cycle movements, for example the particular timing and route of pre- and post-spawning migrations, the proportions of mature and post-spawning fish undertaking such migrations, residence time on spawning grounds, potential spawning site fidelity, and the potential for sex-specific movement behaviours affecting sex ratios in different locations. In 2013, the Scientific Committee identified the need for research fishing in the northern Ross Sea region during winter to address current uncertainties in toothfish life-cycle movements and spawning dynamics (SC-CAMLR-XXXII, para 3.76 (iv)).

For stock assessment purposes, toothfish in the Ross Sea region (Subarea 88.1 and SSRUs 88.2A and 88.2B) are currently treated as a separate stock from toothfish in SSRUs 88.2C–I to the east and toothfish from Division 58.4.1 to the west. Genetic studies have suggested low genetic diversity in Antarctic toothfish populations throughout the Southern Ocean (Parker et al. 2002, Smith & Gaffney 2005, Kuhn & Gaffney 2008, Mugue et al. 2012). Tagging data also suggest that there is a very limited amount of mixing between the Ross Sea region and SSRUs 88.2C–I (Parker et al. 2014). Additional research fishing and associated high tagging levels of toothfish in some of the currently closed or lightly fished SSRUs linking all three areas would shed more light on movement patterns and mixing rates (Hanchet et al. 2013b). In 2013, the Scientific Committee identified the need for research fishing in the south of SSRU 882A (on the slope), and in previously unfished or lightly fished SSRUs (e.g., 882A–B north, 881D and 881F) to identify potential implications for stock structure and potential bias in the stock assessment (SC-CAMLR-XXXII, para 3.76 (iv)). It was also recognised that such research would provide important information to improve the parameterisation of spatially explicit population dynamic models of the Ross Sea region (e.g. Spatial Population Model - see also Section 3.2.3), for example to inform evaluation of the consequences of alternate toothfish movement hypotheses affecting the mixing of tags, and to enable spatially explicit management strategy evaluation.

Movement patterns can be inferred from analysing distributional data and mark-recapture experiments. However, neither method provides the more detailed information on the route between the start and finish locations or other short-term (daily or weekly) movements. Also, because the data come from the fishery itself, they do not provide movement data in other seasons and locations. These additional movement data are important for a number of reasons including a better understanding of reproductive dynamics and stock structure (see above), the spatial overlap with toothfish predators (see also Section 3.3), and parameterisation of the SPM (see also Section 3.2.3). The recent recovery of a pop-up satellite tag (PSAT) from an Antarctic toothfish tagged and recaptured on the Ross Sea slope will provide the first information of this type for Antarctic toothfish (Parker et al. 2014b), but many more releases and successful data recoveries from fish released with PSAT or other archival tags, and preferably in a range of different locations, would be required to more fully quantify it.

There is also uncertainty over the size distribution and relative abundance of Antarctic toothfish in McMurdo Sound. The results of vertical longline research fishing for toothfish in the Sound suggested that there has been a large reduction in the abundance of 100–160 cm long toothfish since 2001 (Ainley et al. 2012). The results of the study were reviewed by WG-FSA who considered that the perceived decline may have been due to changes in fishing location, unstandardised fishing practices, and/or local ecosystem changes due to extreme ice conditions in the Sound over the past decade (SC-CAMLR-XXXI, Annex 7, paragraphs 9.15–9.18). WG-FSA agreed, however, that it was important to have an index of abundance of toothfish from this area, and emphasised the need for standardisation of gear, location, and depths of fishing. The northern portion of McMurdo Sound was recently sampled as a part of the sub-adult longline survey (Mormede et al. 2014a) and the results presented to the 2014 meeting of WG-SAM (WG-SAM-14, paragraph 4.24–4.26). The WG noted that the survey had recorded high catch rates of large (100–160 cm long) toothfish in this area and agreed that monitoring of this location in the future would provide valuable data on the relative abundance of large toothfish in the McMurdo Sound area.

Some of these research questions may be addressed by additional analyses of existing data (e.g., analysis of otolith microchemistry for stock structure is currently being investigated by Tana et al. 2014). Other research questions require targeted research surveys to investigate spawning dynamics and toothfish abundance and size composition in unfished areas (e.g., Hanchet et al. 2013b, Delegations of New Zealand, UK, and Norway 2014, Delegation of Russian Federation 2014).

Medium term research objectives to address uncertainty in life history

(i) To spatially and temporally delineate toothfish spawning grounds.
(ii) To delineate stock structure – especially in relation to SSRUs 88.2C-I.
(iii) To define and quantify fine-scale movement patterns, including by size and sex.

3.2.2 Reduce uncertainty in biological and model parameters

Research has also been underway to reduce some of the key uncertainties in biological and model parameters identified in 2008. Estimates of length/age at maturity have been substantially revised following histological studies and the interpretation of GSI data (Parker & Marriott 2012), maximum ages from otoliths have been validated using lead-radium dating methods (Brooks et al. 2011), and aspects of biology have been reviewed and summarised (Hanchet 2010, Petrov 2012).

The series of sub-adult surveys in the southern Ross Sea has resulted in substantial progress towards developing a data set suitable for monitoring recruitment and estimating recruitment variability and autocorrelation (Hanchet et al. 2012, Parker et al. 2013a, Mormede et al. 2014a). Once a time series of such surveys has been established for a longer period, it will be possible to identify strong and weak year classes and periods of strong and weak recruitment, before the cohorts recruit fully into the fishery. Such a time series will also help to resolve uncertainties in the existing stock assessment, for example over the past three years some vessels have been increasingly catching smaller fish in shallower waters of the Ross Sea slope and it is impossible to determine if these small fisher represent a pulse of good recruitment or alternately, whether these catches reflect market preference for smaller fish or potentially a decline in the availability of larger fish (Hanchet et al. 2013a).

Uncertainties remain in other key parameters, in particular tagging mortality, and tag detection rate (which is assumed to be close to 100%, Mormede et al. 2013a). Empirical estimates of tagging mortality of toothfish are difficult to obtain, and the estimate used in the present assessment came from tank experiments of the closely related Patagonian toothfish on board several fishing vessels (Agnew et al. 2006). Agnew et al. (2006) estimated an initial tagging mortality of 10% based on all toothfish, and of 5% when considering only toothfish in good condition. An initial tag-related mortality of 10% has been assumed for toothfish in the model even though observers are required to only tag toothfish in good condition. It is known that tagging of toothfish leads to their having slower growth rates in the year after tagging, equivalent to about 6 months growth retardation (Parker et al. 2013b) and so it possible that there may be a longer-term tag-related mortality (months to years) related to this. The possibility that tagged fish become “hook-shy” (less likely to be caught than untagged fish) is also unknown. A higher tag mortality and lower tag detection rate than used in the stock assessment model, and hook-shyness would all lead to an overestimate of biomass whilst a lower tag mortality rate would lead to an underestimate of biomass. Furthermore, as the population continues to be fished down and the age structure of the population changes, issues such as size- or age-dependent natural mortality and size- or age-dependent tagging mortality may become important. Although algorithms have been developed to compare tagging performance with respect to tag detection and tagging mortality (Mormede & Dunn 2013a, Mormede 2014), the actual values of these parameters is still uncertain. Both parameters have a direct effect on the results of the stock assessment and have been identified by CCAMLR as having a high priority for further research (SC-CAMLR-XXXI, Annex 5).

Some of these research questions can most effectively be addressed using directed experiments (e.g., estimation of tag parameters – see also Parker et al. 2013b), whilst others will require targeted research surveys or directed monitoring programmes.

Medium term research objectives to address uncertainty in model parameters

(i) To improve estimates of initial and longer-term tagging mortality, and tag detection rates.
(ii) To continue monitoring the relative abundance of sub-adults and to estimate recruitment variability and autocorrelation.
(iii) To monitor key population-level parameters (e.g., growth, age/length at maturity, sex ratio) which could potentially be affected by fishing.

3.2.3 Reduce uncertainty in stock assessment

A key source of uncertainty in the stock assessment identified in 2008 is the potential bias in the results caused by non-mixing of tags (Welsford & Ziegler 2013). In addition to uncertainty over the observations going into the model, and uncertainty over some of the model parameters (see above), there is also structural uncertainty in the stock assessment model arising from spatially unrepresentative patterns of fishing effort and/or from non-mixing of tagged fish. Inter-annual differences in the distribution of fishing effort, when fish do not mix completely across large areas, can create bias in the abundance estimated using mark-recapture methods (Welsford & Ziegler 2013). Studies with mark-recapture data have shown that this incomplete mixing can lead to bias: either an over- or an under-estimate of the true abundance.

Spatially explicit age-structured operating models have recently been developed for the Antarctic toothfish population in the Ross Sea region to characterise the potential extent of this bias within the assessment of the stock, and to test the sensitivity of the bias to scenarios for likely movement patterns (Mormede et al. in press). The operating models for these analyses were developed as generalised Bayesian population models fitted to fishery-based observation data. The spatial structure of the models was represented by dividing the Ross Sea region into 189 equal area (24 000 km^2) cells. Three different spatial assumptions were made concerning the underlying distribution of the population. The first assumed that the stock was restricted to the 65 cells historically fished, the second assumed that the stock occupied the entire Ross Sea region (all 189 cells), whilst the third assumed that the stock was restricted to cells with suitable toothfish habitat (120 cells). Estimates of movement rates were consistent with the results of tagging studies and fits to the observations were adequate. Simulations based on these stock scenarios suggested that biomass estimates in the current single-area stock assessment are biased low by 19–43% (Mormede et al. in press).

Another source of uncertainty in the stock assessment has been the high degree of variability in the recapture rates of tagged fish between vessels and nations (Agnew 2008, Dunn et al. 2009a). This led to the development of algorithms designed to only include fishing trips with high data quality (Middleton & Dunn 2009) and then to the development of a spatially explicit case-control algorithm to ensure that tag data from vessels with low recapture rates are excluded from the assessment (Mormede & Dunn 2013a). This approach has been further developed by Mormede (2014) to enable data from vessels with variable tagging performance to be included but down-weighted proportionally; the revised method has been endorsed by CCAMLR WG-SAM-2014 (paragraphs 235–238).

An important step in improving the transparency and understanding of the stock assessment is to broaden the range of sensitivity tests examined and improve the diagnostic plots. To further facilitate the interpretation of the input data going into the stock assessment it is envisaged that a 'dashboard' concept comprising a number of stock indicators could be developed (Hanchet et al. 2013a). In the first instance, this could include trends in key toothfish population metrics such as median length, median age, sex ratio, and tag recaptures, but in the longer term could be expanded to include key ecosystem indicators. Ideally these would be indices of toothfish population and ecosystem health that are easily interpreted by fishery managers and would be useful in years between stock assessments.

Medium-term research objectives to reduce uncertainty in stock assessment

(i) To continue to improve the stock assessment (e.g., improve diagnostics, selectivity estimates, estimation of year class strength etc).
(ii) To develop stock performance indicators / dashboard.

3.2.4 Carry out Management Strategy Evaluation (MSE) for toothfish

As discussed above, spatially explicit operating models have been under development since 2008 (e.g., Dunn et al. 2009b, Mormede et al. in press). At this stage, the models effectively summarize our current state of knowledge regarding toothfish spatial and life cycle dynamics in the Ross Sea region, and provide useful tools to make explicit the consequences of alternate assumptions or alternate management regimes, identify key areas of uncertainty, define testable hypotheses, and suggest research designs to test them. However, while the models estimate the distribution, abundance and movement of toothfish in the Ross Sea region by fitting to actual data (including CPUE, age frequencies, gonad stages, catch history, and tag returns), movements are determined using preference functions that rely on underlying environmental data layers as predictors of toothfish habitat suitability in different life history stages. The fishery data on which the model relies to parameterise these functions are not uniformly available in space, including large areas from which almost no data are available. Alternate assumptions about the distribution and abundance of toothfish in unfished areas can make a large difference in the predicted biomass of toothfish in some SSRUs (Mormede et al. in press). Further data are required to better parameterise the models (see Sections 3.2.1–3.2.3) and further development will be required to continuously update and improve them.

As noted above (Section 3.2.3) some progress has been made in evaluating the potential bias in the stock assessment results caused by non-mixing of tags. Whilst not constituting a full MSE, these simulations have evaluated one of the key uncertainties in the stock assessment and hence a part of the overall management strategy. These simulations are just one of many which could be carried out to fully evaluate the existing management strategy for the Antarctic toothfish fishery. These models have also been used to address the potential effects of closed areas on the stock assessment (SC-CAMLR-IM-I paragraph 2.31(vii)).

Further development in this area should also focus on developing Management Procedures (MP) which take account of unavoidable uncertainties and can be used to develop robust management systems (Butterworth 2007, de Oliviera et al. 2008). The MP approach involves simulation testing to ensure that the management processes being applied will achieve fishery sustainability despite the uncertainties, and as a part of this provide an appropriate trade-off between catches from, and conservation risk to, the resource under consideration. This robustness must hold not only for present best perceptions of the resource's dynamics and those of the associated ecosystem, but also for alternative scenarios that cover the range of uncertainties that are plausible and compatible with existing information.

An important part of scenario testing using MSE or MP would be to suggest how management could respond if the state of the stock changed in an unexpected way. For example, if the sub-adult survey detected low numbers of sub-adult toothfish in a given year, how should the management respond? MSE and MP simulation could suggest which management response would have the best chance of reversing unexpected declines and to identify the information needed to choose the best response. Identifying and initiating data collection needed to mitigate risk is an important part of the medium-term research plan.

Medium-term research objectives to address uncertainty in management

(i) To develop prioritised list of MSE scenarios and begin MSE testing of high priority issues (e.g., alternative model parameters, spatial management, movement and stock assumptions etc).
(ii) To continue development of the operating models as additional tag and fishery data are collected, through improved predictive layers (e.g., ice coverage), and better knowledge of life cycle.

3.3 Ecosystem effects of fishing

CCAMLR's other two long term goals are related to the mitigation of ecosystem effects of fishing by ensuring the maintenance of ecological relationships between harvested, dependent, and related populations and ensuring that changes in the ecosystem are minimised and reversible within two to three decades. A review of progress in achieving these goals identified a number of medium term research objectives (NZ Delegation 2008). Progress towards addressing these objectives has been carried out through a wide range of ecosystem related research carried out in the Ross Sea region over the past five years. We have divided this into two main sections: the first dealing primarily with ecological relationships between toothfish, its predators and prey, and the second dealing with other effects of fishing.

3.3.1 Ecological relationships

Identification of ecological relationships

The identification of the ecological relationships between Antarctic toothfish and its predators and prey in the Ross Sea region, and the maintenance of those relationships, was extensively reviewed at the Fisheries and Ecosystems Models in the Antarctic (FEMA2) workshop held in 2009 (SC-CAMLR-XXVIII, Annex 4, paragraphs 2.1–2.53). The workshop identified several key research priorities arising from its review (paragraph 2.53) and these are included where appropriate within this Section.

Extensive ecological data were assembled and used in a mass-balanced trophic ecosystem model for the Ross Sea shelf and slope ecosystem (Pinkerton et al. 2010). They identified three main predators of Antarctic toothfish in the Ross Sea region: sperm whales, Weddell seals and 'Type C' killer whales. Model outputs suggested that at the scale of the ecosystem and throughout the annual cycle, toothfish are unlikely to be a major prey item for Ross Sea air-breathing predators (i.e. Weddell seals and 'Type C' killer whales). Model results have been supported by stable isotope analysis which showed that all three species are at the same trophic level (Pinkerton et al. 2014). Furthermore, mixed trophic impact (MTI) analysis suggests that Antarctic toothfish do not have a high trophic importance across the wider Ross Sea ecosystem (Pinkerton & Bradford-Grieve 2014). However, both studies note that effects at smaller spatial and temporal scales, and effects concerning only parts of populations, were not addressed by these analyses (Pinkerton et al. 2010, Pinkerton & Bradford-Grieve 2014). The effects of reduced availability of toothfish in some areas at some times of the year could potentially have substantial impacts on populations of its predators in the Ross Sea region, but this risk is presently unquantified. There is also considerable uncertainty over the model inputs for air breathing predators, including population abundance, energetics and trophic linkages. Although there are other potential predators occurring within the region, including for example leopard seals, elephant seals, Arnoux beaked whales, and colossal squid, these species are unlikely to consume large amounts of toothfish given their feeding habits, distribution, and relatively low stable isotope values (Pinkerton et al. 2010, 2014).

Mixed trophic impact analysis also identified that the trophic impact of toothfish on medium-sized demersal fish was the strongest top-down interaction in the system based on multiple-step analysis (Pinkerton & Bradford-Grieve 2014). This suggests a potential for a strong predation-release effect on some piscine prey of toothfish (especially grenadiers and ice-fish on the Ross Sea slope). However, Antarctic toothfish had moderate trophic importance in the Ross Sea food web as a whole, and the analysis did not support the hypothesis that changes to toothfish will cascade through the ecosystem by simple trophic effects. Because of limitations of this kind of 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.

One of the key objectives identified by the FEMA2 workshop was the need for simulation studies to compare food-webs effects of fishing under alternate exploitation assumptions (SC-CAMLR-XXVIII, Annex 4, paragraph 2.53). A Minimum Realistic Model (MRM) has recently been developed for investigating trophic relationships between Antarctic toothfish and grenadiers and icefish in the Ross Sea (Mormede et al. 2014). These demersal fish are known to form a substantial part of the diet of Antarctic toothfish of a size commonly taken by the Ross Sea fishery and are also taken as bycatch by the fishery. The paper identified the need for targeted sampling of toothfish for diet analysis, and the monitoring of icefish and grenadier populations in SSRUs 88.1H and 88.1K.

Resolving key uncertainties over the interactions between toothfish and its predators

The nature of the relationship between Antarctic toothfish and its predators in the southern Ross Sea has been the subject of much discussion (e.g., Ainley & Siniff 2009, Ainley & Ballard 2012, Eisert et al. 2013, Torres et al. 2013, Eisert et al. 2014a, b). Although toothfish do not appear to be a major prey item for its predators at the scale of the full Ross Sea shelf and slope, research does indicate that toothfish could be important for its predators in particular locations and at particular times of year. The most likely locations occur in parts of the south-western Ross Sea, where Weddell seals and killer whales have been observed feeding on toothfish during the summer months (Ainley & Ballard 2012, Ainley & Siniff 2009, Eisert et al. 2014a, b). Although this area has been closed to commercial fishing since 2008, there could be potential risks to these predators if there is a contraction in toothfish range and the predators are unable to find alternate energy-rich food sources. An important recent finding is the high incidence of suckling calves observed in type C killer whale groups in McMurdo Sound. Caring for young (>6 months old) calves greatly increases the energy requirement of lactating females, not only for milk production, but also because mothers assist their calves through drafting, which increases their own locomotory costs. Revised estimates of energy requirements indicate that lactating female killer whales of the fish-eating ecotype require toothfish to meet their elevated demand. While equivalent energy-dense non-fish prey is available (e.g. penguins or seals), observations in northern hemisphere killer whale populations suggest that switching from fish to endotherm prey is improbable (Eisert et al. 2014b). Research to better understand the potential ecosystem importance of toothfish as predators and prey is required (Eisert et al. 2013, Torres et al. 2013). A key aspect of these interactions is the degree of spatial overlap (both in horizontal and vertical planes) in the distribution of toothfish and these two predators.

Torres et al. (2013) reviewed all information available to date on potential interactions between toothfish and type C killer whales in the Ross Sea. They concluded that the balance of evidence suggests that toothfish are likely to form a significant part of 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 (e.g. Terra Nova Bay, Bay of Whales, Sulzberger Bay) or at the scale of the whole Ross Sea shelf and slope. They identified the information needed to evaluate reliably the interactions between type C killer whales and toothfish in the Ross Sea, including: killer whale abundance (and trends), diet, movements, and foraging behaviour, and the depth distribution (in particular distribution in the water column) of toothfish over the shelf and slope (Torres et al. 2013). Suggested methods are biopsy sampling (analysis for isotopes, fatty acids, genetic tagging), focal-follows (e.g. from boat, ice-edge, helicopter), photographic sightings and photographic mark-recapture analysis, tagging (satellite, suction-cup tags), and aerial and acoustic surveys.

Eisert et al. (2013) carried out a review of information on potential interactions between toothfish and Weddell seals in the Ross Sea. Their ability to conclusively determine possible dependence of Weddell seal populations on toothfish, and hence possible impacts of toothfish removal by fisheries, was primarily hindered by (a) insufficient information on Weddell seal diet, due to inadequate temporal coverage and biased methodology, and (b) uncertainty regarding Weddell seal abundance and spatial foraging patterns in the Ross Sea region. They identified the need for the following additional work: better information on diet of Weddell seals, specifically during periods not currently covered and utilising methodology that can conclusively detect toothfish consumption, updated Weddell seal abundance estimates for the Ross Sea, refined estimates of energy requirements of Weddell seals, in particular during the post-breeding season, and improved understanding of spatial habitat utilisation and foraging behaviour, especially in the post-moult period and during winter.

In the longer term, key uncertainties about predation by seals and whales on toothfish will need to be addressed including mapping the temporal and spatial extent of the predation, the proportion of predators eating *D. mawsoni*, the daily consumption, the degree of overlap in their vertical distribution, whether alternative prey items are present, and to what extent fishing may change the availability of toothfish to its predators. For example, many of the most important overlaps between Weddell seals, killer whales and toothfish seem to occur towards the southern edge of the distribution of toothfish, so any change in the distribution of toothfish, such as a contraction in range, may lead to changes in the availability of toothfish to its predators. It is likely that changes in the availability of toothfish to its predators may not have occurred at this time but may be expected to occur over the coming two decades. It is hence important to establish or develop prediction and monitoring methods for changes to the spatial distribution of toothfish, e.g. using the SPM or sub-adult survey. . In 2014, WG-EMM (paragraph 5.22) noted that spatially explicit multi-species models such as SPM or MRM may also be usefully applied to understand fisheries interactions with top predators.

Monitoring changes in predators and prey

Currently there are no comprehensive methods of monitoring changes in toothfish predators or prey or any means of monitoring their ecological relationships with *D. mawsoni*. Annual counts of Weddell seals in Erebus Bay (McMurdo Sound) have been made since 1974, and other ground and aerial counts have been made sporadically along the Victoria Land coast since the 1960s (Siniff & Ainley 2008, Ainley et al. 2014). WG-EMM in 2014 (paragraph 2.94) noted that interpreting population trends in Weddell seals would likely need to incorporate a large proportion of the population rather than being based on a few selected areas. Eisert et al. (2013) noted the need for updated Weddell seal abundance estimates for the Ross Sea as a whole and further considered that, whilst satellite surveillance may be an option, it needs to be complemented by extensive ground-truthing to ensure accuracy. They also noted the need for monitoring Weddell seal diet, particularly at McMurdo Sound, so that any changes in diet could be detected.

There are no recent estimates of the abundance of type C killer whales in the Ross Sea, which limits any ability to assess population trends or variability (Torres et al. 2013). The establishment of a data series on the type C killer whales population trend is crucial. Two methods are likely to be useful for establishing population size of type C killer whales in the Ross Sea: mark recapture analysis of individual resightings (from photo identification or biopsy samples) and distance sampling surveys (from fixed-wing aircraft, helicopters, or ships). Torres et al. (2013) also noted the need for monitoring killer whale diet so that any changes in diet could be detected. Other data may also be available from killer whale sampling that occurred in the 1970s (Berzin and Vladimirov 1983); accessing this data for analysis at a higher level of taxonomic resolution is a high priority (WG-EMM-14 paragraph 2.105).

No recent information on sperm whale numbers, distribution or diet in the Ross Sea region is available, though fishing vessels report few sightings of these whales in the region.

It has also proven difficult to estimate the abundance of, or monitor trends in, toothfish prey species. Although preliminary estimates of the abundance of macrourids and icefish on the Ross Sea slope were obtained as part of the New Zealand IPY survey in 2008, these were based on very few trawls (Hanchet et al. 2013c). Two other approaches are also currently being explored. O'Driscoll et al. (2012) provided evidence that macrourid abundance on the Ross Sea slope could potentially be monitored using acoustic methods. They found positive correlations between acoustic backscatter and research (IPY) trawl and commercial longline catches of macrourids. The acoustic target strength distribution of single targets was also very similar to that predicted from the measured size range. A second approach is to use catch curve analysis of distributions of catch-at-age data to detect changes in total mortality over time. These approaches have been complicated by the discovery that there are two sympatric macrourid species co-occurring throughout the Ross Sea region (McMillan et al. 2012), which have quite different life history traits (Pinkerton et al. 2013). Monitoring of the catch composition will need to be carried out at regular intervals to determine changes in relative abundance of the two species.

Declines in the abundance of both *D. mawsoni* and macrourids due to fishing may lead to changes in the diet of *D. mawsoni*. Because icefish do not appear to be particularly vulnerable to longline fishing, and may be preferred as a prey item by toothfish, they may replace macrourids to some extent in the diet as the stock size of toothfish decreases. New Zealand scientists have therefore started regular monitoring of the diet of *D. mawsoni* on the Ross Sea slope where such changes in ecological relationships may be expected to take place (Mormede et al. 2014). Although most dietary analysis has so far been based on the examination of stomach contents and stable isotope analysis (e.g., Stevens et al. 2012, Pinkerton et al. 2014), fatty acid analysis has recently been used for assessing toothfish diet in the southern Ross Sea (Jo et al. 2013), and may be a more effective way of quantifying changes in diet in the future.

Additional potential ecosystem effects caused by the removal of toothfish and/or bycatch species by the fishery were reviewed by Pinkerton et al. (2010) and Pinkerton & Bradford-Grieve (2014). They considered these second-order effects to include potential trophic cascades and keystone predator effects. Ecosystem responses to removal or depletion of species may be non-linear, with thresholds where changes may be rapid, substantial, and non-reversible. Characterisations of the nature of the food-web and changes in its relationships over time will need to continue (Pinkerton & Bradford-Grieve 2014). However, these effects are very difficult to predict from trophic models and long-term monitoring of species likely to be affected (both top and meso-predators such as penguins) may be required in order to both assess and manage risk.

Medium-term research objectives to address uncertainty in ecological relationships

(i) To determine the temporal and spatial extent of the overlap in the distribution of toothfish and its key predators (in particular killer whales and Weddell seals).
(ii) To investigate the abundance, foraging ecology, habitat use, functional importance and resilience of key toothfish predators (in particular killer whales and Weddell seals).
(iii) To develop methods of monitoring changes in relative abundance and diet of key prey species (in particular macrourids and icefish) in key areas, especially on the Ross Sea slope.
(iv) To monitor diet of toothfish in key areas, especially on the Ross Sea slope
(v) To simulate the effect of the fishery on populations of toothfish, its predators and its prey on the Ross Sea slope (using Minimum Realistic Models, surveys or similar).
(vi) To develop quantitative and testable hypotheses as to the "second-order" effects (such as trophic cascades, regime shift) and ensure data collection is adequate to monitor for any risks deemed reasonable.

3.3.2 Direct impacts of fishing on bycatch species

We consider here bycatch of fish, seabirds, marine mammals, and benthos.

Although the toothfish fishery is primarily focused on Antarctic toothfish, it does catch small amounts of Patagonian toothfish which are included in the overall toothfish catch limit (Hanchet et al 2013a). Annual catches have ranged from 0 to 30 t per year and have totalled 130 t over the course of the fishery (Stevenson et al. 2012). The catch of Patagonian toothfish in the Ross Sea fishery was characterised by Hanchet et al. (2010). They noted that Patagonian toothfish were mainly taken in the north-west corner of the Ross Sea region (SSRUs 88.1A and 88.1B) and that there were probably sufficient biological and tag-recapture data to determine the local abundance of Patagonian toothfish in the Ross Sea region. However, they also noted that a fully integrated stock assessment would require a better understanding of its stock structure.

The fish bycatch taken in the Ross Sea toothfish fishery has been well documented (e.g., Stevenson et al. 2012). The main bycatch species are macrourids (mainly *M. whitsoni* and *M. caml*), which form 5–10% of the total catch, and skates (mainly *A. georgiana*), which forms <1% of the catch (most are released alive at the surface). There are already several approaches in place to mitigate fish bycatch: these include Subarea and amalgamated SSRU catch limits for macrourids, rajids, and other species which restrict the catch of these species taken in the fishery (CM 41/09, 41/10) as well as a move-on rule in place to help prevent localised depletion of macrourids and rajids (CM 33-03) (see also Section 2.1.2). Potential methods for monitoring macrourids are discussed above (Section 3.3.3) and are not repeated here.

Potential methods for monitoring skates in the Ross Sea region were reviewed by O'Driscoll et al. (2005), who concluded that a tag-recapture experiment was likely to be most successful for monitoring skates. A very preliminary stock assessment based on skate tag-recapture data and ancillary fishery data was completed by Dunn et al. (2007). They identified several problems with the data currently being collected and made the following recommendations: improve species identification, improve detection of tagged skates, increase number of skates measured and sexed, validate the estimates of age and growth, revise skate tagging protocols and undertake additional survivorship experiments. Following the CCAMLR 'Year of the Skate' in 2008/09 an updated characterisation of skate catches was carried out by Mormede & Dunn (2010). They noted that, up to and including the 2010 season, a total of 14,000 skates had been tagged and released and a total of 179 skates had been recaptured. An analysis of the skate length data showed bimodality in the scaled length distribution of the catches of *A. georgiana*, which gave rise to concern that they could include a cryptic species. However, genetic analysis of specimens (Ritchie & Fleming 2012) failed to find a second species, whilst further examination of the raw length data suggested that the bimodality was partly miscoding of the lengths used to measure skates and partly a scaling issue. Further work is now required to determine whether the skate tag data and other fishery data can be used for monitoring skates in the Ross Sea region. Experiments are also required to determine the survivorship of the released skates.

Only two seabirds have been caught on a longline during the history of the fishery. This appears to be due to strict compliance with CMs 24-02 and 25-02 and other related mitigation measures in CMs 41/09 and 41/10 over the course of the fishery. There has been no reported bycatch of marine mammals on longlines in the fishery.

An impact assessment of the effects of the IWL longline system on the benthos was carried out by Sharp (2010); this method was subsequently adopted by the Scientific Committee and is updated annually to produce a combined cumulative impact assessment applied to all historical and current bottom fishing effort in the CCAMLR Area (SC-XXX paragraph 5.4). These assessments suggest that the maximum likely impact of longline fishing gear on potential VMEs in the Ross Sea region is negligible (SC-CAMLR-XXXI/Annex 7 Appendix F Figure 6(i)). The main uncertainties in the assessment are the effective width of the impact of the longline on the seabed (due to uncertainties as to the extent to which the longline may move laterally during hauling) and which benthic species likely to be most impacted.

Despite the assessed extremely low risk of significant adverse effects, a range of approaches to mitigate and reduce risk are in place (CMs 22-06, 22-07, and 22-08). Key in the context of future research are additional data collection by observers, identification of the location of potential VMEs from fishery independent data, and testing the key assumptions in the risk assessment (especially lateral line movement during hauling).

Medium term research objectives for direct impacts of fishing on bycatch

(i) To assess the impact of the toothfish fishery on Patagonian toothfish
(ii) To assess the potential impacts of the toothfish fishery on key fish bycatch species
(iii) To estimate survivorship of released skates
(iv) To develop semi-quantitative risk assessments for macrourids and Antarctic skates (*A. georgiana*) in the slope fishery of the Ross Sea.
(v) Develop methods to assess whether the potential impacts of the toothfish fishery on the ecosystem are likely to be reversible in two to three decades.

3.3.3 Other factors

Climate Change

Pinkerton et al. (2007) considered risks associated with the combination of climate change and the fishery for Antarctic toothfish. They noted that Antarctic toothfish could be affected by climate change in a number of ways including changes in recruitment, location, depth, natural mortality, and trophic linkages. Climate change could also have a more far reaching impact on other aspects of the ecosystem including regime shifts (Pinkerton et al. 2007).

Since the start of the 3-year experiment there has been a system of open and closed SSRUs in Subareas 88.1 and 88.2. The continuing closure of these SSRUs can allow effects from fishing to be distinguished from other extraneous factors (including climate change, ocean acidification, freshening of the Ross Sea, and other environmental effects) in the long-term.

Alien species

Changes to the physical environment near the sea bed in the Ross Sea may, in time, change the geographic ranges of species and could allow temperate fishes to colonise these areas at the expense of polar species (Pinkerton et al. 2007). The frequency of these incursions, and the chances of the novel species gaining a permanent niche in the ecosystem, are likely to increase if the age structure of fish is truncated (for example due to fishing), if the resident fish is stressed (for example due to change of local environmental conditions), or conditions change more rapidly than normal (for example due to climate change). In these cases, fishing in concert with climate change has the potential to facilitate significant changes in ecosystem function in the Ross Sea region.

Other vessel activities

Other activity occurs in the Ross Sea region that may either directly or indirectly impact Antarctic toothfish and the ecosystem within which they occur. These activities may be managed through other parts of the Antarctic Treaty system. They are described here for completeness.

Direct activities requiring ongoing consideration include quantification of catches from scientific research and tourist vessels (if any). Indirect impacts requiring ongoing consideration include potential secondary effects on areas of particular significance for toothfish (e.g. contaminated runoff from a base affecting key juvenile habitat), and additive cumulative impacts on habitat from maritime activity beyond fishing (e.g. anchoring of tourist vessels on potential VME sites).

No additional research is proposed on these issues at this time, however these are areas for continuing engagement with other parts of the Antarctic Treaty system.

4. DISCUSSION

4.1 Key factors for management

The key factors for management of the fishery remain unchanged from the previous review (NZ Delegation 2008) and include:

- flexibility to extend the fishing period and/or fishing area to undertake targeted projects (e.g. out-of-season sampling for stock structure work),
- a framework to allow for a proper “exploratory / experimental” fishery through a structured research plan, which doesn’t penalise fishers carrying out research,

- stability in the management system and continuity of key data collection to allow answers to come out of existing work: changing data collection for specific short term projects may create bias problems and compromise long term efforts such as population modelling,
- optimisation of data collection by observers/industry and continuity of key data inputs: in the past the observer manual, requirements, and protocols have been subject to change every year, and may not reflect current research priorities
- administrative ease of management by the Secretariat and Commission
- improved collaboration between fishers to address issues of data quality and optimised data collection
- improved coordination between those involved in fishery or region-specific science and management discussions or other discussions affecting CCAMLR at a wider spatial scale (e.g., MPAs, ecosystem modelling)
- continued biennial assessments
- continued improvement and optimisation of the toothfish tagging programme and associated protocols

The development of the operational framework needs to be carried out in conjunction with various working groups and *ad hoc* groups of the Scientific Committee including WG-FSA, WG-EMM, TASO, FEMA etc. Therefore an important aspect for the framework is to ensure it will allow the streamlining of the work of the Scientific Committee.

The last five years has seen a period of stability in the Ross Sea toothfish fishery. This stability has not only led to an improved stock assessment of Antarctic toothfish, but has also assisted the development of a preliminary stock assessment model for Antarctic skates and toward the development of a risk assessment for macrourids and other potential ecosystem effects of the toothfish fishery. The additional move to a biennial assessment of toothfish since 2006/07 has also allowed resources to be redirected into the development of a Spatial Population Model and Minimum Realistic Model of multispecies interactions, both of which will be important for future MSE of the toothfish fishery. We strongly encourage the continuation of the existing operational framework in the medium term (next 4–5 years), noting that changes to the spatial management of the fishery and other operational management changes may occur in accordance with, or independent of, the proposed MPA, or consistent with Scientific Committee advice arising from new toothfish surveys in the Ross Sea region (SC-CAMLR-XXXII paragraph 3.76 (iv)).

However, one of the operational issues which needs some consideration was identified by WG-FSA in 2013 (SC-CAMLR-XXXII, Annex 6, para 4.80). It noted that catch limits for the Ross Sea fishery are managed under two conservation measures (CMs 41-09 and 41-10) and recommended that the boundary between Subareas 88.1 and 88.2 be revised or that the scope of CMs 41-09 and 41-10 be revised such that the Ross Sea Region (Subarea 88.1 and SSRU 882A–B) is managed within a single conservation measure (SC-CAMLR-XXXII, Annex 6, para 4.80). Although the proposal was generally supported by the Scientific Committee (SC-CAMLR-XXXII paras 3.155–3.160), the Commission was unable to reach consensus on the boundary change between these two CMs. We concur with WG-FSA and recommend that the Subarea 88.1 – Subarea 88.2 boundary be moved to 150ºW so that SSRUs 88.2A and 88.2B would become part of Subarea 88.1 and so the assessment area and management areas would be consistent. Once the boundary change has been enacted then we further recommend that the current combined Fishery Report for Subarea 88.1 and 88.2 be split into separate Fishery Reports, one for each Subarea.

4.2 An updated Medium Term Research Plan for the Ross Sea toothfish fishery

In general, we have focused on a limited number of tangible and achievable research objectives which will reduce uncertainty in key parameters and improve understanding of ecological relationships with predators and prey in the short-medium term. However, we also recognise the need for further developing the MSE and MP approaches in the medium-long term.

4.2.1 Maintenance of the Antarctic toothfish population in the Ross Sea region above target levels

(a) Reduce uncertainty in toothfish model parameters

(i) To spatially and temporally delineate toothfish spawning grounds.
(ii) To delineate stock structure – especially in relation to SSRUs 88.2C-I.
(iii) To define and quantify fine-scale movement patterns, including by size and sex.
(iv) To improve estimates of initial (and longer-term tagging) mortality, and tag detection.
(v) To continue monitoring the relative abundance of sub-adults and to estimate recruitment variability and autocorrelation.
(vi) To monitor key population-level parameters (e.g., growth, age/length at maturity, sex ratio) which could potentially be affected by fishing.

(b) Reduce management uncertainty

(i) To continue to improve the stock assessment (e.g., improve diagnostics, estimation of year class strength etc).
(ii) To develop simple stock performance indicators / dashboard.
(iii) To develop prioritised list of MSE scenarios and begin MSE testing of high priority issues (e.g., alternative model parameters, spatial management, movement and stock assumptions etc).
(iv) To continue development of operating models as additional tag and fishery data are collected, through improved predictive layers (e.g., ice coverage), and better knowledge of life cycle.

4.2.2 Maintenance of ecosystem structure and function

(i) To determine the temporal and spatial extent of the overlap in the distribution of toothfish and its key predators (in particular killer whales and Weddell seals).
(ii) To investigate the abundance, foraging ecology, habitat use, functional importance and resilience of key toothfish predators (in particular killer whales and Weddell seals).
(iii) To develop methods of monitoring changes in relative abundance of key prey / bycatch species (in particular macrourids and icefish) on the Ross Sea slope and hence assess the potential impact of the toothfish fishery on these species.
(iv) To monitor diet of toothfish in key areas, especially on the Ross Sea slope.
(v) To simulate the effect of the fishery on populations of toothfish, its predators, and its prey (using Minimum Realistic Models or similar).
(vi) To develop quantitative and testable hypotheses as to the "second-order" effects (such as trophic cascades, regime shift) and ensure data collection is adequate to monitor for any risks deemed reasonable.
(vii) To assess the impact of the toothfish fishery on Patagonian toothfish.
(viii) To estimate survivorship of released skates.
(ix) To develop semi-quantitative and spatially explicit risk assessments for macrourids and Antarctic skates (*A. georgiana*), especially in the slope fishery of the Ross Sea.

(x) To develop methods to assess whether the potential impacts of the toothfish fishery on the ecosystem are likely to be reversible in two to three decades.

4.3 Data collection Plan

It is recommended that the specific data collection plan and research plan developed for the Ross Sea fishery by Mormede & Hanchet (2010) be updated.

In addition to the existing data collection and research plan (CM 41/01), we recommend:

(i) The development of clear, refined and rationalized observer data requirements (e.g. length measurements, otoliths collection, gonad weights, percent hooks observed) and enhanced industry data collection.

(ii) The need to critically review and examine individual data sets to reject non-valid data, improve data collection over time, and the use of accredited observers.

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