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Title	**ECOLOGICAL RISK MANAGEMENT AND THE FISHERY FOR ANTARCTIC TOOTHFISH (*DISSOSTICHUS MAWSONI*) IN THE ROSS SEA, ANTARCTICA**	
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ABSTRACT

Ecological risk management is increasingly being applied to marine fisheries worldwide as an aid to developing management strategies to avoid, mitigate, or manage adverse outcomes. Risk management encompasses four major steps: recognition of risk; assessment of risk; development of strategies to avoid, mitigate, manage or tolerate risk; and monitoring of risk. Here we begin the development of an ecological risk assessment for Antarctic Toothfish (*Dissostichus mawsoni*) longline fishery in the Ross Sea, Antarctica. We propose that, by defining risks and quantifying potential impacts, the limited research and management resources can be prioritised so as to meet the objectives of Article II of CCAMLR. Risks are considered in 4 categories:

1. Target species harvest: Risks of depletion of Antarctic Toothfish to below a level that ensures stable recruitment.
2. Bycatch species harvest: Risks of depletion of other harvested species to below a level that ensures stable recruitment.
3. Ecosystem impacts: Risks of changes to the marine ecosystem relationships due to the removal of harvested and bycatch species.
4. Exogenous effects: Risks of change in the marine ecosystem due to, or exacerbated by, exogenous effects (e.g., the introduction of alien species, effects of associated activates on the ecosystem, and effects of environmental change).

The assessment of risk is based on combining the likelihood of an adverse outcome occurring and the consequence should it occur. Numerical models, such as stock or ecosystem mass-balance models can provide insights into these factors for some risks. In addition, semi-quantitative and qualitative estimates are needed because of a lack of knowledge and inability to predict the future dynamics of some parts of the system. It is also recognised that some risks (e.g., impacts of climate change) may not be able to be well predicted. The uncertainty arising from the complexity of the system and external factors acting on it means that risk management and ongoing monitoring will be required to ensure that the fishery is managed according to the conservation principles of Article II of CCAMLR.

SUMMARY OF FINDINGS AS RELATED TO NOMINATED AGENDA ITEMS

Agenda Item	*Findings*
FEMA	Management of adverse outcomes resulting from the Antarctic toothfish longline fishery in Subareas 88.1 and 88.2 can be aided by the development of an ecological risk assessment. By defining risks and quantifying potential impacts, research and management resources can be prioritised so as to meet the objectives of Article II of CCAMLR.

1. INTRODUCTION

Toothfish are the major finfish resource currently exploited in the Southern Ocean, with only krill exceeding the catch in recent years. There are two species of toothfish, both with a circumpolar distribution: Patagonian toothfish (*Dissostichus eleginoides*) are generally found north of 65° S and Antarctic Toothfish (*D. mawsoni*) generally south of 65° S. This paper presents a preliminary view of a risk-based framework for the management of the Antarctic Toothfish longline fishery in the Ross Sea, and discusses how this may aid in its management.

Fisheries in Antarctic waters are managed through the Commission for the Conservation of Antarctic Marine Living Resources. The Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR, hereafter referred to as the Convention) was the first international regional agreement to stipulate explicitly that management consider the effects of any harvesting on dependent and associated species as well as on the target species, and to stipulate that the ecological relationships between harvested, dependant, and related species be maintained. The overall aim of the Convention is to conserve the marine life of the Southern Ocean, while allowing harvesting that is carried out in a rational manner (Anonymous 2000). Article II allows harvesting of marine resources in the CCAMLR Area, subject to the following three principles of conservation;

> Article II.3 (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;
>
> Article II.3 (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;
>
> Article II.3 (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.

In general, we do not understand enough about the dynamics of marine ecosystems to be confident that we can predict how the system will change in response to fishing. It is plausible that that we never will be able to do so with any useful reliability. Ecosystems (that is, the interaction of species with each other and with the physical-chemical environment) typify complex adaptive systems. Complex adaptive systems often display chaotic behaviour that defies simple analysis and for which it is not possible to develop general predictive models. Such systems often have “emergent” properties that, if well understood, allow limited prediction of states in the near future from a knowledge of the current state. It is also sometimes possible to predict changes to some components of the system in isolation from the rest of the system. Both of these insights into the dynamics of complex systems are likely to be reliable only for relatively small perturbations from the current state. As we move further away from the current state, changes to complex systems become less predictable, and it may no longer be possible to consider individual components in isolation.

Risk management provides a methodology for formally appraising the risks and associated outcomes of alternative management actions when information is imperfect, and provides a framework for the targeting and prioritisation of limited research and management resources. Risk management in marine ecological systems has increasingly been used to supplement more conventional stock assessment methods. Although usually applied to data-rich fisheries (e.g., Linder et al. 1987, Hilborn et al. 1993, Rosenberg & Restrepo 1994), it has become increasingly widespread in recent years. For example, a risk assessment framework adapted from the Standards Australia/New Zealand 4360 was recently applied to Australian fisheries (Fletcher 2005, Astles et al. 2006). Within CCAMLR, risk assessment approaches have been proposed, for example, to assess seabird-fishery interactions in the CCAMLR area (Waugh 2006b, 2006a).

Given that the ecology of toothfish and ecosystem function in the Ross Sea are a part of a complex ecosystem that is not well understood, how can we ensure that the toothfish fishery meets the conservation principles of Article II? The current management framework for Antarctic Toothfish in the Ross Sea has been based on an ad-hoc approach to risk identification and hence management. While Antarctic toothfish catch limits have been developed using the decision rules of Constable & de la Mare (1996) (i.e., addressing Article II.3 (a)), less formal methods have been applied to the development of catch limits for associated and dependant species that make-up the target fishery bycatch, or to the maintenance of the ecological relationships between harvested, dependent and related species.

We propose that a formal risk management appraisal can be used to assist in identification of areas where management activity may be required to address the principles of Article II, assist in the prioritisation of research, as well as assisting in the evaluation of alternative management decisions that have an implicit trade-off between utilisation and conservation.

2. THE RISK MANAGEMENT MODEL

Risk management is a way of formally appraising the risks and associated outcomes of alternative management actions when information is imperfect. Here, we define risk as the expected loss resulting from the occurrence of an event multiplied by the probability of the event occurring. There are four steps in the typical approach to risk management used in many areas of human activity: (1) recognition of the risks; (2) assessment of the risks, (3) development of alternative strategies that avoid, mitigate, manage or tolerate risk; (4) monitoring of the risks.

2.1 Identifying the risks

The first step in a risk assessment is to identify risks. Here, “risks” are activities, conditions, situations or events which may lead to an adverse outcome, i.e. a outcome that does not meet one or more of the conservation principles set out in Article II of the Convention. Note that the first part of the risk management process needs to identify all potential hazards, even if some are later considered and discarded as being of negligible risk.

2.2 Assessment of risk

In the second step, assessment of risk, two factors are combined to give a measure of the level of risk: (1) the likelihood of an adverse outcome occurring (i.e., the probability), and (2) the consequence, significance, or importance of the impact (i.e., the loss that would result if the event occurred). The criteria used in assessing risk can be quantitative, semi-quantitative (i.e. values which have no physical meaning but represent the relative importance of different outcomes), or qualitative.

In qualitative or semi-quantitative risk assessment, likelihood is often categorised or divided into ordered categories, for example the six categories: ‘remote’, ‘rare’, ‘unlikely’, ‘possible’, ‘occasional’, ‘likely’, Table 1 after Fletcher (2005). When quantitative modelling is used, it may be possible to determine the probability of an adverse outcome risk within some given period, which can then be used directly as for likelihood in the risk equation. Similarly, the impact or consequence can also be defined on some categorical scale, for example the six level scale: ‘negligible’, ‘minor’, ‘moderate’, ‘severe’, ‘major’, ‘catastrophic’, Table 2 after Fletcher (2005).

Table 1: Likelihood definitions after Fletcher (2005).

Likelihood level	Descriptor
1 – Remote	Never heard of, but not impossible
2 – Rare	May occur in exceptional circumstances
3 – Unlikely	Uncommon, but has been known to occur elsewhere
4 – Possible	Some evidence to suggest that it is possible here
5 – Occasional	May occur sometimes
6 – Likely	It is expected to occur

2.3 Development of strategies that avoid, mitigate, manage or tolerate risk

Management approaches are next developed for each of the risks identified and assessed above. This process usually considers the most significant risks first. The management actions can be designed to: (a) reduce the chance of the adverse activity occurring (“avoid”); (b) reduce the likely impact of damage if it occurs (“mitigate”); (c) put in place a response strategy if the adverse outcome occurs (“manage”); or (d) involve simply accepting the risk (“tolerate”). We note that different approaches and tools are appropriate to consider risks from different sources. Also we note that management activities may address multiple risks or may even be in conflict (i.e., a strategy that, while reducing one risk, may make another worse).

2.4 Monitoring of risk

Finally, it is important to collect information with which to determine whether the applied risk management model is effective. Monitoring information can be used to confirm that management actions have had the desired outcomes as well as highlighting areas where the risk management model needs to be improved.

3. THE ROLE OF NUMERICAL MODELS IN RISK MANAGEMENT

When we talk about “models” in risk management of fisheries we need to distinguish people’s intrinsic conceptual models of how the world works from numerical models (typically computer simulations). At a very fundamental level, conceptual beliefs about the world underlie the way they assess risk. This is true institutionally as well as individually (Lawton 2007). For example, different opinions on the nature of interconnections between species within an ecosystem (i.e., the conceptual model) lead to different structures and numerical models that may be used to assess those risks.

We suggest that the principles from the 1996 report to the US Congress of the Ecosystems Principles Advisory Board (Longhurst 2006) provide the most basic conceptual view of marine ecosystems from which to develop a risk-based approach to management:

(a) our predictive capacity for ecosystem behaviour is limited;
(b) ecosystems have thresholds and limits, which, when exceeded, can lead to irreversible change;
(c) ecosystem components are linked;
(d) ecosystems have open boundaries;
(e) ecosystems change with time.

Table 2: Summary of consequence levels after Fletcher (2005).

Consequence level	Recovery time if stopped	Target species	By-catch species	Ecosystem
0 – Negligible	No recovery time needed	Undetectable for population	Area where fishing occurs is negligible compared to where species reside (<1%)	Interactions may be occurring but it is unlikely that there would be any change outside of natural variation
1 – Minor	Rapid recovery - months	Possibly detectable but little impact on population size and none on their dynamics	Take and area of capture by fishery is small compared to known area of distribution (<20%)	Captured species do not play a keystone role – only minor changes in relative abundance of other constituents
2 – Moderate	Probably months-years	Full exploitation rate where long-term recruitment/dynamics not adversely affected	Relative area of capture is suspected to be <50% and species are known not to have vulnerable life history traits	Measurable changes to the ecosystem components without there being a major change in function (i.e. no loss of components)
3 – Severe	Years	Affecting recruitment levels of stocks/or their capacity to increase	No information available on: - relative area impacted - susceptibility to capture - vulnerability of life history traits	Ecosystem function altered measurably and some function or components missing/ declining/ increasing well outside historical acceptable range and/or allowed/ facilitated new species to appear
4 – Major	Years to decades	Likely to cause local extinctions if continues	N/A	A major change to ecosystem structure and function. Different dynamics now occur with different species or groups present
5 – Catastrophic	>decades or never	Local extinctions are imminent/immediate	N/A	Total collapse of ecosystem processes

Numerical models have an important part to play in identifying risks, assessing risk levels, and assisting in developing risk management strategies. However, no single numerical model is adequate on its own. We do not believe that ecological risk assessment based solely on numerical models, as has been advocated for data-rich fisheries (e.g., Punt & Walker 1998, McAllister et al. 1999, Jiao et al. 2005), is appropriate for Antarctic fisheries given the paucity of information on many aspects of high-latitude fisheries and ecology. Instead we suggest that a number of plausible numerical models addressing different aspects of the system, viewed in different ways, will be required. Note that a "plausible model" here is defined as any model that does not contravene existing evidence. As there are considerable gaps in our knowledge of fisheries and ecosystems, there will be several plausible models leading to several future scenarios which could result from each potential set of conditions. The use of multiple models and approaches to provide acceptable fisheries management even if our understanding of the fishery system is flawed (Levin 1993) fits well with a risk-based approach. A risk management approach provides a framework to bring together this range of plausible numerical models, semi-quantitative approaches and qualitative approaches as appropriate to assess the likelihood of a risk occurring, assess its potential consequence and help formulate management approach.

4. DEVELOPMENT OF A RISK ASSESSMENT FOR THE ANTARCTIC TOOTHFISH FISHERY IN THE ROSS SEA

4.1 Introduction

In this preliminary paper, we begin the process of risk identification, but do not progress these to the second step of the risk management approach ("assessment of risk"). In this section, we introduce categories of risks that may be further developed in future work to identify all of the risk factors involved.

4.2 The Antarctic toothfish fishery

Toothfish are large Nototheniids endemic to Antarctic and sub Antarctic waters. There are two main species: Antarctic toothfish (*Dissostichus mawsoni*) and Patagonian toothfish (*D. eleginoides*). Both have a circumpolar distribution, although *D. mawsoni* has a more southern distribution and is found in higher latitudes south of the Antarctic Convergence (Figure 1). A toothfish species profile, covering aspects of the biology, fisheries and stock assessment of both toothfish species was completed by Everson (2002). Aspects of the biology and fishery for *D. mawsoni* were summarised by Hanchet et al. (Hanchet et al. 2004, Hanchet et al. 2005, Hanchet et al. 2006), mostly based on fish taken from the Ross Sea.

The Ross Sea fishery (CCAMLR Subarea 88.1 and SSRUs 88.2A and 88.2B following Dunn et al. 2005) is entirely a long-line fishery. The fishery began in 1996/97, and has increased to an average annual catch of about 3000 t. The current annual catch limit was set as 3072 t for the most recent season (SC-CAMLR-XXV 2006). In addition to toothfish, the fishery takes a significant bycatch of species of rattails, skates, and rays.

A single-stock sex- and age-structured stock assessment model (Dunn & Hanchet 2006) has been used to estimate yields of Antarctic toothfish, under the CCAMLR decision rules (Constable & de la Mare 1996). The model of Dunn & Hanchet (2006) estimated the current biomass of Antarctic Toothfish to be 82–90% of the virgin (unfished) biomass. The approach used by CCAMLR for determining catch limits of Antarctic toothfish in the Ross Sea has been to develop and review the age structured models, and set annual yields based on an agreed assessment. For the previous two seasons, the stock assessment models have been updated annually and used to determine the annual catch limit under the CCAMLR decision rules (Constable & de la Mare 1996).

The CCAMLR areas 88.1 and 88.2 are subdivided into small-scale research units (SSRUs), the number, size, and catch limits of which have varied over time (Hanchet et al. 2006). In addition to the catch limits on the target species, a number of other management measures have been introduced over the course of the fishery. These include restrictions on by-catch, by-catch mitigation measures, and mandatory scientific observers on all vessels. Observers monitor discards, with at least 40% of all hooks hauled being observed. Discarding of fish is prohibited (CM 26 (2006), CAMLR-XXV 2006), although fish are occasionally lost from the line near the surface (CAMLR-XXV 2006). Measures to minimise local depletion of toothfish (SSRU catch limits and temporary closure of SSRUs to fishing) have also been used. The level of illegal and unreported catch is thought to be low (Dunn & Hanchet 2007). Ice conditions and by-catch limits are another important factor in the fishery and significantly affect the locations where catch can be taken.

Antarctic toothfish feed on a wide range of prey but are primarily piscivorous. In continental slope waters *Macrourus whitsoni*, the icefish (*Chionobathyscus dewitti*), eel cods (*Muraenolepis* spp.), and cephalopods predominate in the diet, while on oceanic seamounts *M. whitsoni*, violet cod (*Antimora rostrata*) and cephalopods are important. In the coastal waters around McMurdo Sound adults feed on Antarctic silverfish, whilst in the open oceanic waters they feed on small squid. The diet of Antarctic toothfish also varies with fish size. Crustaceans are more common prey species in the stomachs of smaller fish, whereas squid are more commonly found in larger fish.

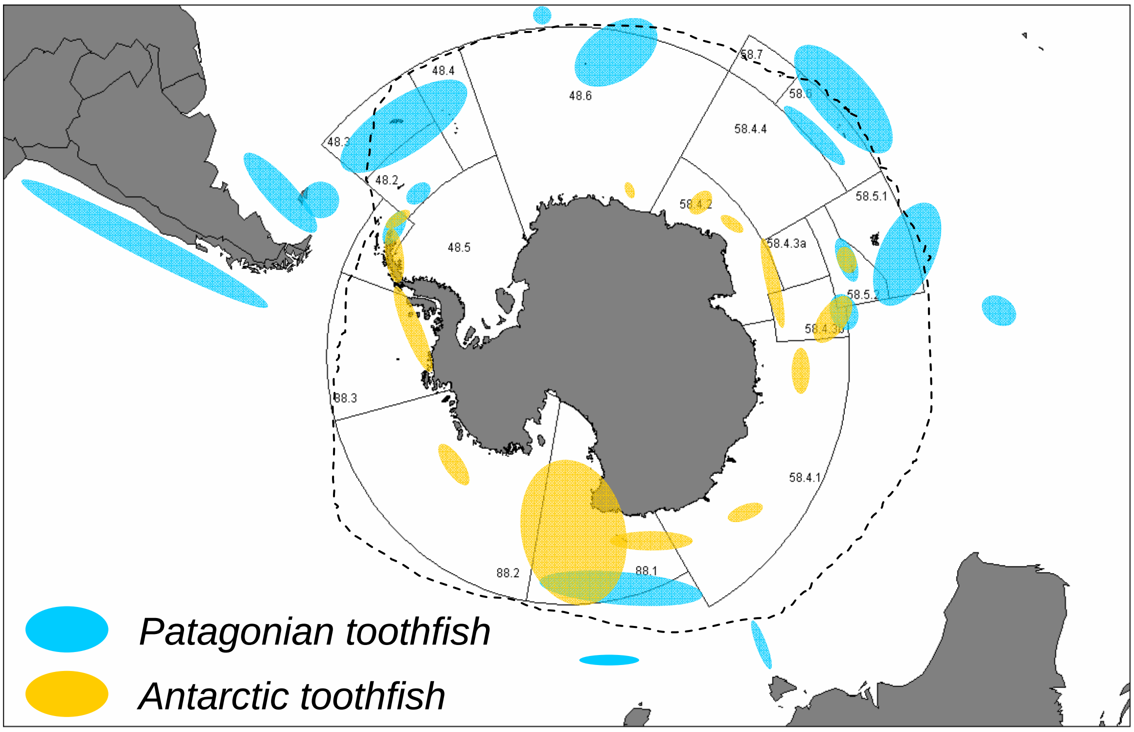

Figure 1: Main centres of distribution of Patagonian and Antarctic toothfish. The approximate location of the Antarctic Convergence is shown by the dotted line.

4.3 Identification of risks for the Antarctic Toothfish fishery in the Ross Sea

Article II of the Convention sets out the conservation objectives for fishing within the CCAMLR area. We can use these principles as the basis for identifying the risks associated with utilisation of the Antarctic Toothfish resource in the Ross Sea. Here, we define risk as the risk of adverse outcomes that do not meet the objectives of Article II of Convention. (Note that under the Antarctic Treaty System of which CCAMLR is part, these risks take precedence to socio-economic risks, such as setting catch levels below the level where the maximum long-term profit from the fishery may be achieved.) We consider risks over timescales from the immediate to many decades.

To aid the identification of risks, we first identify four risk categories;

1. Target species harvest: Risks of depletion of Antarctic Toothfish to below a level that ensures stable recruitment.
2. Bycatch species harvest: Risks of depletion of other harvested species to below a level that ensures stable recruitment.
3. Ecosystem impacts: Risks of changes to the marine ecosystem relationships due to the removal of harvested and bycatch species.
4. Exogenous effects: Risks of change in the marine ecosystem due to, or exacerbated by, exogenous effects (e.g., the introduction of alien species, effects of associated activates on the ecosystem, and effects of environmental change).

The work presented here provides an initial overview of important risks whereby the conservation principles given in the Convention may be breached, but it is far from complete. If a risk-based management approach to the fishery for Antarctic toothfish is considered useful, considerable work will be needed through CCAMLR to determine the probability, consequence and possible management action for each risk.

4.4 Target species harvest

Risks associated with the target species (Antarctic toothfish) harvest have been the focus of most of the work associated with the Antarctic toothfish fishery in the Ross Sea. Many of the risks that could be assigned to this category are associated with and, to a certain extent, captured within, the single-species stock assessment models for Antarctic toothfish in the Ross Sea. Even so, no formal risk assessments have been applied to the current assessment models.

What are the risks associated with relying on the future stock projections of the current stock model? In order to assess the risk, we break this question into two parts which we deal with in turn below. (1) What is the chance that the predictions from the current stock model will be wrong? (2) What will be the consequences if the predictions are wrong?

4.4.1 Assessing the chance of inaccurate stock predictions

The predictions of the stock model will be wrong under two scenarios: (1) the structure, parameters, or data used to develop the model are flawed, or (2) the model is appropriate now, but things change in an unforeseen way in the future leading to inaccurate predictions.

For the first of these two scenarios, we consider each of the key issues which were used to develop the stock model and discuss the uncertainty associated with each, and their potential impact on the validity of the stock model

Stock structure, including spatial distribution, areal heterogeneity, and association with other areas
The current assessment model for Antarctic toothfish in the Ross Sea focuses on Subareas 88.1 and SSRUs 88.2A & B (Dunn & Hanchet 2006), but the sensitivity of alternative assumptions about the nature of the stock structure of Antarctic toothfish have not been investigated. And, are current model estimates of yield sensitive to assumptions of the stock structure? Risks that could be identified in this category include possibilities of a different

stock structure than assumed, the nature of the relationship of Antarctic toothfish in the Ross Sea with other Antarctic toothfish in Subareas 88.2, 88.3, and Division 58.4.1.

Assumptions of the nature and value of model productivity parameters
The assessment model of Dunn & Hanchet (2006) assumed various fixed parameters for growth, natural mortality, and maturity. Typically, stock assessment model have a high degree of sensitivity to choices of values of growth parameters, natural mortality, and the age of maturity. Risks that could be identified in this category include assumptions of the value of, for example, natural mortality (M), relationships between M and age, and variability in M over time. Similar risks could be identified about the nature and shape of the growth curve, and the location and shape of the maturity curve. For example, Heppell et al. (1999) show that rates of population change of long lived marine animals can be very sensitive to adult mortality but relatively insensitive to O-group (pre-recruit) mortality.

Observations and their assumptions
The single-species model of Dunn & Hanchet (2006) is based on the interpretation of observational data (catch, catch-at-age frequencies, CPUE, and tag-release and recapture data), given assumptions about productivity and stock structure. What are the risks associated with the choice of the current sets of observations used to develop the stock model? For example, a naïve interpretation of the standardised CPUE indices for the Ross Sea would suggest that Antarctic toothfish abundance has increased over the duration of the fishery. There are risks associated with using incorrect assumptions in the choice of observation data sets, or in incorrect assumptions of how the observations are interpreted within the model.

Unknown historical IUU fishing
The level of illegal, unregistered and unreported (IUU) catch of Antarctic toothfish is thought to be low. If the current estimates of IUU fishing catch are not correct, there is a risk associated with the use of a stock model which uses this information.

Now we consider the second way in which inaccurate future stock predictions may occur, namely that the stock model is appropriate and parameters are well fitted to reliable data, but things change in an unforeseen way in the future. How could this occur and what are the potential impacts?

IUU fishing
As more vessels compete for the catch allocation of Antarctic toothfish, there may be increased likelihood of higher IUU catches in the future. There is a risk of contravening the Convention if IUU catches increase and are not considered in the management process.

Unexpected impact of fishery on spawning
In long-lived species of fish, older individuals are disproportionately more important to overall reproductive success than younger fish (Longhurst 2006). In some marine fisheries as each cohort dwindles, changes occur in its reproductive ecology so that survivors reproduce more efficiently. Large individuals produce larger numbers of eggs than small individuals, indeed, relative fecundity (ova produced per gram of body weight) increases progressively through the life of most fish (Longhurst 2006). For example, a single cohort of cod may remain its reproductive power for more than 15 years – long enough to bridge gaps between years of adequate spawning (Longhurst 1999). The relatively small eggs of first spawning fish tend to have low viability compared with larvae resulting from the eggs of older fish. For Baltic cod (another long-lived cold water fish), older females produce eggs that remain in suspension and hence avoid asphyxiation better than eggs by younger females (Vallin & Nissling 2000). Older females of many species produce batches of ova over a longer period each year which increases the chance that at least one batch would lead to good recruitment (Trippell et al. 1997). The Canadian Department of Fisheries and Oceans Stock Status report

for 2003 for cod on the astern Scotian shelf states: "larger, older and repeat spawners make disproportionately larger contributions to production of viable eggs and larvae".

Fishing typically truncates the age structure of fish by preferentially removing older, larger fish, and this will occur in the Ross Sea as current fishing patterns favour the taking of larger Antarctic toothfish. There is a risk that truncation of the age structure of Antarctic toothfish will significantly impact spawning success in a way that is not captured by the current stock model. It is not possible to assess *a priori* how significant this may be for Antarctic toothfish in the Ross Sea because we lack basic information on the spawning behaviour of this species.

Reduction or unexpected variability in recruitment
The early life history (i.e. before recruitment) of Antarctic toothfish is not known. No larval or juvenile (<5 years old) Antarctic toothfish have been found in the Ross Sea. There is hence a risk that our lack of knowledge on the factors affecting recruitment of Antarctic toothfish will allow us to act in a way that jeopardises the long term viability of the stock.

4.4.2 Consequence of inaccurate stock predictions

The consequences of poor predictions of future stock depend on the way the model predictions are used in management. Model estimates of yields of Antarctic toothfish in the Ross Sea have been evaluated using a modified version of the decision rules of Constable & de la Mare (1996). While CCAMLR has accepted that these rules provide an appropriate realisation of the principles of Article II.3 (a), are these rules an appropriate choice given the level of uncertainty in predicting the future dynamics of the stock? Annual monitoring and reassessment of the state of the stock and allowable catch reduces the significance of errors in stock predictions only if the management response is fast enough to allow recovery.

4.5 Risk to bycatch species

As with the target species risks, no formal risk assessments have been applied to the management approaches for bycatch species. Risks for these species, while similar to those for target harvest species, are often less well specified or informed. However, as above, we can we can group risks in this category into two areas,

- What are the risks associated with the choice of alternative model structures, productivity assumptions, observation reliability, and catch used to assess the current state of bycatch species in the Ross Sea.
- What are the risks associated with assumptions of the future productivity under alternative scenarios of future recruitment and catch of bycatch species in the Ross Sea?

4.5.1 Adverse impact on skates due to by-catch

The significance of the by-catch of skates depends on the population size of skates in the area, and their vulnerability to this removal. No formal assessments have been carried out of the impact of the target toothfish fishery on by-catch of skate *Amblyraja georgiana*, (O'Driscoll 2005). Insufficient biological information is currently available to estimate γ for skates in the Ross Sea. Estimates of age and growth of *A. georgiana* in Subarea 88.1 based on interpretation of caudal thorns were presented by Francis & O Maolagáin (2005). These gave a conservative estimate of 14 years for the maximum age, with age-at-maturity estimated to be 6–7 years for males and 8–11 years for females. These estimates suggest that *A. georgiana* may have higher productivity, and therefore be less vulnerable to overexploitation, than rattails. However, these estimates of age and growth are unreliable due to the uncertain and unvalidated age estimates. The relatively fast growth rates reported for *A. georgiana* also contrasts with the much slower growth of tagged *Bathyraja eatonii* in Division 58.5.2. The risk of overexploitation may be mitigated by the requirement to release rajids from long-lines whilst still in the water, but this depends on the survival rate of released animals.

O'Driscoll et al. (2005) considered approaches to monitoring and assessing rajids in Subarea 88.1 and recommended that on the basis of the biology of the species and the practicalities of sampling these species in the Ross Sea a random bottom trawl survey would be the best approach to obtaining estimates of standing stock. Tag-recapture experiments and experimental manipulation of fishing effort are alternative methods that could be used to monitor abundance of rajids. Results of the experimental tagging programme in the Ross Sea fishery have shown that over 9,000 rajids have been tagged since 2000, and a total of 47 (0.5%) have been recaptured (Ballara et al. 2006). This programme is being further developed and expanded as it appears that it may be useful for stock assessment purposes and evaluation of its utility for this purpose is underway.

There are number of Conservation Measures in place regarding bycatch of rajids. Current catch limits for rajids in the Ross Sea are 5% of the catch limit of Dissostichus spp. or 50 tonnes whichever is greater (Conservation Measure 33-03 (2004)). These limits for skates are generally not exceeded.

Since the start of the 2000/01 season, rajids likely to survive have been cut free and released at the surface as a measure to reduce rajid mortality. The survival of at least some of these skates has been demonstrated by the recapture of some 47 tagged skates (Ballara et al. 2006), and by the results of survivorship experiment in tanks carried out by the United Kingdom.

There is also a 'move-on' rule in place to help prevent localised depletion of bycatch species. This rule requires 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. The vessel is not allowed to return to within 5 n. miles of the location where the bycatch exceeded 1 tonne for a period of at least five days (Conservation Measure 33-03, 2005).

4.5.2 Adverse impact on Whitson's grenadier due to by-catch

No formal assessments have been carried out of the impact of the target toothfish fishery on bycatch species Whitsons' grenadier (*Macrourus* whitsoni) (O'Driscoll et al. 2005). Biological data show that *M. whitsoni* is a relatively slow-growing, long-lived species with an estimated mean age-at-maturity of 10.6 years for males and 13.6 years for females (Marriott et al. 2005). The best estimate of the precautionary pre-exploitation yield level (γ) for *M. whitsoni* in Subarea 88.1 was 0.01439. The low γ indicates that this species has relatively low productivity and thus may be vulnerable to overexploitation. However, catch rates in the toothfish fishery have not declined, juveniles are not selected by the fishery, and comparison of long-line and trawl catch rates with other Antarctic areas suggest that the population in the Ross Sea may be large.

Potential mitigation measures for macrourids were examined by Ballara & O'Driscoll (2005). They used a standardised CPUE analysis to determine factors affecting by-catch rates of macrourids in the Ross Sea. The analysis was based on fine-scale haul-by-haul data and observer data from all vessels in the fishery from 1997/98 to 2004/05. The major factors influencing macrourid bycatch were vessel, area, and depth (Ballara & O'Driscoll 2005). Catch rates of *M. whitsoni* were highest along the shelf edge (SSRUs 88.1E, 88.1I, 88.1K and 88.2E) in depths from 600 to 1000 m, and there was an order of magnitude difference in reported macrourid catch rates between different vessels. Examination of vessel characteristics showed that catch rates of macrourids were lower with the Spanish line system than with the autoline system. This effect was confounded by the bait type, as Spanish line vessels tended to use the South American pilchard as bait, whereas autoline vessels used varying species of squid and/or mackerel. However, the difference in macrourid catch rates between the few Spanish line vessels that used squid and mackerel for bait and the majority that used pilchards was much less than the overall difference between Spanish line and autoline vessels. Russian and Korean vessels reported extremely low catch rates compared to other vessels fishing in the same location.

Current catch limits for macrourids in the Ross Sea are 16% of the catch limit of Dissostichus spp. or 20 tonnes whichever is greater (Conservation Measure 33-03 (2004)). In each of the last three seasons, the by-catch limit for macrourids has been exceeded in at least one of the SSRUs. There is also a ‘move-on’ rule in place to help prevent localised depletion of macrourids. This rule requires 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. The vessel is not allowed to return to within 5 n. miles of the location where the bycatch exceeded 1 tonne for a period of at least five days (Conservation Measure 33-03 (2005)).

4.5.3 Adverse impact on bird populations

Seabirds have not been caught in the toothfish fishery in the last nine years with the exception of one bird caught in 2003/04. Considerable effort has been put into mitigation of seabird captures in the fishery, through implementation of CCAMLR Conservation Measures regarding line sink rate, use of streamer lines, seasonal restrictions on fishing, prohibition of offal dumping, line weighting and only allowing daytime setting under strict conditions.

Mitigation measures were implemented in line with recommendations form the CCAMLR *ad hoc* Working Group on Incidental Mortality Associated with Fishing (WG-IMAF). This group again in 2006 assessed the risk level of seabirds in the fishery in Subarea 88.1 as low (category 1, lowest risk, with highest risk being category 5) south of 65° S, medium (category 3) north of 65°S and overall as medium (category 3) and recommended daytime setting to be permitted subject to line sink rate requirements and seabird by-catch limits, and that latitude specific conditions should apply. Longline fishing north of 65° S should be restricted to the period outside the breeding season of at risk species (where known or relevant).

WG-IMAF assessed the risk level of seabirds in the longline toothfish fishery in Subarea 88.2 as low (category 1) and recommended strict compliance with Conservation Measure 25-02 (with exemption to paragraph 4 to allow for daytime setting) and no need to restrict the longline fishing season. Conservation Measure 25-02 applies to these areas and in recent years has been linked to an exemption for night setting in Conservation Measure 24-02 and subject to a seabird by-catch limit. Vessels catching three birds are required to stop fishing in the sub-area concerned. Offal and other discharges are regulated under annual CCAMLR conservation measures (e.g. CCAMLR Conservation Measures 41-09 and 41-10).

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

4.5.4 Adverse impact on mammals (seals) populations

There is no reported direct by-catch of mammals in the Ross Sea by the longline fishery for toothfish.

4.6 Ecosystem impacts

4.6.1 Fishery effects on habitat

Direct damage to the benthic habitat due the long-line fishing activity is likely to be low. There may be some mortality of benthic invertebrates from the line, but this is unlikely to be significant. There is a risk of significant damage to the benthos if the fishery were to operate in areas where there is large-scale benthic structure, for example, cold water corals.

4.6.2 Gear loss

The loss of gear (lines, hooks and other gear) in the Ross Sea is not reported by fishing vessels, but is unlikely to be large. There is a risk that discarded or lost gear will lead to mortality of predators such as seabirds, pinnipeds, or cetaceans.

4.6.3 Pollution, chemical discharge, sinking

Fishing vessels are likely discharge small amounts of oily pollution while working in the Ross Sea but this is unlikely to be significant. Environmental risks due to catastrophic damage to vessels (e.g. fire, sinking) are present, but may not be significant because of the small size of vessels (relatively little fuel is carried) and their distance from land while working.

4.6.4 Effects of offal discharge on ecosystem relationships

Fishing vessels are prohibited from discharging offal within the CCAMLR jurisdiction, which here extends to 60°S. It is likely that all offal is discharged just north of this limit. The water depth here is greater than 1000 m and no lines are set, so this is may not be a significant risk.

4.6.5 Toothfish as prey: first order effects on predators of toothfish

Natural predators of toothfish in the Ross Sea include sperm whales, type-C killer whales, Weddell seals and large squid. Relatively fresh, large adult *D. mawsoni* have been found in sperm whale stomachs collected from over deep water over parts of the Southern Ocean (Yukhov 1971, 1972). Killer whales are known to take toothfish from long lines, but the amount of predation in the absence of fishing is not known. Direct observation of *D. mawsoni* in the pelagic zone at McMurdo Sound made using a video mounted on a Weddell Seal showed a high rate of encounter (Fuiman et al. 2002). There is some information suggesting high predation by Weddell seals on toothfish in McMurdo Sound. Antarctic toothfish are occasionally caught with evidence of squid depredation (i.e., sucker marks and large flesh wounds), and there is camera evidence of squid taking toothfish from long-lines. Although toothfish are known to be taken by this range of predators, their significance as a food source is not known. Preliminary trophic budget considerations (Pinkerton et al. 2006) suggest that Antarctic toothfish are unlikely to be a major component of the overall diets of these predators. However, there may be important localised effects, where the consumption of toothfish in particular locations, at particular times of the year, or by particular parts of the predator population is important, even though the total consumption of toothfish by all individuals of a species is relatively low.

4.6.6 Toothfish as predators: first order effects on prey of toothfish

Antarctic toothfish feeds on a wide range of prey but is primarily piscivorous (Fenaughty et al. 2003, Stevens 2004). In continental slope waters, the macrourid *Macrourus whitsoni*, icefish *Chionobathyscus dewitti*, eel cods (*Muraenolepis* spp.) and cephalopods predominate in the diet, while on oceanic seamounts *M. whitsoni*, violet cod (*Antimora rostrata*) and cephalopods are important. In the coastal waters around McMurdo Sound, adults feed principally on Antarctic silverfish (*Pleuragramma antarcticum*). In the open oceanic waters, Antarctic toothfish feed on small squid. The diet of Antarctic toothfish also varies with fish size. Crustaceans are more common prey items in smaller toothfish, whereas squid are more common in larger toothfish.

A mass-balance trophic model of the Ross Sea (Pinkerton et al. 2006) suggested that Antarctic toothfish have the potential to exert considerable predation pressure on demersal fish. Reducing toothfish predation on demersal fish may lead to significant increases in their abundance. It is likely that fishery-induced changes to the age structure of toothfish in the Ross Sea will affect the prey species disproportionately, i.e. prey that are generally taken by large toothfish will show the largest response. Better estimates of population sizes, and biological characteristics of these prey species are required to evaluate the likely magnitude of this effect.

4.6.7 Second order effects: potential trophic cascades/ keystone predator effects

The potential for removal of a predator to have a significant effect on the rest of the ecosystem through trophic effects is well studied (e.g., Brose et al. 2005 and references therein). A well-studied example involves “keystone” predators. These maintain biodiversity in a variety of ecosystems by preferentially consuming competitively dominant prey species. If keystone predators are removed or their biomass reduced, the prey species can increase in abundance to levels where they start to exclude other subordinate competitors. In the case of the Ross Sea, an increase in demersal fish biomass due to a reduction in predation by Antarctic Toothfish may lead to negative impacts on the prey items of demersal fish. Other potential indirect effects include trophic cascades, where links in an ecosystem are changed by the removal of a species by fishing (e.g., McCann et al. 1998, Pinnegar et al. 2000, Frank et al. 2005). Empirical studies show that the manifestation of second-order effects is dependent on the particular ecosystem, and that they are difficult to predict. Recent work (Libralato et al. 2005) suggests that it may be possible to identify keystone species from mass balance ecosystem models, but this is largely unvalidated to date. In the absence of being able to predict changes, long term monitoring of species which may be affected by second-order effects may be required to assess and manage risk.

4.6.8 Effects on ecosystem relationships due to removal of bycatch species

Direct removal of bycatch species has the potential to alter ecosystem relationships in the Ross Sea sector in three ways: (1) by directly reducing their availability for predators; (2) by directly reducing their predation on prey species; (3) indirectly through second order effects on organisms that are more than one trophic level removed from the bycatch species. The two main bycatch species are likely to be *Macrourus whitsoni* and *Amblyraja georgiana.* Several factors affect how much bycatch of these species will affect ecosystem relationships. The key factor is the significance of the bycatch on the population size of these species. The effect on ecosystem relationships due to bycatch of these species is likely to be less significant than the effect on the organisms themselves, and this risk is considered above in Section 4.5.

4.6.9 Loss of opportunity to study relatively “pristine” shelf-slope ecosystem

The Ross Sea is likely to be one of the last largely intact continental shelf marine ecosystem on the planet and is likely to offer an unparalleled opportunity to study a shelf-slope ecosystem that is rich in large, long-lived predatory fish (Ainley 2002, Smetacek & Nicol 2005, Ainley et al. 20047). Studying such a region may benefits ecological scientific knowledge above and beyond simply providing an improved knowledge of Antarctic ecosystems. Any significant fishing in the region, such as reducing biomass of the major top-predatorial fish to half its unfished level, will mean that this opportunity is lost. While this risk is not considered by the Convention, it may impact on our ability to determine the relative importance of fishing activity and environmental variability (including climate change) on ecosystem changes in the future.

4.7 Risks due to, or exacerbated by, exogenous effects

4.7.1 Climate change impacts on harvested populations

Climate change is currently impacting, and will likely increasingly impact, marine fish and fisheries (Roessig et al. 2004). There are two risks associated with the combination of climate change and the fishery for Antarctic toothfish. First, what is the risk that fishing the toothfish will reduce its resilience to climate-related changes? Second, if toothfish are significantly affected by climate-related changes to the environment or ecosystem, how should the management of the fishery respond?

Antarctic toothfish may be affected by climate change in a number of ways, including: (1) reduced or more variable recruitment; (2) change of location; (3) change of depth; (4) increased natural mortality, due to increased predation or loss of condition; (5) change of trophic linkages, in particular, reduction of prey availability (Roessig et al. 2004).

Fishing a stock is likely to reduce its resilience to exogenous stress. It is axiomatic that the life history traits of fish (including age distribution, sex ratio, age-structured fecundity) are evolved to maximise fitness to all aspects of their living space (Begg et al. 1999, Longhurst 2006). Truncating the age structure of Antarctic toothfish in 88.1 and 88.2 may reduce their resilience to stress associated with climate change. Loss of older fish has the potential to disproportionately affect spawning success, and reduce the capacity of the population fish to remain reproductively viable for long enough to provide a sufficiently strong year class (Stearns 1992, Longhurst 2002, 2006).

In addition, Nototheniidae may be particularly sensitive to changes in water temperature at the depth inhabited because they lack heat-shock proteins which deal with heat-related cell damage (Kock 1992, Hofmann et al. 2000, Roessig et al. 2004, Hofmann et al. 2005). Because of their narrow tolerance of higher temperature, toothfish may change movement patterns, geographical ranges, or depth ranges to seek cooler waters if bottom waters in the Ross Sea increase (Roessig et al. 2004). Managing this risk may involve monitoring for climate-related stress to toothfish, which may include testing for changing expression of genes related to thermal tolerance, testing for changing in geographic, depth distribution, or monitoring toothfish diet over time.

4.7.2 Climate-related risks of ecosystem (biological) regime shifts in the Ross Sea

Changes to the Ross Sea due to climate change could bring about large scale changes to the structure and function of the ecosystem (“biological regime shift”). Potential changes to Ross Sea due to climate change include: (1) freshening of the Ross Sea from increased melting (Coles et al. 1996, Jacobs et al. 2002); (2) changes to circulation patterns; (3) changes in temperature (Coles et al. 1996); (4) increased ocean acidification; (5) lowered primary production (Sarmiento et al. 2004).

The changes may impact almost all species in the Ross Sea to some extent. For example, Roessig et al. (2004) summarises physiological data on polar fishes and concludes that they tend to be well adapted to only a narrow range of cold temperatures because of adaptations of their blood composition, temperature-sensitive enzymes, and enzyme-ligand interactions (Kock 1992). For example, cold temperatures increase oxygen solubility in polar waters, decrease the oxygen requirements of polar ectotherms, and lead to reduced numbers of red blood cells in Antarctic fish compared to temperate fish (Kock 1992, Nikinmaa 2002). Some Antarctic fish (e.g., Channichthyidae) have dispensed with haemoglobin and red blood cells entirely which makes them highly stenothermic.

Changes to organisms and ecosystems due to climate change are not predictable: we don't know which species will be affected, how they will be affected, how fast or extensively these changes may occur, or what will be the system-level effects of the changes to species. The risk needs to be considered as part of the management of Antarctic toothfish fishery because it is established, though evidence is incomplete, that ecosystem degradation (which includes the effect of fishing on target and by-catch species) may increase the likelihood that climate change will precipitate unexpected changes in ecosystem function (Barrett 2006)..

4.7.3 Invasive 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 (Roessig et al. 2004). Longhurst (2006) argues that, in unfished populations, the life histories of each age group of each fish stock can accommodate incursions of novel predators on the millennial scale. 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.

5. DISCUSSION AND CONCLUSION

The challenge for the management of the Antarctic toothfish longline fishery in the Ross Sea is to ensure that the management is consistent with the conservation principles set out in Article II of the Convention. The range of risks, the complexity and variability of the system, the relatively low level of understanding of ecosystem interactions, and the poorly understood impacts of the fishery all contribute to that challenge. The Convention requires that the impacts resulting from utilisation of marine resources are consistent with the principles of conservation in Article II, even if our current understanding is flawed or if unexpected changes occur in the future.

In general, the current management of the longline fishery in the Ross Sea has focussed on four parts: (1) defining a stock assessment model for Antarctic toothfish; (2) setting precautionary yields as defined by the sustainability criteria suggested by Constable & de la Mare (1996); (3) varying spatial distribution of toothfish catch using small scale areal catch limits; (4) *ad hoc* conservation measures to, for example, reduce by-catch (mitigation measures), and localised depletion ("move-on rule"), as well as measures to minimise impacts form other exogenous effects (waste disposal, vessel discharge, etc.). Ongoing monitoring of the impact of the fishery on toothfish and annual reappraisal of catch limits means that, to some extent, the current management is responsive and robust to problems with stock assessment. However, there has been less consideration given to potential impacts of the fishery on ecosystem structure, sustainability of by-catch species, or potential exacerbation of impacts by, for example, climate-related changes.

Table 3: A preliminary risk assessment matrix for the fishery for Antarctic Toothfish in the Ross Sea.

	Risk category	Risk	Like-lihood[1]	Con-Sequence[2]	Risk factor[3]	Action (Avoid/Manage /Mitigate/Tolerate)
1	Target species harvest: depletion of Antarctic Toothfish to below a level that ensures stable recruitment	Estimates of the stock status of Antarctic Toothfish are incorrect as assumptions of stock structure, parameters, or data are inappropriate Future productivity changes in manner not considered leading to inaccurate model predictions (e.g., IUU fishing, unexpected impact of fishery on spawning, reduction or unexpected variability in recruitment, loss of genetic diversity, etc.)				
2	Bycatch species harvest: depletion of other harvested species to below a level that ensures stable recruitment	Adverse impact on skates due to by-catch Adverse impact on Whitson's grenadier due to by-catch Adverse impact on other bycatch species Adverse impact on bird populations Adverse impact on mammals (e.g., seals) populations				
3	Ecosystem impacts: changes to the marine ecosystem relationships due to the removal of harvested species	Fishery effects on habitat Gear loss Pollution, chemical discharge, sinking Effects of offal discharge on ecosystem relationships Toothfish as prey: first order effects on predators of toothfish Toothfish as predators: first order effects on prey of toothfish Second order effects: potential trophic cascades/ keystone predator effects Effects on ecosystem relationships due to removal of by-catch species Loss of opportunity to study relatively "pristine" shelf-slope ecosystem				
4	Exogenous effects: Risks of change in the marine ecosystem due to, or exacerbated by, exogenous effects	Climate change impacts on harvested populations Climate-related risks of ecosystem (biological) regime shifts in the Ross Sea Invasive species				

1. Likelihood: 1–Remote; 2–Rare; 3–Unlikely; 4–Possible; 5–Occasional; 6–Likely (Table 1)
2. Consequence: 0–Negligible; 1–Minor; 2–Moderate; 3–Severe; 4–Major; 5–Catastrophic (Table 2)
3. Risk category (Fletcher 2005): 0 Negligible; 1–6 Low; 7–12 Moderate; 13–20 High; 20–30 Extreme.

Risk management is a way of formally appraising the risks and associated outcomes of alternative management actions when information is imperfect. This process can aid management by defining risks and quantifying potential impacts, and hence allowing the best use of limited research and management resources. In this paper we begin the development of an ecological risk assessment for Antarctic toothfish longline fishery in the Ross Sea, Antarctica. The first step in a risk assessment is to identify risks. A very preliminary risk assessment matrix for the fishery for Antarctic toothfish in the Ross Sea is given in Table 3, and we propose to further develop the risks identified in this table. At this early stage, we have not attempted to assess the risks and suggest that the development of methodologies to enable risk assessments is a matter that CCAMLR may wish to consider during future working group meetings.

This work should be considered a working draft, and discussion is welcomed.

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