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Is current management of the Antarctic krill fishery in the Atlantic sector of the Southern Ocean precautionary?

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ABSTRACT

This paper is a revised version of WG-EMM-15/28, which uses a question and answer format to explain the management of the Antarctic krill (*Euphausia superba*) fishery in the subareas 48.1 to 48.4, and current knowledge about the state of the regional krill stock. The revisions provide a new, precautionary assessment of exploitation rate in this fishery. The effective regional catch limit (or “trigger level”), established in 1991, is 0.62 million tonnes year^{-1}, equivalent to ~1% of the regional biomass estimated in 2000. Additional subarea catch limits were established in 2009. There is some evidence for a decline in the abundance of krill in the 1980s, but no evidence of further decline over more recent decades. Biomass indices from local monitoring programmes established in the 1990s and 2000s also show no evidence of a further decline. Extrapolation from these local monitoring programmes provides conservative estimates of the regional biomass in recent years. This suggests that the trigger level would be equivalent to a long-term exploitation rate (catch divided by biomass) of <7%, which is below the 9.3% level considered precautionary for Antarctic krill. However, the permitted exploitation rate in each subarea, derived from the subarea catch limit, appears to exceed this level in up to 20% of years due to high variability in krill biomass indices. The actual exploitation rate in each subarea has remained <3% because annual catches have been <50% of the regional trigger level since 1991. The subarea catch limits help prevent higher exploitation rates.
The CAMLR Commission also needs to manage the risk of adverse impacts on the ecosystem which might occur as a result of climate change or concentrated fishing in sensitive areas. Frequent assessment of the krill stock will enhance the

Commission's ability to manage these risks. Continuing the local monitoring programmes will provide valuable information on krill variability, but more information is required on how the monitored biomass relates to biomass at the subarea scale. The most effective means to acquire this information is likely to be through the use of fishing vessels to collect data.

INTRODUCTION

This paper is intended to provide an accessible overview of the status and management of the Antarctic krill (*Euphausia superba*) stock in the Atlantic sector of the Southern Ocean (CCAMLR statistical subareas 48.1 to 48.4; Fig. 1). Krill fishing is also permitted in the Indian Ocean sector (subareas 58.4.1 and 58.4.2) but it currently occurs only in subareas 48.1 to 48.3, around the South Shetland Islands and Bransfield Strait, the South Orkneys and South Georgia. There has not been any krill fishing in subarea 48.4 (the South Sandwich Islands) since 1992.

This paper uses a question and answer format to introduce the current catch limits; to explain the basis for these catch limits and clarify their relationship with krill biomass estimates; to introduce the data available for analysing changes in the krill stock; to assess the effective catch limits (the amount of krill that the fishery is currently allowed to catch in each subarea) against biomass estimates; and to determine whether these catch limits are precautionary.

WHAT ARE CCAMLR'S OBJECTIVES?

The principles governing CCAMLR Commission's fisheries management in the Southern Ocean are set out in the Convention on the Conservation of Antarctic Marine Living Resources (https://www.ccamlr.org/en/organisation/camlr-convention-text). These include objectives for fished stocks and the wider ecosystem, including predators that feed on fished stocks. Fished stocks must be maintained at or above the level "which ensures the greatest net annual increment", meaning that fishing should not reduce the ability of each stock to replace itself. The "ecological relationships between harvested, dependent and related populations" must be maintained and "the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades" must be minimised. This paper focuses mainly on the objectives for the fished stock but it includes a section on whether current krill management is sufficient to achieve the objectives for the wider ecosystem.

WHAT ARE THE KRILL CATCH LIMITS AND HOW WERE THEY CALCULATED?

The regulations governing fisheries in the Southern Ocean, which are agreed by all Commission members, are set out in documents called Conservation Measures (https://www.ccamlr.org/en/conservation-and-management/conservation-measures). The main Conservation Measure governing the Antarctic krill fishery in subareas 48.1 to 48.4 is CM 51-01. This identifies two catch limits: a higher limit, called the precautionary catch limit (5.61 million tonnes, established in 2010), and a lower limit, called the trigger level, (0.62 million tonnes, which was first stated as a limit for the krill fishery in CM 32/X in 1991). Each of these limits defines an amount of krill that the fishery could catch in each fishing season (December to November) if associated conditions are met. The precautionary catch limit specifies the catch that could be permitted when “the Commission has defined an allocation of this total catch limit between smaller management units”. This means that the Commission agrees that catches of 5.61 million tonnes per season spread out through subareas 48.1 to 48.4 will not reduce the ability of the krill stock to replace itself. The Commission also agrees that excessive concentration of this catch in any part of the area might be harmful to either the krill stock or the wider ecosystem, and that localised catch controls are necessary to prevent this possible harm. The trigger level limits the catch that can be taken before these localised catch controls are established. An additional conservation measure, CM 51-07, initially established in 2009, sets individual catch limits for subareas 48.1 to 48.4. These limits are 25%, 45%, 45% and 15% of the trigger level for subareas 48.1, 48.2, 48.3 and 48.4 respectively. These subarea catch limits sum to more than 0.62 million tonnes to allow flexibility for the fishery, but the overall catch is still capped at 0.62 million tonnes.

Calculation of the precautionary catch limit involved four main steps:

(1) Identification of a set of conservation criteria for the krill stock intended to help the Commission to meet its objectives for the stock and the wider ecosystem. These criteria are that the long term average krill spawning stock biomass (i.e. the total weight of reproductively mature individuals) should not fall below 75% of a reference level (SSB_0) and that the probability of the spawning stock biomass falling to 20% of SSB_0 should be no more than 10%. Constable et al. (2000) and

Miller & Agnew (2000) provide full details of these criteria and their underlying logic. See also https://www.ccamlr.org/en/fisheries/setting-catch-limits.

(2) Estimation of reference levels for spawning stock biomass (SSB_0), and unexploited biomass (B_0 which includes immature individuals and is necessarily greater than SSB_0).These estimates were originally based on data from the FIBEX survey conducted in 1981, which covered 0.55 million km^2 in subareas 48.1 to 48.3 (Trathan et al. 1995). These estimates have been updated based on the CCAMLR synoptic survey (SC-CAMLR- 2010a; Fielding et al. 2011) which provided data on krill biomass in 2 million km^2 of subareas 48.1 to 48.4 in January 2000.

(3) Estimation of a precautionary exploitation rate. This is the maximum proportion of B_0 that model projections suggest can be taken each season while ensuring that the conservation criteria for the krill stock are met. Constable and de la Mare (2003) provide details of the modelling process.

(4) Calculation of the precautionary catch limit, which is the precautionary exploitation rate multiplied by B_0.

Thus the precautionary catch limit is a long-term measure which is intended to help the Commission meet its objectives for the krill stock and for dependent and related species, providing that the underlying assumptions are robust and that it is used in conjunction with localised controls on catch. Because these localised controls have not yet been established, the trigger level remains the effective catch limit.

The trigger level is slightly higher than the sum of maximum historic catches in each subarea. The CCAMLR Scientific Committee, which advises the Commission, reported in 1991 that "there is no evidence thus far to suggest that historical catch levels in Statistical Area 48 [have] significantly impacted either on krill stocks or on associated predators dependent on these stocks for food" (SC-CAMLR 1991).

WHAT WAS THE CCAMLR SYNOPTIC SURVEY?

The CCAMLR synoptic survey was a major international research effort, involving four ships (Watkins et al. 2004, Hewitt et al. 2004). It was conducted in early 2000 and covered a nominal area of 2 million km^2. This compares with a total area for subareas 48.1 to 48.4 of about 3.5 million km^2. The survey used multi-frequency acoustics to assess the post-larval krill biomass (that is the total weight of individuals aged more than about 1 year) in the upper 500m of the water column. Krill are also found in lower numbers in deeper waters and have been recorded at the seabed to depths of 3500m (Clarke and Tyler 2008, Schmidt et al. 2011). The unsurveyed parts of the subareas also include suitable krill habitat (Atkinson et al. 2008). Therefore the survey estimate probably underestimates the total krill biomass in the four subareas.

The synoptic survey estimate of Antarctic krill biomass was 60.3 million tonnes (sampling CV, which measures how density varies between transects = 12.8%) (SC-CAMLR- 2010a; Fielding et al. 2011). The precautionary catch limit (5.61 million tonnes per season) specified in CM 51-01 is based on this estimate (SC-CAMLR-2010c) and was intended to apply over a number of years pending new information or improved methods (Constable et al. 2000, Hewitt et al. 2004). Consequently, the synoptic survey was designed as a single event. There was no intention to repeat the survey to provide regular assessments of krill biomass.

Since the trigger level, rather than precautionary catch limit, is currently the effective catch limit for the fishery, the biomass estimate from the synoptic survey does not currently influence the total amount that the fishery is allowed to catch.

WHAT OTHER INFORMATION IS AVAILABLE FOR ASSESSING VARIABILITY AND CHANGE IN THE KRILL STOCK?

There are several local krill monitoring programmes which provide annual estimates of krill biomass (Kinzey et al. 2015; Fielding et al. 2014; Skaret et al. 2015) in consistent survey areas covering 20%, 3% and 1% of subareas 48.1, 48.2, and 48.3 respectively (Figure 1 and Table 1). These monitoring programmes provide valuable information about year-to-year changes in the krill stock at relatively small spatial scales. The local biomass estimates for subareas 48.1 and 48.3, like that for the synoptic survey, are based on the analysis of acoustic data at three frequencies (38, 120 and 200 kHz), while the estimates for subarea 48.2 are based on the analysis of two-frequency combinations. SG-ASAM, CCAMLR's expert group on acoustics, endorses the use of the combination of 120 and 38 kHz (used in 2011 and 2014) but requires further assessment of other frequency combinations (including the combination of 120 and 70 kHz used in 2012) (SG-ASAM 2016).

Kinzey et al. (2015) provide biomass estimates for the local krill monitoring programme in 48.1 based on krill catches in scientific nets in addition to estimates based on acoustic data. Scientific netting is also conducted during other surveys, many of which are single surveys of a particular location rather than regular (e.g. annual) events. Net data have been used to indicate changes in krill abundance (e.g. Atkinson et al. 2004, 2014) and to model krill habitats (Atkinson et al. 2008).

Several studies have used the average size of krill in predator diets as an index of krill availability to those predators (Murphy et al. 2007; Forcada et al. 2008, Forcada & Hoffman, 2014). This is based on the observation that greater average sizes often indicate lower availability (Reid et al. 1999).

Catch per unit effort (CPUE), based on information from fishing vessels, is widely used as an index of abundance for fished species. Butterworth (1988), Mangel (1988) and Siegel et al. (1998) have previously concluded that CPUE is not an appropriate abundance index for krill, but in 2010 WG-SAM, CCAMLR's expert group on stock assessment, proposed further work on investigating “the utility of CPUE data from the fishery ... particularly in areas of Area 48 which have limited research survey data” (SC-CAMLR 2010b).

Fishing vessels are able to collect acoustic information during normal operations and fisheries observers already collect information on krill size, sex and reproductive status (Tarling et al. 2016). Both of these data sources offer potential insights into krill stock dynamics, particularly if fishing vessels incorporate a number of standard acoustic transects into their voyage plan. In the longer term, it might also be possible to monitor changes in the stock using unmanned underwater vehicles (e.g. Guihen et al. 2014) and acoustic moorings (e.g. Saunders et al. 2007).

Ongoing work within WG-EMM, CCAMLR's expert group on ecosystem monitoring and management, includes the development of an integrated stock assessment intended to make use of multiple data sources (including the fishery, surveys and krill predators) (SC-CAMLR 2010c) and to provide an alternative to synoptic surveys as a means of assessing krill stock status (SC-CAMLR 2007).

These current and potential data sources provide information on parts of the krill stock. More progress is needed to understand how the stock changes at larger scales (particularly across subareas 48.1 to 48.4). Recent krill habitat models (Atkinson et al. 2008, Silk et al. in press) show important relationships with features such as chlorophyll-a and sea level anomalies which vary over time and can often be determined using remote-sensed data. Such habitat models may be useful for linking data sources and scaling up local biomass estimates, especially if krill data from repeated larger scale surveys (e.g. conducted by fishing vessels) becomes available.

IS A SINGLE SYNOPTIC BIOMASS ESTIMATE SUFFICIENT?

CCAMLR does not have the resources to commission regular synoptic surveys. Thus the intention to manage the Antarctic krill fishery with a precautionary catch limit that applies over a number of years was pragmatic. However, in the period since the synoptic survey, various studies have demonstrated the degree to which krill populations change over time. These studies used some of the data introduced in the previous section to examine changes at a range of spatial scales. Data from scientific netting in subareas 48.1 to 48.4 shows a decline in the mean numerical density of post-larval krill in the 1980s (Loeb et al. 1997, Atkinson et al. 2004). A recent update shows that the high numerical densities which occurred in five of seven years from 1982 to 1988 did not occur in any subsequent year (Atkinson et al. 2014). It is important to recognise that numerical density (the number of krill under 1 m^2 of sea surface area) is different from biomass density (the total weight of krill under 1 m^2). Murphy et al (2007) show that net based estimates of low numerical density at the regional scale coincide with low biomass estimates from the local krill monitoring programme in subarea 48.3 (South Georgia), but there are no published studies which show how the reported decline in numerical density affects biomass at the regional scale. Nonetheless, in 2007 a group of experts suggested that, based on personal field experience of the ecosystem, it is likely that the krill biomass in subareas 48.1 (the South Shetlands and Bransfield Strait) and 48.2 (the South Orkneys) fell significantly between the 1970s and late 1980s (Watters et al. 2013).

The same group suggested that krill biomass also declined in subarea 48.3 between about 1980 and 2000.

Published studies indicate significant variability in krill biomass and abundance at various spatial scales. Local monitoring programmes produced biomass estimates below 25% of the long-term mean in 2 of 16 years in subarea 48.3, and 3 of 16 years in subarea 48.1 (Fielding et al. 2014; Kinzey et al. 2015). Net data show numerical densities below 25% of the long-term mean in 13 of 32 years for the sector 10ºE to 90ºW (Atkinson et al. 2014). It is unclear how variability in these indices relates to variability at the scale of subareas or the synoptic survey area. Some aspects of krill distribution are well described, including an association with shelf and shelf-break areas in the Scotia Sea (e.g. Trathan et al. 2003; Siegel 2005; Atkinson et al. 2008). However, it is unclear how this distribution varies over time (within and between years) and the extent to which krill move between areas, either through active migration or being carried on ocean currents (processes that are collectively known as “flux”) (Thorpe et al. 2004). Because of this uncertainty, it might be difficult to distinguish the effects on biomass or abundance estimates of changes in the biomass of the whole stock versus shifts in distribution. Changes in the timing of surveys relative to the timing of recruitment or immigration (i.e. when young krill join the adult population, or new krill arrive in the survey area) could also cause apparent changes in biomass or abundance indices. Nonetheless there is increasing evidence that observed changes are linked to environmental factors including sea ice extent and the climate (indicated by the Southern Annular Mode or ENSO variability) (Atkinson et al. 2004, Murphy et al. 2007, Loeb et al. 2010, Saba et al. 2014), which provides good evidence that the published time-series indicate real changes in krill populations.

With such variability, the single snapshot estimate of krill biomass provided by the synoptic survey is a highly uncertain representation of the unexploited biomass. If the snapshot estimate is higher than the mean unexploited biomass, the precautionary catch limit will represent a higher exploitation rate and be less precautionary than intended, and vice versa. This catch limit is based on model projections in which the conditions affecting the krill stock vary around constant averages (Constable & de la Mare 2003). If the krill stock declines over time due to factors other than fishing, then the precautionary catch limit that results from these model projections will become less precautionary than intended.

There are clear benefits to incorporating regular updates on stock status into the management of the krill fishery. Such updates will facilitate assessment of whether catch limits remain precautionary, and allow more robust estimation of uncertainties associated with biomass estimates.

IS A NEW SYNOPTIC SURVEY FEASIBLE?

A new synoptic survey would provide an updated snapshot estimate of krill biomass. This would be an appropriate basis for assessing and, if necessary, refining the precautionary catch limit. The synoptic survey also provided valuable additional information on the distribution and ecological role of krill (e.g. Reid et al. 2004; Siegel et al. 2004; Silk et al. in press). A new synoptic survey would provide a platform for further research into these factors, the understanding of which is important to ensure that management of the krill fishery remains consistent with the Commission's objectives. There is a significant potential for climate change to impact both the biomass and distribution of krill, and high uncertainty associated with attempts to predict this impact (Flores et al. 2012; Kawaguchi et al. 2013; Hill et al. 2013). Regular (circa decadal) synoptic assessments of krill biomass and distribution would be useful for monitoring such impacts and allowing timely adaptation of management measures. However, research vessel surveys have significant costs (surveying the 2000 synoptic grid would cost roughly US$3.4 million in ship time alone). A repeat survey using only research vessels (as in the 2000 survey) is therefore unlikely in the current economic climate. SG-ASAM has endorsed the use of fishing vessels to collect acoustic data on krill for addressing scientific questions (Watkins et al. in press). Future synoptic surveys are most likely to occur if they are supported by the fishing industry and make extensive use of fishing vessels for data collection.

HAS KRILL BIOMASS CHANGED SINCE THE SYNOPTIC SURVEY?

Table 2 shows biomass indices from local krill monitoring programmes. These data are a resource with which to address the concern that there might have been a systematic change in krill biomass since the CCAMLR 2000 synoptic survey. It is difficult to separate systematic change from natural variability in noisy time series such as these. Multi-decadal series (30 to 40 years of data, Henson et al. 2010) or parallel series that control for the putative cause of the change (Smith et al. 1993) are usually necessary to make such distinctions. Nonetheless, it is appropriate to consider the evidence, with the caveat that formal statistical tests have very low power (i.e. may not detect real changes). Each index features considerable year-to-year variability, the magnitude of which is indicated by the inter-annual CV. The three indices have similar CVs (51% to 75%). Table 3 presents statistics for each post-2000 index, including correlations with year and inter-annual averages for the first and last 6 year period in the time series. P values less than 0.05 are generally taken to indicate a real effect. Therefore there is no evidence of a systematic change in any of the indices. Saba et al. (2014) also found no evidence of a decline in the southern part of subarea 48.1 between 1991 and 2012. This evidence, together with information from Atkinson et al. (2014) suggests a period of relative stability in both abundance and biomass in the early 21st century. This relative stability follows a probable reduction in krill abundance in the late 20th century (Atkinson et al. 2004, 2014, Watters et al. 2013).

IS CURRENT MANAGEMENT PRECAUTIONARY FOR THE KRILL STOCK?

The main consideration in assessing the implications of current management for the krill stock is whether the effective catch limit (trigger level) and its division amongst subareas is precautionary. In the context of CCAMLR's conservation objectives, this means that these measures should be likely to prevent fishing from reducing the stock below the level "which ensures the greatest net annual increment". This level is generally referred to as the biomass corresponding to maximum sustainable yield (B_{MSY}) and is an international standard for managing high seas fisheries, which is explicitly stated in the United Nations Convention on Law of the Sea (article 61.3). Theory suggests that B_{MSY} occurs at approximately 25% to 50% of the unexploited biomass (Worm et al. 2009). However, because of the obligation to maintain ecological relationships, the precautionary catch limit is designed to maintain average krill biomass above B_{MSY}, at 75% of unexploited biomass (Miller & Agnew 2000, Constable et al. 2000). This is an arbitrary but conservative midpoint between the 50% level suggested by theory and the 100% level that represents no fishing (Hill et al. 2006). The precautionary catch limit was calculated using the biomass estimate for 2000 as a proxy for unexploited biomass. This assumed equivalence was justified on the basis that catches had always been low relative to biomass (Hewitt et al. 2004). Indeed the results of the synoptic survey suggest that the maximum historic catch (0.53 million tonnes in 1981/1982) was <1% of biomass. Thus, the precautionary catch limit, which is higher than the trigger level, aims to maintain krill biomass above the level specified in CCAMLR's conservation objectives.

The precautionary catch limit is equivalent to 9.3% of the biomass estimate for 2000. If fishing were to reduce biomass to 75% of the 2000 level, the precautionary catch limit would be equivalent to 12.4% of this new biomass. These exploitation rates are conservative compared to those that would reduce the biomass to B_{MSY}.

The trigger level is equivalent to ~1% of the estimated krill biomass in 2000. A model-based study suggested that fishing at the trigger level would, over time, reduce krill biomass by 2% resulting in a small increase in exploitation rate to 1.05% (SC-CAMLR 2011). However the difficulty remains that this apparently low exploitation rate is based on the biomass estimate for a single year (2000). It is appropriate to evaluate how management measures perform over time.

Biomass estimates from local krill monitoring programmes indicate the minimum known biomass in each subarea. Comparing these with subarea catches (Table 4) gives a maximum feasible exploitation rate in each year. In subarea 48.1, this maximum has been consistently below 9%. In subarea 48.2, it was below 3% of the local biomass estimate in each year with comparison data. In subarea 48.3, it was below 22% in all years except 2000, when it was apparently 88%.

These comparisons with local krill biomass estimates are a useful starting point for evaluating the performance of management measures, but each subarea clearly supports more krill biomass than is observed in the local krill monitoring programme. The programmes in subareas 48.1 and 48.3 provided biomass estimates in the year

2000, so direct comparisons with the synoptic survey are possible. This puts the seemingly high exploitation rate for 2000 in 48.3 into perspective as the catch represents about only 0.2% of subarea krill biomass.

It is also possible to extrapolate local biomass estimates to the subarea scale based on the ratios of biomass estimates at the two scales in 2000 (Table 5). There is no local biomass estimate for subarea 48.2 for the year 2000, so Table 5 uses the mean of the available local estimates. However, this crude scaling risks overestimating subarea biomass. A more conservative scaling using the maximum biomass estimate from each local krill monitoring programme gives a series of plausible estimates of minimum krill biomass in each subarea. The crude scaling suggests that the local monitoring programmes observe about 14% of the krill biomass in the synoptic survey area while the conservative scaling suggests that this figure may be as high as 26%. The conservative scaling also suggests that local monitoring programmes observe 8% to 37% of the biomass in each subarea.

It is therefore possible to calculate indicative exploitation rates by comparing subarea catches and catch limits (as specified in CM 51-07) with estimates of the biomass in the whole subarea. Given the uncertainties in the scaling, it is appropriate to use the biomass estimates based on the conservative scaling (Figs 2 to 4).

Although useful for assessing exploitation rates, these scaled biomass estimates do not provide any new information on variability. Catches are low compared to some of the scaled biomass estimates for each subarea, so it is necessary to show these two variables on different axes. The indicative exploitation rates associated with reported catches has consistently been below 4%, 1% and 2% for subareas 48.1, 48.2 and 48.3 respectively (Table 6).

CCAMLR considers that the exploitation rate associated with the precautionary catch limit (9.3%) is currently appropriate for meeting its conservation objectives for Antarctic krill (SC-CAMLR 2010c). Therefore, apparent exploitation rates above this level require further exploration. In subareas 48.1 and 48.3 the average indicative exploitation rate associated with the subarea catch limits was 6%, but high indicative exploitation rates (>9.3%) occurred in 3 of 15 and 2 of 16 years respectively. These fluctuations are associated with variability in the local biomass estimates.

This comparison, based on conservative estimates of subarea biomass, suggests that the trigger level together with the subarea catch limits generally ensure low exploitation rates but might allow occasional relatively high exploitation rates in the worst case scenario (where true biomass is as low as the conservative estimate). The trigger level effectively limits the overall exploitation rate for subareas 48.1 to 48.3 to an average of <7% (Table 6). The local catch limits specified in CM-51-07 ensure that the exploitation rate in each subarea also averages <7%.

Table 7 shows indicative exploitation rates for a set of scenarios in which the entire trigger level is caught in one subarea. In these scenarios, the indicative exploitation rate for subarea 48.1 exceeds 9.3% in most years and that for 48.3 exceeds 9.3% in half of all years. CM 51-07 is designed to prevent such concentration of catches and, as a result of this measure, the fishery in subarea 48.1 has been closed in 4 years (2010, 2013, 2014 and 2015) when it approached the 155,000 tonne limit. This has clearly contributed to the maintenance of low exploitation rates.

DOES CURRENT MANAGEMENT PROTECT KRILL PREDATORS?

The conservation criteria for the krill stock make some provision for the dependent and related populations mentioned in the Convention. Specifically, the objective of maintaining average biomass above 75% of B_0 aims to reserve part of the stock's production (new biomass resulting from recruitment and growth) for predators and is consistent with recent recommendations for fisheries targeting forage species (Smith et al. 2011). By maintaining exploitation rates below 9.3% the trigger level provides additional protection for predators (Miller & Agnew 2000, Constable et al. 2000).

The Commission also needs to manage the risk of concentrated fishing in sensitive areas, such as predator foraging grounds. CM 51-07 notes "that the distribution of the trigger level needs to provide for flexibility in the location of fishing in order to ... alleviate the potential for adverse impacts of the fishery in coastal areas on land-based predators" and that "advances are urgently needed as the trigger level itself is not related to the status of the krill stock". Some post-hoc evidence on the performance of CM 51-07 is available from a model-based risk assessment (Watters et al. 2013). This study modelled 34 predator populations in subareas 48.1 to 48.3

and simulated fishing at the trigger level, distributed between subareas according to reported catches and the catch limits specified in CM 51-07. It assessed the risk of the fishery depleting predator populations by 25%. For most of the 34 predator populations considered, the risk associated with the trigger level was negligible, but for six populations this probability of depletion was between 1% and 12%. The risk to all populations was negligible when catches were below 65% of the trigger level, which equates to 0.4 million tonnes. Current annual catches remain below 0.3 million tonnes.

The trigger level prevents excessive exploitation of the krill stock at the regional scale (subareas 48.1 to 48.4) and therefore protects a vital food source for predators. However, the Commission acknowledges that this does not necessarily protect sensitive areas. CM 51-07 provides additional protection, but its wording acknowledges the need for more scientifically-based management measures.

CONCLUSIONS

Local krill monitoring programmes in subareas 48.1, 48.2 and 48.3 indicate considerable inter-annual variability but provide no evidence of a systematic change in krill biomass. Catches within subareas have always been <22% (and mainly <3%) of the biomass observed in these monitoring programmes which, in turn, represent <37% of the krill biomass in the whole subarea. The exploitation rates associated with current catches (<4%) are low compared to benchmarks for fisheries management in general and the krill stock in particular. Thus the catch levels seen in the last two decades are unlikely to have adversely impacted the krill stock as a whole or in each subarea.

The trigger level and the associated subarea catch limits are generally precautionary with average exploitation rates <6%, but they could allow relatively high exploitation rates in years when biomass is low. This conclusion is based on conservative estimates of subarea biomass, which are appropriate in the absence of direct estimates. Until better information is available to monitor exploitation rates, the subarea catch limits specified in CM 51-07 should be maintained to minimise the risk of even higher exploitation rates.

The Commission recognises that neither the precautionary catch limit nor the trigger level is sufficient to prevent concentrated fishing in sensitive areas and acknowledges that “advances are urgently needed” (CM 51-07). Understanding the effects of the fishery on krill stocks and on dependent and related populations requires improved information on the krill stock (biomass, stock structure and, ideally, production) at scales that are relevant to the Commission’s conservation objectives. The challenge is to develop an effective monitoring system for the krill stock which makes efficient use of the available resources. The current study demonstrates that information from local krill monitoring programmes is useful for the provision of management advice (in this case, evaluating management measures) but is limited by the relatively small spatial coverage of these programmes. The value of these programmes could be enhanced by improving understanding of the relationship between the local biomass and biomass at the larger (subarea or regional) scale. Habitat modelling might help to improve this understanding by assessing how krill biomass varies with environmental characteristics. This work will also require data on krill biomass and distribution at the larger scale. CCAMLR’s ongoing work with commercial operators provides an opportunity to acquire these data via surveys conducted using commercial vessels.

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Table 1. Summary of local krill monitoring programmes in subareas 48.1 to 48.3

Subarea	Organisation	Type	Start year	Survey area (km^2)	Subarea (km^2)
48.1	US-AMLR (US)	acoustic/net	1992	125,000	639,317
48.2	IMR (Norway)	acoustic/net	2011	27,000*	856,086
48.3	BAS (UK)	acoustic	1997	10,560	1,029,732

* The survey area is 65,000 km^2, but comparisons are based on a 27,000 km^2 stratum.

Table 2. Biomass indices from local krill monitoring programmes (tonnes km^{-2}).

Year	48.1 (Kinzey et al. 2015)	48.2 Skaret et al. 2015)*	48.3 (Fielding et al. 2014)
1996	35.5		
1997	46.5		31.7
1998	20.7		38.9
1999	7.8		9.7
2000	23.6		2.7
2001	4.1		36.7
2002	2.2		137.0
2003	16.6		84.6
2004	3.7		26.1
2005	5.9		89.4
2006	9.7		119.1
2007	32.4		61.1
2008	16.8		
2009	16.1		28.8
2010	13.3		15.1
2011	13.2	212.8	59.0
2012		94.8	90.1
2013			61.8
2014		301.4	31.1

*The three estimates for 48.3 presented here are based on the analysis of 120 kHz data plus either 38 kHz in 2011 and 2014 or 70 kHz in 2012.

Table 3. Summary statistics for biomass indices in Table 2. r indicates the correlation between year and biomass for the post-1999 period.

Statistic	48.1	48.2	48.3
r	0.22	0.59	-0.08
P (trend)	0.25	0.12	0.49
	2000-2005		*2000-2005*
mean	9.4		70.8
CV	0.9		0.8
	2006-2014		*2009-2014*
mean	16.9	203.0	47.6
CV	0.5	0.5	0.6
P (difference in means)	0.15		0.53

Table 4. Subarea catch as a percentage of the biomass estimate from the local krill monitoring programme (where available).

Year	48.1	48.2	48.3
1996	1%		
1997	1%		8%
1998	2%		7%
1999	4%		1%
2000	2%		88%
2001	9%		14%
2002	4%		3%
2003	2%		7%
2004	3%		21%
2005	1%		5%
2006	7%		1%
2007	0%		3%
2008	0%		
2009	2%		0%
2010	9%		5%
2011	1%	2%	9%
2012		1%	6%
2013			5%
2014		1%	
Maximum	9%	2%	88%
Average	3%	1%	11%

Table 5 Comparison of subarea krill biomass (tonnes) estimated in the CCAMLR 2000 synoptic survey (from Fielding et al. 2014) with local biomass estimates from krill monitoring programmes.

Subarea	Synoptic estimate	Local estimate (2000)	Subarea /local	Local estimate (max)	Subarea /local
48.1	15,892,735	2,950,000	539%	5,812,500	273%
48.2	24,638,790	5,480,370*	450%	8,137,530	303%
48.3	17,211,300	28,934	59484%	1,447,037	1189%
48.4	2,553,600				
Total	60,296,425	8,459,304	713%	15,397,067	392%

* There is no local estimate for the year 2000 for subarea 48.2. The value shown is the mean of the 2011, 2012 and 2014 estimates.

Table 6 Indicative exploitation rates (catch metric divided by lower scaled biomass for each subarea) associated with subarea catch limits and reported catches. The "All" column shows the trigger level divided by the sum of available lower scaled biomass estimates (and is therefore likely to overestimate exploitation rates when the set of scaled estimates is incomplete). Results for 2000 are not shown as the results of the CCAMLR 2000 synoptic survey (Table 5) offer a definitive comparison for this year.

	Subarea catch limit/lower scaled biomass				Subarea catch/lower scaled biomass		
Year	48.1	48.2	48.3	All	48.1	48.2	48.3
1996	1%			5%	1%		
1997	1%		7%	3%	0%		1%
1998	2%		6%	5%	1%		1%
1999	6%		23%	16%	1%		0%
2000							
2001	11%		6%	10%	3%		1%
2002	21%		2%	3%	1%		0%
2003	3%		3%	4%	1%		1%
2004	12%		9%	14%	1%		2%
2005	8%		2%	5%	0%		0%
2006	5%		2%	3%	3%		0%
2007	1%		4%	3%	0%		0%
2008	3%			11%	0%		
2009	3%		8%	7%	1%		0%
2010	3%		15%	10%	3%		0%
2011	3%	2%	4%	2%	0%	0.7%	1%
2012		4%	2%	3%		0.4%	0%
2013			4%	8%			0%
2014		1%		3%		0.3%	
Maximum	21%	4%	23%	16%	3%	1%	2%
Average	6%	2%	6%	6%	1%	0%	1%

Table 7 Indicative exploitation rates (catch metric divided by lower scaled biomass for each subarea) associated with fishing at the trigger level in each subarea. Results for 2000 are not shown as the results of the CCAMLR 2000 synoptic survey (Table 5) offer a definitive comparison for this year.

	Whole trigger/lower scaled biomass		
Year	48.1	48.2	48.3
1996	5%		
1997	4%		16%
1998	9%		13%
1999	23%		51%
2000			
2001	44%		13%
2002	83%		4%
2003	11%		6%
2004	49%		19%
2005	31%		6%
2006	19%		4%
2007	6%		8%
2008	11%		
2009	11%		17%
2010	14%		33%
2011	14%	4%	8%
2012		8%	5%
2013			8%
2014		3%	17%
Maximum	83%	8%	51%
Average	22%	5%	14%

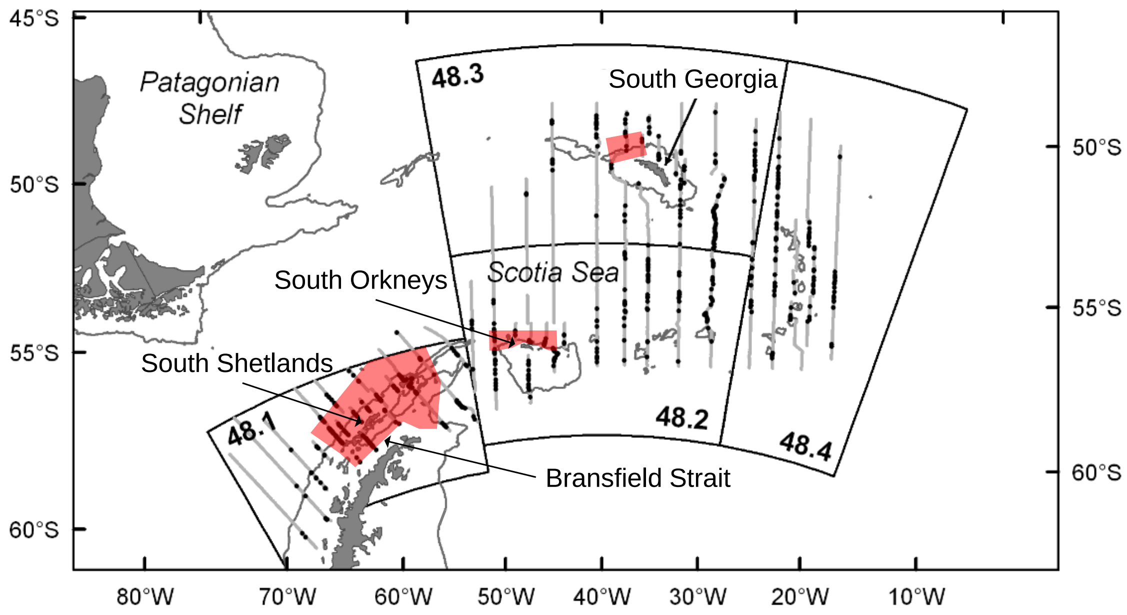

Figure 1. The main krill fishing area in the Southern Ocean, showing CCAMLR subareas 48.1 to 48.4, the CCAMLR 2000 synoptic survey transects (grey lines: black dots indicate locations of high krill biomass), and the areas surveyed in local krill monitoring programmes (red polygons). The local krill monitoring area shown in subarea 48.2 is the smaller stratum used for between-year comparisons.

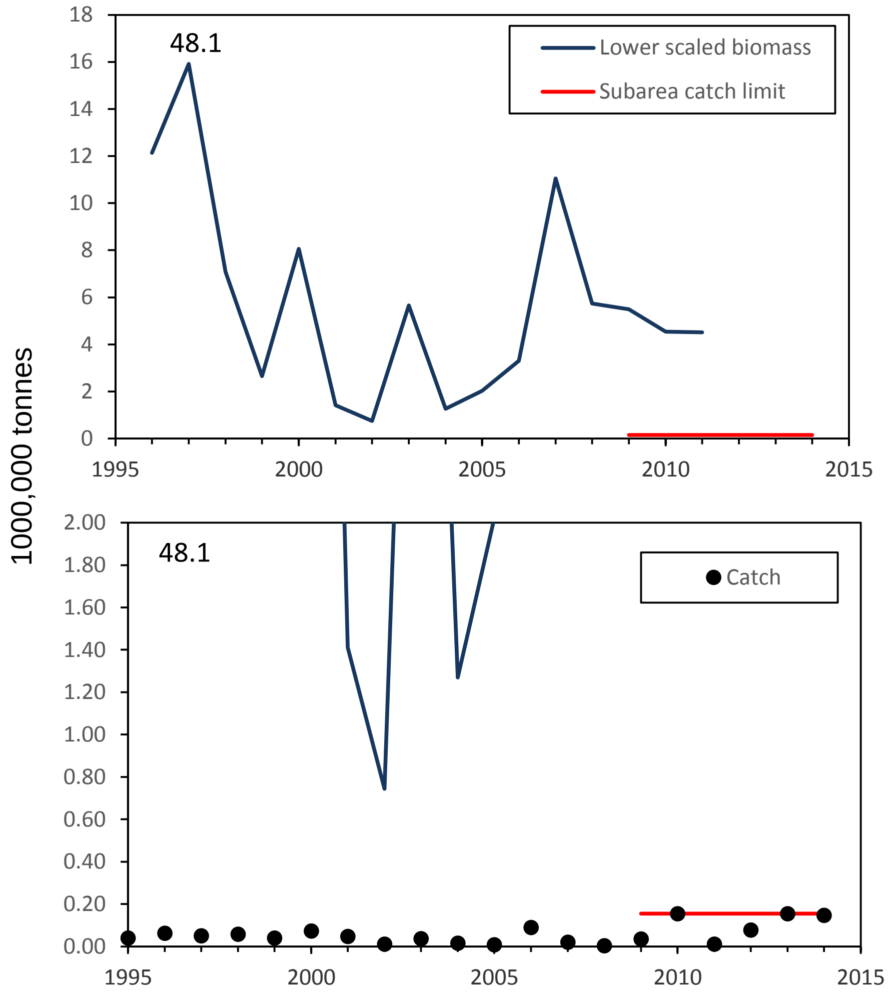

Figure 2. Conservative estimates of krill biomass for subarea 48.1 (calculated by scaling up biomass estimates from the local krill monitoring programme) shown in comparison with the subarea catch limit specified in CM 51-07, and annual catches.

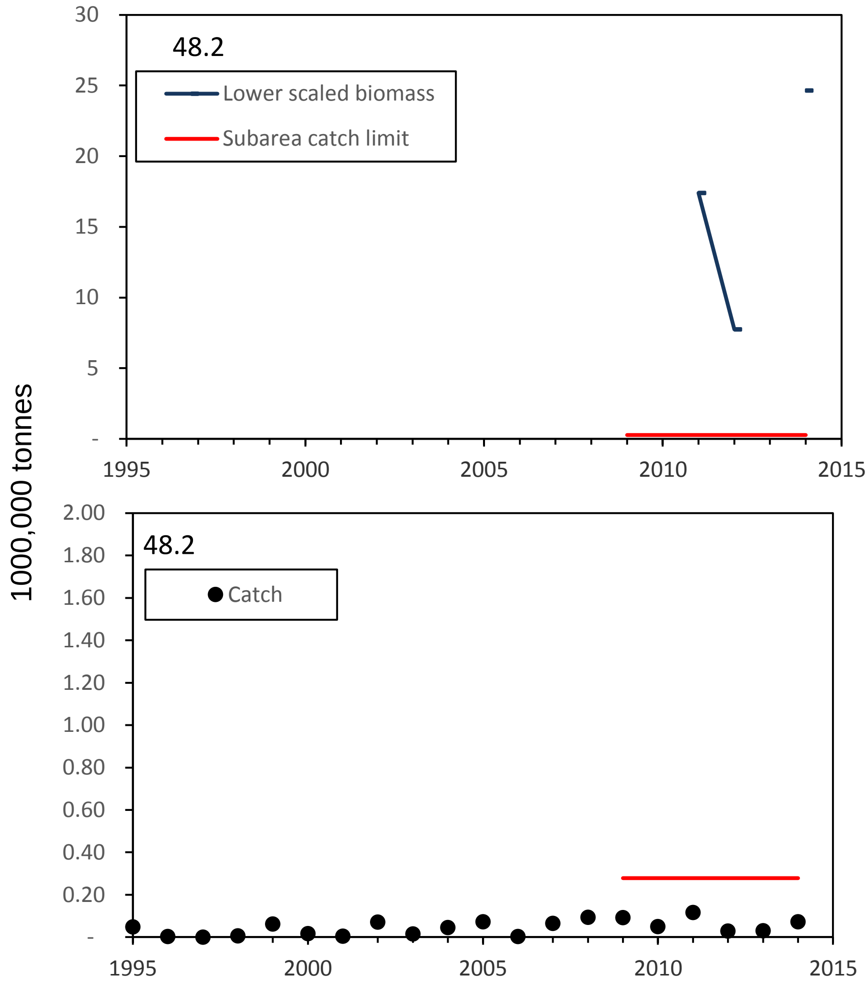

Figure 3. Conservative estimates of krill biomass for subarea 48.2 (calculated by scaling up biomass estimates from the local krill monitoring programme) shown in comparison with the subarea catch limit specified in CM 51-07, and annual catches.

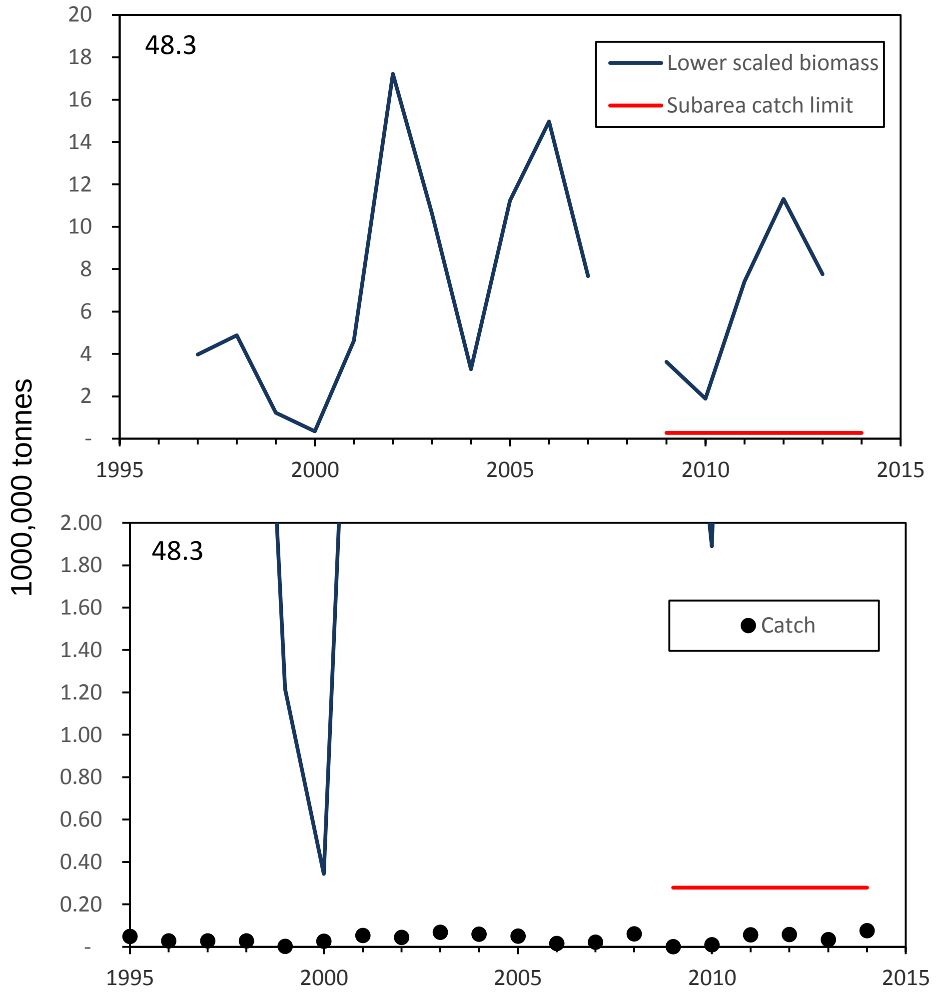

Figure 4. Conservative estimates of krill biomass for subarea 48.3 (calculated by scaling up biomass estimates from the local krill monitoring programme) shown in comparison with the subarea catch limit specified in CM 51-07, and annual catches.