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

S.L. Hill✉
British Antarctic Survey
High Cross, Madingley Road
Cambridge CB3 0ET
United Kingdom
Email – sih@bas.ac.uk

A. Atkinson
Plymouth Marine Laboratory
Prospect Place, Plymouth
Devon PL1 3DH
United Kingdom

C. Darby
CEFAS
Pakefield Road, Lowestoft
Suffolk NR33 0HT
United Kingdom

S. Fielding
British Antarctic Survey
High Cross, Madingley Road
Cambridge CB3 0ET
United Kingdom

B.A. Krafft, O.R. Godø and G. Skaret
Institute of Marine Research
Nordnesgaten 50, 5005 Bergen
Norway

P.N. Trathan and J.L. Watkins
British Antarctic Survey
High Cross, Madingley Road
Cambridge CB3 0ET
United Kingdom

Abstract

This paper explains the management of the Antarctic krill (*Euphausia superba*) fishery in the Atlantic sector of the Southern Ocean, and current knowledge about the state of the regional krill stock. In this region, krill fishing is permitted in an area of approximately 3.5 million km^2 which is divided into four subareas (labelled Subareas 48.1 to 48.4) for management and reporting purposes. 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. Each subarea has also had its own catch limit, between 0.093 and 0.279 million tonnes year^{-1}, since 2009. There is some evidence for a decline in the abundance of krill in the 1980s, but no evidence of a further decline in recent decades. Local-scale monitoring programs have been established in three of the subareas to monitor krill biomass in survey grids covering between 10 000 and 125 000 km^2. Cautious extrapolation from these local monitoring programs provides conservative estimates of the regional biomass in recent years. This suggests that fishing at the trigger level would be equivalent to a long-term exploitation rate (annual catch divided by biomass) of <7%, which is below the 9.3% level considered appropriate to maintain the krill stock and support krill predators.

Subarea catch limits exceed 9.3% of conservatively estimated subarea biomass 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 trigger level since 1991. Comparison with the 9.3% reference exploitation rate suggests that current management is precautionary at the regional scale. The subarea catch limits help prevent excessive concentration of catch at the subarea scale. Finer-scale management might be necessary to manage the risk of adverse impacts which might occur as a result of concentrated fishing in sensitive areas or climate change. Frequent assessment of the krill stock will enhance CCAMLR's ability to manage these risks. Continuing the local monitoring programs will provide valuable information on krill variability, but more information is required on how the monitored biomass relates to biomass at the subarea and regional scales.

Introduction

Krill are highly abundant marine crustaceans, some species of which are fished for various products including meal and oil rich in omega-3. The world's largest krill fishery targets Antarctic krill (*Euphausia superba*) in the Atlantic sector of the Southern Ocean and is managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Antarctic krill is a major food source for many whales, seals, birds, fish and invertebrates, although few of these feed exclusively on krill. This importance to predators is a major consideration in the management of the fishery.

The current paper is intended to provide an accessible overview of this management and the status of the Antarctic krill stock in the Atlantic sector (CCAMLR Statistical Subareas 48.1 to 48.4; Figure 1), and to assess whether management is precautionary. Krill fishing is also permitted in the Indian Ocean sector (Divisions 58.4.1 and 58.4.2) but it currently occurs only in Subareas 48.1 to 48.3, around the South Shetland Islands, the South Orkney Islands and South Georgia, and in Bransfield Strait. There have been no reported catches in Subarea 48.4 (the South Sandwich Islands) since 1992.

The following sections use 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 compare the effective catch limits (the amount of krill that the fishery is currently allowed to catch) with biomass estimates; and to assess whether these catch limits are precautionary. The section headings state the questions, and the answers present any evidence available from the primary literature.

What are CCAMLR's objectives?

CCAMLR's management of the krill fishery follows the principles set out in Article II of the Convention on the Conservation of Antarctic Marine Living Resources (www.ccamlr.org/node/74528). 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.

What does precautionary mean?

CCAMLR follows a precautionary approach. This approach is generally used when it is difficult to assess the risks associated with an action (such as fishing). Precautionary policies 'reduc[e] the probability of occurrence of bad events within acceptable limits' when the potential for these events is plausible but not necessarily demonstrated 'and the potential costs are significant' (Garcia, 1996). In a general sense, the 'bad events' that are relevant to krill fishery management are those which prevent CCAMLR from achieving its objectives.

It is appropriate to assess whether policies remain precautionary as circumstances change and new information becomes available. The current paper aims to use the available evidence to assess whether the current catch limits for krill in the Atlantic sector are indeed precautionary. This assessment therefore needs a practical definition of 'precautionary'. Hewitt et al. (2002) explain an implementation of the precautionary approach which aims to maintain the krill stock and support krill predators and which is further described in the next section. This implementation results in a precautionary exploitation rate (the percentage of an initial biomass that can be caught each year) of 9.1%. The inputs to this implementation were updated in 2010 and the precautionary exploitation rate was revised upwards to 9.3% (SC-CAMLR, 2010a).

The 9.3% exploitation rate is a reference point for assessing current catch limits. If the catch limits ensure that exploitation rates are below 9.3%, then the catch limits are precautionary by the logic of Hewitt et al. (2002). The section headed ‘Is current management precautionary for the krill stock?’ presents this assessment and explores the relationship between the 9.3% reference point and other reference points considered appropriate for maintaining fished stocks.

The 9.3% exploitation rate is intended to reserve sufficient krill production (new biomass resulting from recruitment and growth) to support predator populations, and is therefore a relevant reference point in assessing whether current catch limits help CCAMLR to meet its objectives for the wider ecosystem. However, these objectives are ambiguous, meaning that there is no consensus on what bad events management should seek to minimise (Hill, 2013) and, therefore, limiting the scope of the current assessment. The section headed ‘Is current management precautionary for krill predators?’ discusses these issues further.

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 (www.ccamlr.org/node/57043). The main conservation measure governing the Antarctic krill fishery in Subareas 48.1 to 48.4 is Conservation Measure (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 CCAMLR 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. CCAMLR also agrees that excessive concentration of this catch in any part of the region might be harmful to either the krill stock or the wider ecosystem. The localised catch controls necessary to prevent this possible harm have not yet been established, so the trigger level limits the catch that can be taken in the interim. 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:

(i) Identification of a set of conservation criteria for the krill stock intended to help CCAMLR to meet its objectives for the stock and the wider ecosystem. These criteria are that the median krill spawning stock biomass (i.e. the total weight of reproductively mature individuals) after 20 years of fishing should not be below 75% of a reference level (the median of SSB_0 estimates) and that the estimated probability of the spawning stock biomass falling to 20% of the reference level at any time should be no more than 10%. Constable et al. (2000) and Miller and Agnew (2000) provide full details of these criteria and their underlying logic. See also www.ccamlr.org/node/74616.

(ii) Estimation of reference levels for unexploited spawning stock biomass (SSB_0), and unexploited biomass (B_0, which includes immature individuals, and is 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 2000 Krill Synoptic Survey of Area 48

(CCAMLR-2000 Survey) (SC-CAMLR, 2010b; 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.

(iii) 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.

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

This approach provides specific definitions of the bad events that it is trying to avoid (spawning stock biomass falling below 75% and 20% of the reference level) and one of the 'acceptable limits' on risk (10% probability of falling below 20%).

The precautionary catch limit is for the whole of Subareas 48.1 to 48.4. It was intended to be allocated 'between smaller management units' and to help CCAMLR to meet its objectives, providing that the underlying assumptions are robust. Because the spatial allocation has not yet been established, the trigger level remains the effective catch limit.

The trigger level was calculated as the 'sum of the maximum catch in each subarea' (Subareas 48.1 to 48.4) (SC-CAMLR, 1991), although current data suggest that the sum of maximum pre-1991 catches in each subarea was 0.68 million tonnes (Table 1). 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-2000 Survey?

The CCAMLR-2000 Survey was a major international research effort, involving four ships (Watkins et al., 2004; Hewitt et al., 2002, 2004a). It was conducted in early 2000 and covered an area of about 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 500 m of the water column. Krill are also found in lower numbers in deeper waters and have been recorded at the seabed to depths of 3 500 m (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 probably underestimated the total krill biomass in the four subareas.

The CCAMLR-2000 Survey estimate of Antarctic krill biomass was 60.3 million tonnes (sampling CV, which measures how density varies between transects = 12.8%) (SC-CAMLR, 2010b; 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, 2010a) and was intended to apply over a number of years pending new information or improved methods (Constable et al., 2000; Hewitt et al., 2002, 2004a).

Since the trigger level, rather than the precautionary catch limit, is currently the effective catch limit for the fishery, the biomass estimate from the CCAMLR-2000 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-scale krill monitoring programs 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 (Table 2 and Figure 1). These monitoring programs 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 CCAMLR-2000 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. CCAMLR's Subgroup on Acoustic Survey and Analysis Methods (SG-ASAM) endorses the use of the combination of 120 and 38 kHz used in 2011 and 2014 in Subarea 48.2, but requires further assessment of other frequency combinations (including 120 and 70 kHz, as used in 2012) (SC-CAMLR, 2016).

Table 1: The numerical basis of the 'trigger level': The maximum krill catches in each subarea in the period before 1991 based on data available in 1991 (CCAMLR, 1991) and in 2015 (CCAMLR, 2015). The table also shows the fishing season in which each maximum occurred.

Subarea	CCAMLR (1991)		CCAMLR (2015)	
	Maximum (tonnes)	Season	Maximum (tonnes)	Season
48.1	105 554	1988/89	105 554	1988/89
48.2	257 695	1981/82	258 596	1981/82
48.3	256 206	1986/87	312 134	1986/87
48.4	10	1982/83	19	1972/73
Total	619 465		676 303	

Table 2: Summary of local krill monitoring programs 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 the area accessible each year varies with ice coverage. Comparisons are therefore based on a 27 000 km^2 stratum at the northern end of the survey area.

Kinzey et al. (2015) provide biomass estimates for the local krill monitoring program in Subarea 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, 2008, 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 and 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 CCAMLR's Working Group on Statistics, Assessments and Modelling (WG-SAM) 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, 2010c).

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 CCAMLR's Working Group on Ecosystem Monitoring and Management (WG-EMM) includes the development of an integrated stock assessment model intended to make use of multiple data sources (including the fishery, surveys and krill predators) (SC-CAMLR, 2010a) and to provide an alternative to synoptic surveys as a means of assessing krill stock status (SC-CAMLR, 2007).

These current and potential methods 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., 2016) 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. Habitat models may be useful for linking data sources and scaling up local biomass estimates, especially if krill data from repeated larger-scale surveys become available.

Is a single synoptic biomass estimate sufficient?

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 CCAMLR-2000 Survey, various studies have demonstrated the degree to which krill populations change over time. Some of these studies, which are discussed in the section headed 'Is the krill stock declining?', also suggest that krill might be less abundant now than it was several decades ago.

Irrespective of whether the krill stock has declined, most long-term studies indicate significant variability in krill biomass and abundance at various spatial scales. Local monitoring programs 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 10°E to 90°W (Atkinson et al., 2014).

It is unclear how the observed variability relates to variability at the scale of subareas or the CCAMLR-2000 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 indices of changes in the size 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 climate fluctuations (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). These linkages provide evidence that the published indices indicate real changes in krill populations.

With such variability, the single snapshot estimate of krill biomass provided by the CCAMLR-2000 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. The precautionary catch limit is based on model projections in which the conditions affecting the krill stock vary around constant averages (Constable and 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 calculation of revised catch limits. They will also allow more robust estimation of uncertainties associated with biomass estimates.

Is a new synoptic survey likely?

A new synoptic survey would provide an updated snapshot estimate of krill biomass. The CCAMLR-2000 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., 2016). 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 CCAMLR'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; Piñones and Fedorov, 2016). 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 CCAMLR-2000 Survey grid would cost several million dollars in ship time alone). A repeat survey using only research vessels (as in the CCAMLR-2000 Survey) is therefore unlikely in the current economic climate. SG-ASAM has encouraged the use of fishing vessels to collect acoustic data on krill for addressing scientific questions (Watkins et al., 2016). However, there are no concrete plans at present for a new synoptic survey using either research or fishing vessels.

Is the krill stock declining?

There is a perception that the 'krill stock is already experiencing a long-term decline' (Piñones and Fedorov, 2016). According to simulations, harvesting the trigger level each year for 20 years would reduce the krill stock by 2% (SC-CAMLR, 2011). Clearly, any significantly greater decline since the CCAMLR-2000 Survey would reduce the validity of the precautionary catch limit and the 9.3% reference exploitation rate.

Loeb et al. (1997) analysed the numerical density of post-larval krill from scientific nets around Elephant Island in Subarea 48.1 and stated that 'densities from 1984/85 until 1995/96 were on average an order of magnitude less than during previous years' (beginning 1977/78). Data from a larger set of scientific net samples in Subareas 48.1 to 48.4 also showed a decline in the mean numerical density of post-larval krill in the 1980s (Atkinson et al., 2004, 2008). 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) and that there was no further decline between 1989 and 2011 (the last year of data analysed). Loeb and Santora (2015) show no evidence of a decline between 1992 and 2009 in net samples from the local monitoring program in Subarea 48.1, and Steinberg et al. (2015) conclude that there was no decrease between 1993 and 2013 in the southern part of Subarea 48.1.

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 of sea surface area). 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 program 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 (South Shetland Islands and Bransfield Strait) and 48.2 (South Orkney Islands) 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.

Biomass indices from local krill monitoring programs (Table 3) show no evidence of a decline since the CCAMLR-2000 Survey (Table 4). 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 potential cause of change (Smith et al., 1993) are usually necessary to make such distinctions. Also, the relationship between local biomass indices and biomass of the whole stock is unknown. Therefore, the absence of evidence for a post-2000 decline is not definitive evidence of the absence of a post-2000 decline. Indeed, definitive identification of changes in the krill stock might only be possible with repeated assessments of stock status at the scale of the CCAMLR-2000 Survey. However, it is clear that the perception of an ongoing decline is based on data collected before the CCAMLR-2000 Survey, whereas none of the published krill numerical density and biomass time series show a decline since 2000.

Table 3: Biomass indices from local krill monitoring programs (tonnes km^{-2}).

Year	Subarea		
	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 Subarea 48.2 presented here are based on the analysis of 120 kHz data plus either 38 kHz in 2011 and 2014 or 70 kHz in 2012. Although a survey was conducted in Subarea 48.2 in 2013, the vessel could not access the whole stratum due to ice cover.

Table 4: Two statistical tests for a decline (between 2000 and 2014) in the biomass indices shown in Table 3. A negative correlation (*r*) between year and biomass, or a late period mean that is lower than the early period mean could indicate a decline, if the *P* value indicated a low probability (generally $P < 0.05$) that the result was due to chance. None of the tests indicate a decline.

Statistic	Subarea		
	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

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 the 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 requirement to maintain ecological relationships, the precautionary catch limit is designed to maintain average krill biomass above B_{MSY}, at 75% of unexploited biomass (Miller and 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., 2004a). Indeed, the results of the CCAMLR-2000 Survey suggest that the maximum historic catch (0.40 million tonnes in 1986/87) was <1% of biomass.

The precautionary catch limit is equivalent to 9.3% of the biomass estimate for 2000, which is conservative compared to the exploitation rates that would reduce the biomass to B_{MSY}. The trigger level is equivalent to ~1% of the estimated krill biomass in 2000, but would increase to ~1.05% if fishing at this level reduced krill biomass by 2% as simulations suggest (SC-CAMLR, 2011). These exploitation rates are clearly precautionary. However, the difficulty remains that this comparison is based on the biomass estimate for a single year (2000). It is appropriate to evaluate how management measures perform over time.

The logic underlying the CCAMLR-2000 Survey and the precautionary catch limit is that the krill in the survey area constitute a single coherent stock. On that basis the regional scale (e.g. the CCAMLR-2000 Survey area or the whole of Subareas 48.1 to 48.4) might be appropriate for calculating annual exploitation rates and assessing whether they are precautionary for the krill stock. However, there are further spatial considerations. Firstly, the available time-series data on krill biomass are for small fractions of the CCAMLR-2000 Survey area, and any extrapolation of these to the regional scale is highly uncertain. Secondly, the requirement to maintain ecological relationships means that the smaller scales at which these relationships exist (e.g. the foraging ambits of krill predators) are also important. The following section further discusses this second point. The current section assesses whether annual exploitation rates are precautionary at the successively larger scales of the local surveys, individual subareas and the whole region.

Local krill monitoring programs indicate the minimum known biomass in each subarea. Comparing these with subarea catches (Table 5) gives a maximum feasible exploitation rate in each year. In Subarea 48.1, this maximum has been consistently ≤9%. In Subarea 48.2, it was ≤2% in each year with comparison data. In Subarea 48.3, it was ≤21% in all years except 2000, when it was apparently 88%.

Each subarea clearly supports more krill biomass than is observed in the local krill monitoring program. The programs in Subareas 48.1 and 48.3 provided biomass estimates in the year 2000, so direct comparisons with the CCAMLR-2000 Survey are possible. This puts the seemingly high exploitation rate for 2000 in Subarea 48.3 into perspective as the catch represents about only 0.2% of the subarea krill biomass.

It is possible to crudely extrapolate local biomass estimates to the subarea scale based on the ratios of biomass estimates at the two scales in 2000 (Table 6). The local monitoring program in Subarea 48.2 did not begin until 2011, so Table 6 uses the mean of the estimates from this program. Table 6 suggests that the local monitoring programs observe about 14% of the krill biomass in the CCAMLR-2000 Survey area. However, crude extrapolation risks overestimating subarea biomass. Table 6 also presents a conservative extrapolation, using the maximum biomass estimate from each local krill monitoring program, which suggests that local monitoring programs observe 8% to 37% of the biomass in each subarea.

Table 5: Subarea catch as a percentage of the biomass estimate from the local krill monitoring program (where available).

Year	Subarea		
	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 6: Comparison of subarea krill biomass (tonnes) estimated in the CCAMLR-2000 Survey (from Fielding et al., 2014) with local biomass estimates from krill monitoring programs. Scaling factors to extrapolate local biomass estimates to subarea scale (CCAMLR-2000 Survey estimate/reference local estimate) are shown for crude and conservative scaling.

Subarea	CCAMLR-2000 Survey estimate	Local estimate (2000)	Crude scale factor	Local estimate (max)	Conservative scale factor
48.1	15 892 735	2 950 000	5.39	5 812 500	2.73
48.2	24 638 790	5 480 370*	4.50	8 137 530	3.03
48.3	17 211 300	28 934	594.84	1 447 037	11.89
48.4	2 553 600				
Regional scale total	60 296 425	8 459 304	7.13	15 397 067	3.92

* There was no local monitoring program in Subarea 48.2 in 2000. The value shown is the mean of the 2011, 2012 and 2014 estimates.

Figures 2 to 4 show the conservative estimates of krill biomass in each subarea for each year where local survey data were available. The figures also show subarea catches and catch limits (as specified in CM 51-07). Although useful for assessing exploitation rates, these conservative biomass estimates do not provide any new information on interannual variability in the krill stock. Catches are low compared to some of the conservative 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 have consistently been ≤3%, ≤1% and ≤2% for Subareas 48.1, 48.2 and 48.3 respectively, and ≤3% at the regional scale (Table 7).

Table 7 also shows indicative exploitation rates associated with the subarea and regional catch

Table 7: Indicative exploitation rates (catch metric divided by conservative biomass estimate for each subarea) associated with subarea catch limits and reported catches. The ‘All’ columns show the trigger level or catch divided by the sum of available conservative biomass estimates (and are therefore likely to overestimate exploitation rates when the set of biomass estimates is incomplete). Results for 2000 are not shown as the results of the CCAMLR-2000 Survey (Table 6) offer a definitive comparison for this year.

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

limits. Rates above 9.3% occurred in 3 of 15, 2 of 16, and 5 of 18 years in Subareas 48.1 and 48.3 and at the regional scale respectively. These fluctuations are associated with variability in the local biomass estimates and there is no apparent trend.

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 6% (Table 7). The local catch limits specified in CM 51-07 ensure that exploitation rates in each subarea also average ≤6%.

Table 8 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 Subarea 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 five years (2010, 2013, 2014, 2015 and 2016) when it approached the 155 000 tonne limit. This has clearly contributed to the maintenance of low exploitation rates.

Is current management precautionary for krill predators?

The objective of maintaining average krill biomass above 75% of its unexploited level aims to reserve part of the stock’s production for predators and is consistent with recent recommendations for fisheries targeting lower trophic level species such as herring, anchovy and krill (Smith et al., 2011). By maintaining average exploitation rates below

Table 8: Indicative exploitation rates (catch metric divided by conservative biomass estimate 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 Survey (Table 6) offer a definitive comparison for this year.

Year	Whole trigger/conservative biomass estimate		
	Subarea		
	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

9.3%, the trigger level prevents excessive exploitation of the krill stock at the regional scale and therefore protects a vital food source for predators (Miller and Agnew, 2000; Constable et al., 2000).

CM 51-07 notes 'the need to distribute the krill catch … in such a way that predator populations, particularly land-based predators, would not be inadvertently and disproportionately affected by fishing activity' 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 krill and 34 predator populations in the 'smaller management units' referred to in CM 51-01 (also known as small-scale management units (SSMUs), which have a typical area of 10 000 to 50 000 km^2) (Hewitt et al., 2004b). Fishing was distributed among SSMUs according to reported catches and the catch limits specified in CM 51-07. Watters et al. (2013) assessed the risk of fishing causing predator populations to fall by 25%. For most of the predator populations considered, the risk associated with the trigger level was negligible, but for six populations, the 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.

This risk assessment provides a potential definition of 'precautionary' for krill predators, where the bad event to avoid is a ≥25% depletion of a population of predators within an SSMU. In this sense, the reported catches were precautionary and CM 51-07 might also be precautionary if a 12% probability is 'within acceptable limits' and catches do not become significantly more concentrated in sensitive areas. CM 51-01 recognises that managing the fishery at a finer-than-subarea scale would help to prevent such concentration. Beyond this, it is not possible to definitively assess whether current management is precautionary for krill predators, because there is no consensus about what constitutes a bad event and what constitutes an acceptable risk. CM 51-07 provides more protection for predators than the regional trigger level alone, but it also acknowledges the need for more scientifically based management measures. As the development of the precautionary catch limit shows, such scientifically based measures can usefully incorporate definitions of the bad events to avoid and the acceptable limits on risk.

Conclusions

Local krill monitoring programs in Subareas 48.1, 48.2 and 48.3 indicate considerable interannual variability but provide no evidence of a systematic change in krill biomass since the CCAMLR-2000 Survey. Catches within subareas have always been ≤21% (and mainly <3%) of the biomass observed in these monitoring programs which, in turn, represent <37% of the krill biomass in each subarea. The exploitation rates associated with current catches (≤3%) 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, subarea catch limits should be maintained to minimise the risk of even higher exploitation rates.

CCAMLR 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 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 CCAMLR’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 programs 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 programs. The value of these programs could be enhanced by improving understanding of the relationship between the local biomass and biomass at the larger (subarea or regional) scale. Such work is likely to require data on krill biomass and distribution at the larger scale.

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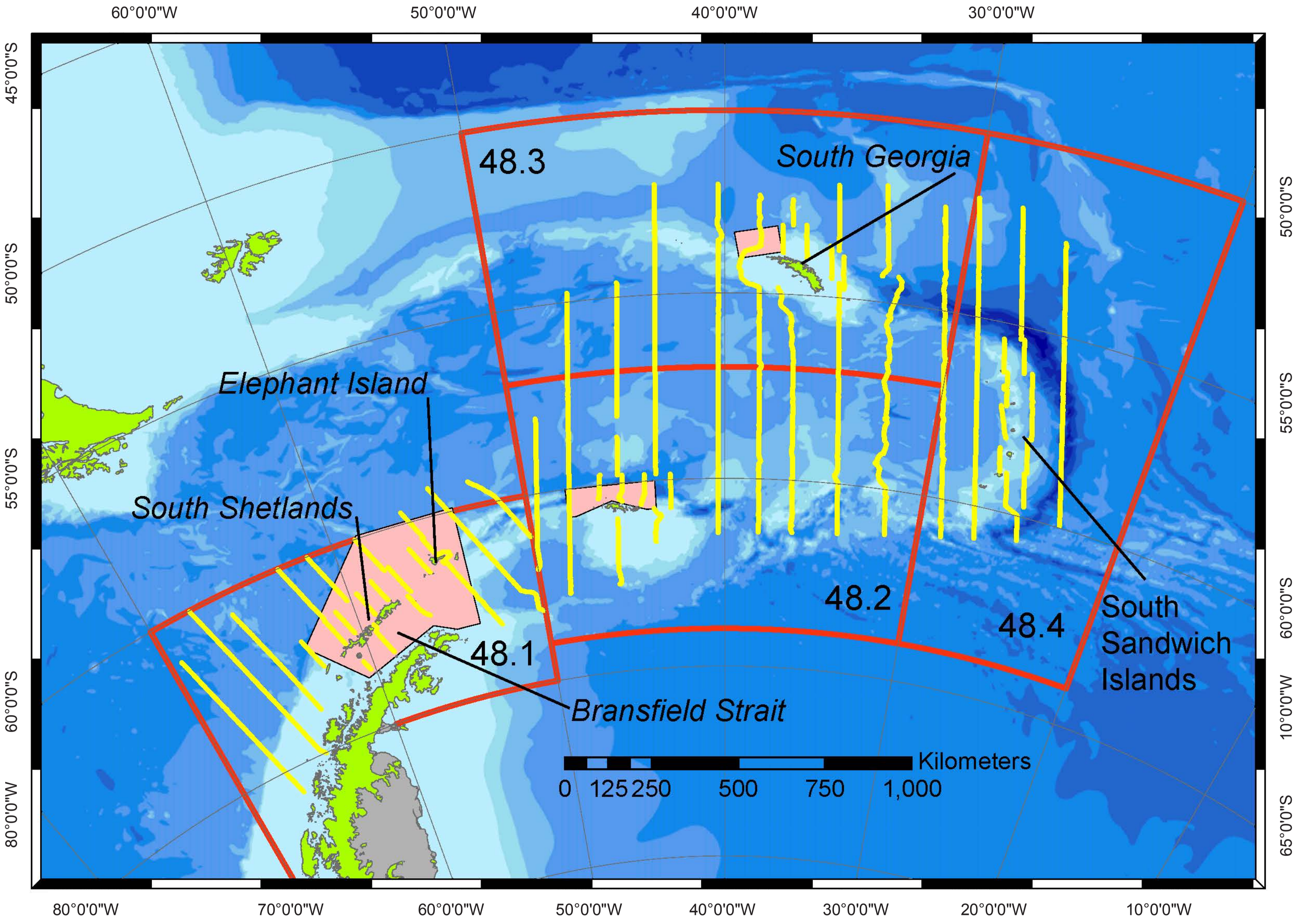

Figure 1: The main krill fishing area in the Southern Ocean, showing CCAMLR Subareas 48.1 to 48.4, the CCAMLR 2000 Krill Synoptic Survey of Area 48 transects (yellow lines), and the areas surveyed in local krill monitoring programs (pink polygons). The local krill monitoring area shown in Subarea 48.2 is the smaller stratum used for between-year comparisons.

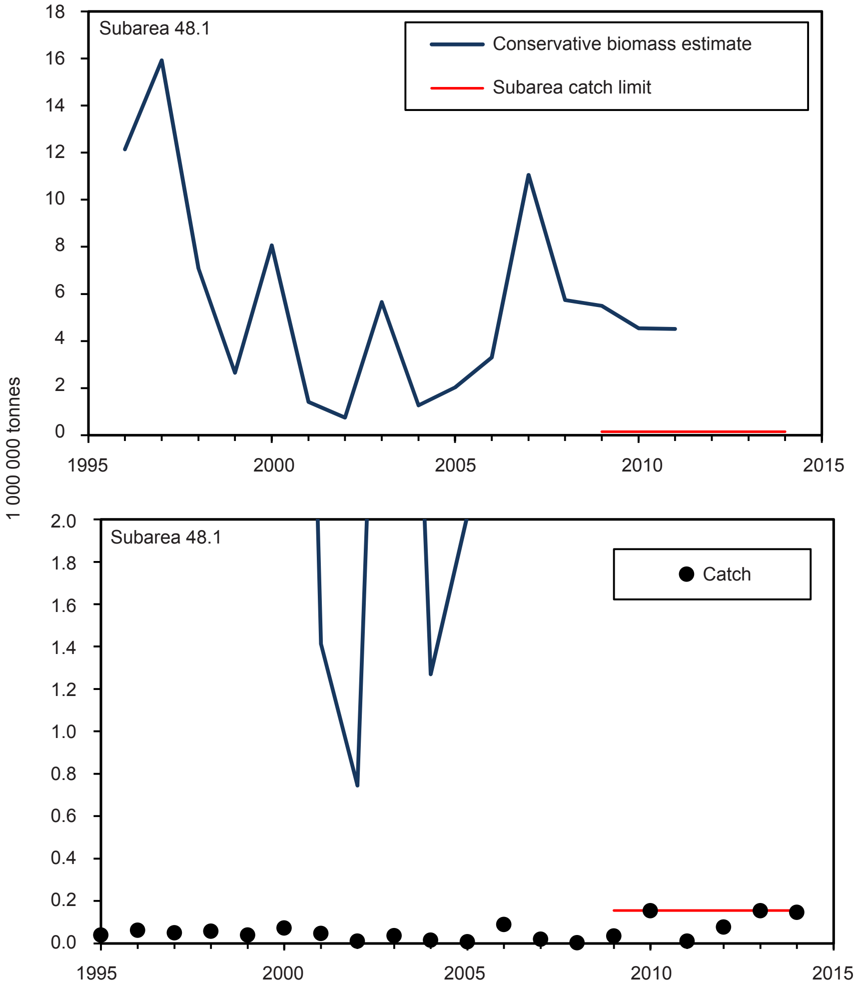

Figure 2: Conservative estimates of krill biomass for Subarea 48.1 (calculated by scaling up biomass estimates from the local krill monitoring program) shown in comparison with annual catches and the subarea catch limit specified in CM 51-07.

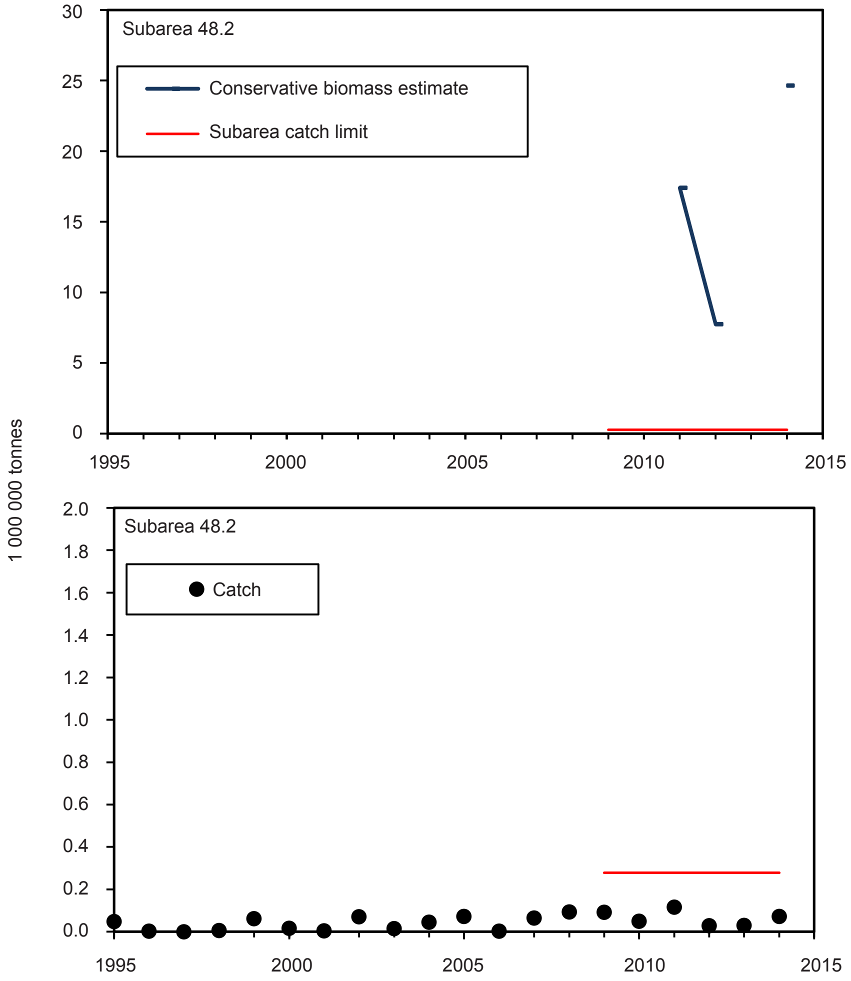

Figure 3: Conservative estimates of krill biomass for Subarea 48.2 (calculated by scaling up biomass estimates from the local krill monitoring program) shown in comparison with annual catches and the subarea catch limit specified in CM 51-07.

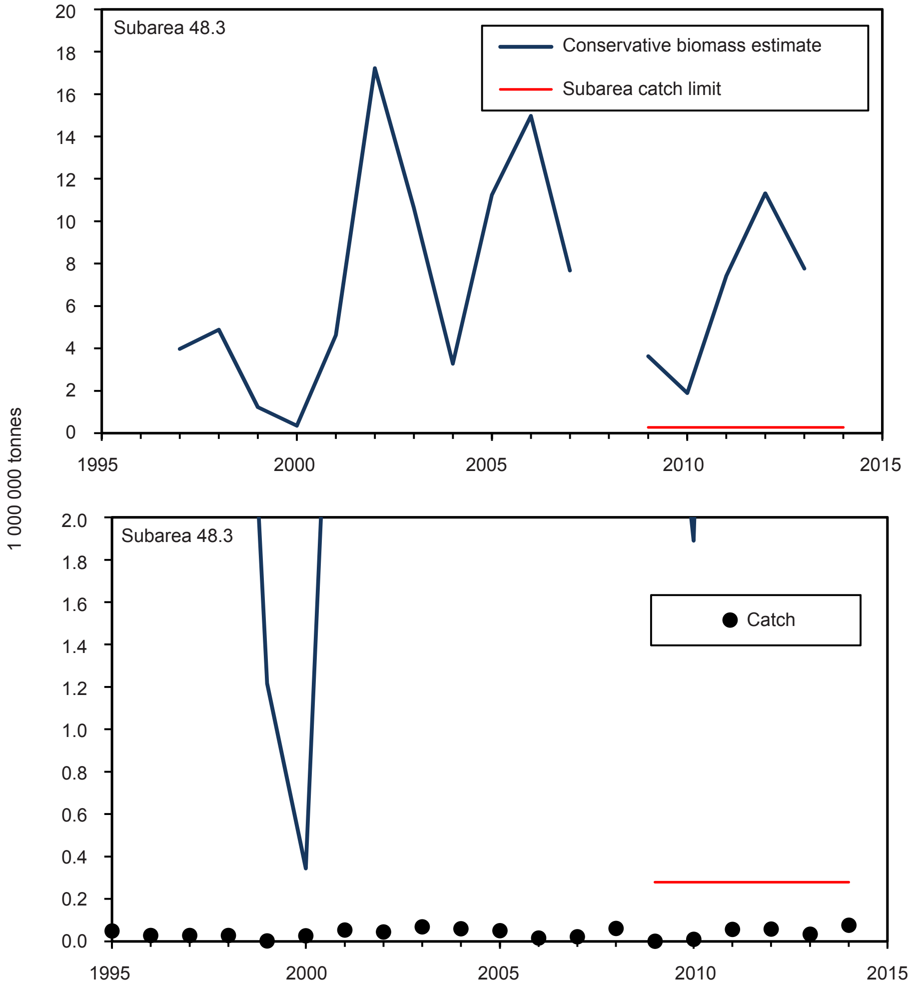

Figure 4: Conservative estimates of krill biomass for Subarea 48.3 (calculated by scaling up biomass estimates from the local krill monitoring program) shown in comparison with the annual catches and subarea catch limit specified in CM 51-07.