FISH and FISHERIES

The fishery for Antarctic krill – recent developments

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Abstract

The fishery for Antarctic krill (*Euphausia superba*) is the largest by tonnage in the Southern Ocean. The catch remained relatively stable at around 120 000 tonnes for 17 years until 2009, but has recently increased to more than 200 000 tonnes. The Commission for the Conservation of Antarctic Marine Living Resources precautionary catch limits for this species total over 8.6 million tonnes so it remains one of the ocean's largest known underexploited stocks. Recent developments in harvesting technology and in products being derived from krill indicate renewed interest in exploiting this resource. At the same time, there are changes in the Southern Ocean environment that are affecting both krill and the fishery. This paper summarizes the current state of this fishery and highlights the changes that are affecting it.

Keywords Antarctic krill, CCAMLR, fishery

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Introduction

The fishery for Antarctic krill (*Euphausia superba*, Euphausidae) has been operating for over 35 years, and it has been highlighted many times as one of the world's last under-exploited fisheries (Garcia and Rosenberg 2010). For several decades, this fishery has been held in check by economic factors rather than through low stock levels or management action (Nicol and Foster 2003). Indeed, this

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fishery is probably unique in that the internationally recognized precautionary catch limits (totalling 8.6 million tonnes year^{-1}) set by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is over 40 times the current annual catch (approximately 210 000 tonnes year^{-1}). What apparently has prevented the development of this fishery has been a combination of the cost of fishing in the Southern Ocean coupled with the difficulty of producing saleable products from what has proved to be a difficult source material (Budzinski *et al.* 1985; Nicol and Endo 1997; Nicol and Foster 2003). There are indications that the krill fishery is currently in a state of change with new entrants, new harvesting technologies being applied and new products being developed. Additionally, there are a number of changes in management procedures as well and significant change in the environment of the Southern Ocean all of which have the potential to affect the fishery. This short review provides an update on the current status of the krill fishery, its management and its prospects. The review focuses on developments that have occurred this century; several reviews have described the development of the krill fishery prior to 2000 (Budzinski *et al.* 1985; Everson 2000; Nicol and Endo 1997; Nicol and Foster 2003), and these references should be consulted for considerations of earlier developments.

Current status of the fishery

The krill fishery is currently operating exclusively in the South Atlantic with catches being taken from waters off the Antarctic Peninsula, the South Orkney Islands and South Georgia. The catch level in 2009/10 was 211 180 tonnes (This tonnage was that reported at the CCAMLR Commission meeting on the 24th of October 2010. The fishing season finishes on the 30th of November so the actual catch for the 2009/10 season is likely to be slightly higher than that reported at the 2010 meeting of CCAMLR), which is nearly double the average annual catch taken over the period between 1994 and 2009 (108 863 tonnes) (Fig. 1).

The fishery has passed through several distinct phases. During the 1980s, the krill fishery was dominated by large fleets from the USSR with annual catch levels generally over 200 000 tonnes and catches being taken from the waters off East Antarctica as well as from South Atlantic where the fishery is currently concentrated (Nicol and Endo 1999).

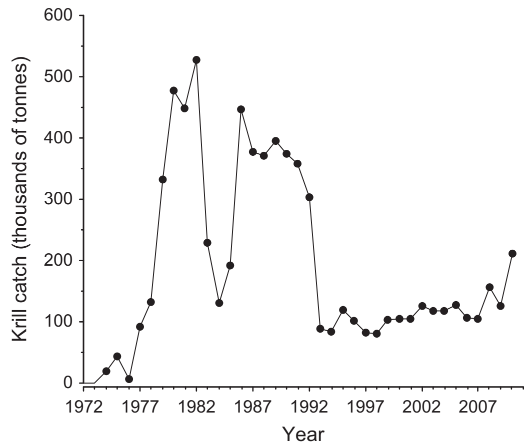

Figure 1 The annual catches of Antarctic krill (data from CCAMLR Statistical Bulletins, http://www.ccamlr.org/pu/e/e_pubs/sb/intro.htm).

Following the demise of the USSR, catches fell and from 1992/93 to 2003/04 catches were predominantly by vessels from Japan with an overall catch level of between 100 000 and 120 000 tonnes (Table 1). Following the 2003/04 fishing season, the Japanese catch began to decline, but the overall catch began to rise slowly driven by increasing catches from South Korea and new entrants, such as Norway. Today, Norwegian and Korean companies dominate the catch, and the projected overall catch for 2010/11 is 410 000 tonnes. Additionally, vessels from China have recently entered the fishery, and Russian vessels are once again fishing for krill (SC-CAMLR 2010). China is the world's largest aquaculture producer, and given the recent emphasis on using krill as an aquaculture feed, this development is not surprising.

Changes in technology

Krill fishing has traditionally been conducted using large pelagic trawls that are hauled about ten times a day with about ten tonnes of krill being caught in each trawl (Budzinski *et al.* 1985; Nicol and Endo 1997; Kawaguchi and Candy 2009). Since 2007, Norwegian vessels have used a continuous pumping method, and catch rates as high as 800 tonnes per vessel per day have been recorded. This patented system (US Patent Application US 2006 0048436 A1) injects air into the cod end of the net, and this air bubble lifts the content of the cod end through a hose into the ship's factory. The advantages of this system are that the net can remain submerged for several weeks (Anon 2007), a constant feed of krill is supplied to the factory, and the krill arrive on deck alive and undamaged and can thus be used for a variety of products. Crushing of krill in large catches from conventional trawls had been viewed as a problem in the past, leading to leakage of valuable chemicals and spoilage (Nicol and Endo 1999). This new fishing method has been referred to as 'eco-friendly trawling' because of its selectivity and because it is able to deliver the required quantities for processing with no wasted catch and the ability to reduce by-catch. Although there has been an unprecedented level of scientific observer coverage on the vessels using this technology, the use of this system to reduce the ecosystem effects of fishing is still largely unproven because of its novelty.

Conventional trawling for krill has also developed with average catch rates rising approximately from 100 tonnes day^{-1} to 400 tonnes day^{-1} today (SC-CAMLR 2010). Additionally, conventional trawls with pumped cod ends and pelagic beam trawls have been trialled in the krill fishery, but no reports of their effectiveness have yet been presented to CCAMLR.

There has been some concern raised that the reported catches of krill may not actually reflect the total fishery mortality inflicted on the krill population (SC-CAMLR 2010). There have been reports that trawl nets may damage and kill large numbers of krill that do not end up in the cod end; thus, the mortality may not be reflected in the tonnage landed. Additionally, there is a wide variety of methods used to calculate the 'green weight' of krill – the actual amount of krill landed for processing – and this introduces considerable uncertainty into estimating the total fishery removal. Both of these topics have been given a high priority for research by CCAMLR's Scientific Committee (SC-CAMLR 2010).

Development of products

There has been considerable recent expansion in the range of products being extracted from krill with an emphasis on aquaculture and on pharmaceuticals and health foods. Changes in product type are reflected in the types of krill-related patents being taken out (Nicol and Foster 2003). Publicly available patent databases (http://ep.espacenet.com/) can be used to examine both the number and type of patents related to krill that are lodged annually. A total of 812 krill-related patents were lodged in the period from 1976 to March 2009, with a notable increase in the rate of patent lodging since 2000 (43% of total patents have been lodged since 1999; Fig. 2).

Patents relating to medical uses now account for 38% of total patents lodged, a marked increase from the 1970s and 1980s when they accounted for only 4% of total patents. In the same period, patents relating to aquaculture have also increased from 11% in 1976–1986 to 39% in 1999–2008 period (Delegation of Australia 2009). There are also trends emerging from the databases that indicate increased patent activity from non-krill fishing nations, such as Canada and USA, and decreased patent activity from traditional fishing nations, such as Japan and Poland.

An increase in demand for fish meals and marine by-products and their limited availability because of

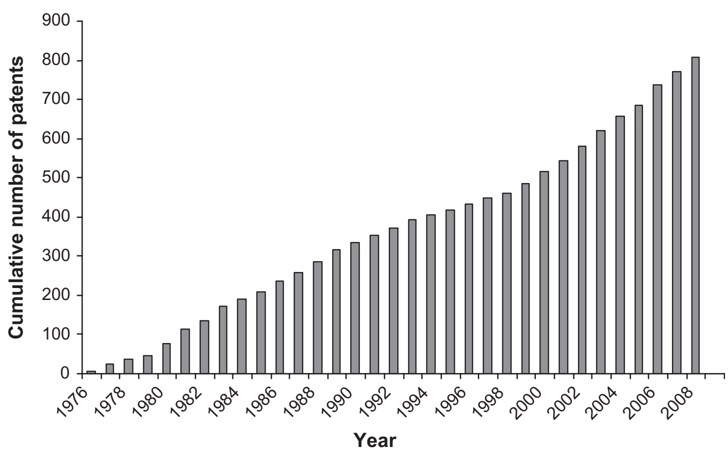

Figure 2 Cumulative number of krill-related patents lodged from 1976 to 2008 (see text for sources).

dwindling fish stocks are leading to investigations into the supplementation of currently used proteins and additives in aquaculture with lower-cost alternatives, or items that are likely to be more available in the future (Yoshitomi *et al.* 2007; Davis and Arnold 2000). Experiments have shown that krill meal has a nutritional value equal to, or surpassing, that of regular fish meals when used as a substitute in the diets of various farmed species, including Atlantic cod, Atlantic salmon and Pacific white shrimp (Yoshitomi *et al.* 2007; Karlsen *et al.* 2006; Opstad *et al.* 2006; Gaber 2005). However, krill is most commonly used as a high-value additive to aquaculture feeds (Floreto *et al.* 2001) rather than the primary ingredient. Given proven benefits of utilization of krill meal and oils [the addition of fish oil to meals is used to boost Omega-3 content of farmed species (IFFO, 2008)] in fish meals and the decline of traditional sources of these meals and oils, krill is being examined as a means to satisfy demand in a market niche that will be under increasing pressure as traditional fish stocks continue to decline.

The high fatty acid properties of krill oil make it effective in the treatment of various medical conditions (Chandrasekar *et al.* 1996), including cardiovascular disease (Batetta *et al.* 2009; Bunea *et al.* 2004), arthritis (Deutsch 2007), liver disease (Tandy *et al.* 2009) and maintenance of general health and well-being (Bridges *et al.* 2010). Such oils with high levels of Omega-3 command a premium price in complementary medicine markets (Nichols 2007), and the use of krill oil in pharma- and nutraceutical products will continue to drive investment in the krill industry (Anon 2007).

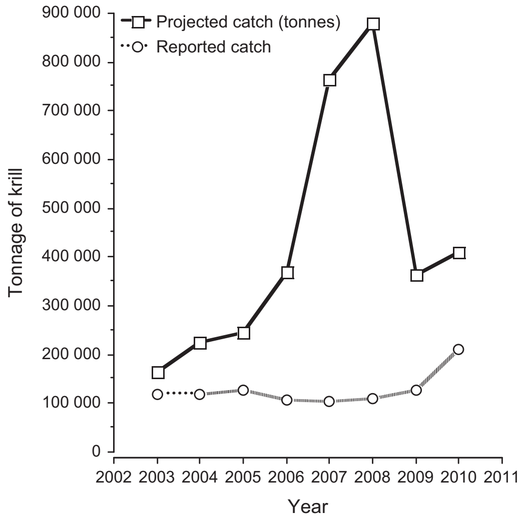

Figure 3 The projected catch of krill, as indicated in the notifications to participate in the krill fishery provided annually to CCAMLR, compared to the annual catch reported to CCAMLR (data from Reports of the CCAMLR Scientific Committee).

Developments in management

Notifications

In 2003, CCAMLR instituted a formal process whereby Nations wanting to participate in the krill fishery had to notify the Commission in advance (CCAMLR 2003). The purpose of this scheme was so that the Commission was aware of significant increases in fishing effort that they might need to take into account when making management decisions. It was not meant as an accurate predictor of the following season's catch but would provide information on: the number of Member Nations interested in fishing, the number of vessels, the type of fishing technology proposed, the fishing grounds of interest to the fishery and some idea of the overall catch. It has also been a useful process for non-Member Nations to register their interest, whereas beforehand, there was no formal process to do this. The notifications of projected catches have increased, but the projections of the number of nations and the numbers of vessels have fluctuated. The annual catch has begun to increase in line with notifications, and the increase in interest has been reflected in the change in the mix of Nations participating in the fishery and the types of vessels involved (Fig. 3).

Precautionary catch limits

Precautionary catch limits on the krill fishery were first introduced by CCAMLR in 1991 (Nicol and Endo 1999) and now cover much of the potential and actual fishing grounds in the CCAMLR Area (Fig. 4). These catch limits are under constant review and have been updated by CCAMLR on the basis of new information, particularly from large-scale scientific surveys. In the south-west Atlantic (Subareas 48.1, 48.2, 48.3 and 48.4), the current catch limits were set using data from a 4-ship acoustic survey conducted in 2000 (Hewitt *et al.* 2002). The results of this survey have been re-analysed as the acoustic methodology improves, and the overall catch limit has changed from an

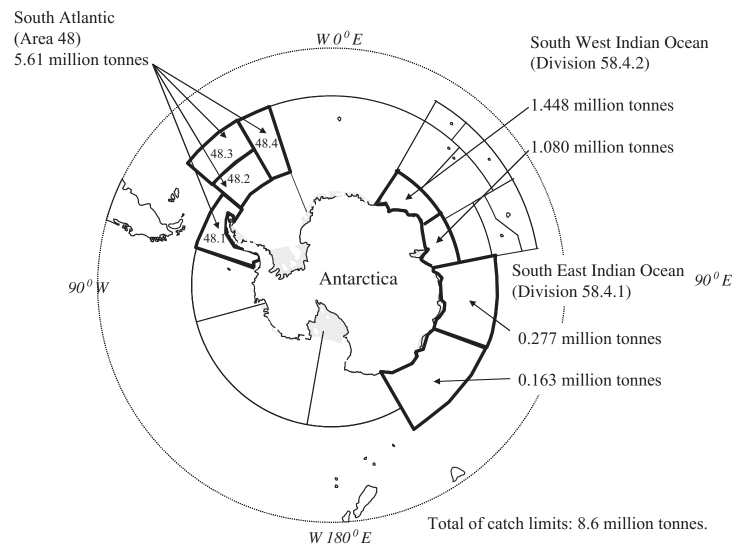

Figure 4 Precautionary catch limits on the krill fishery in the CCAMLR Area. The various statistical areas are indicated; surveyed areas have been heavily outlined and labelled. The fishery is currently only operating in the South west Atlantic (Area 48.1, 48.2 and 48.3), but it operated in parts of the South Indian and Pacific Ocean sectors in the 1970s to mid-1990s.

Table 1 Annual reported krill catches, in tonnes, by fishing nations at the start of each decade (data from CCAMLR Statistical Bulletins, http://www.ccamlr.org/pu/e/e_pubs/sb/intro.htm, accessed January 2010, preliminary figures for 2010).

	Fishing season			
	1980	1990	2000	2010
Japan	36 275	62 187	67 377	29 910
Poland	226	1275	13 696	7007
USSR	440 516	302 376		
Chile		4501		
East Germany		396		
Republic of Korea		4040	7525	43 805
Ukraine			14 023	
USA			1561	
Norway				120 429
Russia				8065
China				1956

initial 4.0 million tonnes a year in 2000 to 5.61 million tonnes a year in 2010 to take account of developments in the way in which the acoustic data are processed (SC-CAMLR 2010). In the South Indian and Pacific sectors (Area 58), the catch limits have been set using the results of two acoustic surveys, one conducted in 1996 (Nicol and Foster 2003) and one conducted in 2006 (Nicol *et al.* 2010). The catch limits for both of these Statistical Divisions were divided into two on the basis of environmental data collected on the surveys (SC-CAMLR 2008). The catch limits in Division 58.4.1 and 58.4.2 were set using an older formulation of the acoustic analysis methods and are currently being updated.

There have been no acoustic surveys of other statistical areas of the Southern Ocean that could be used to set additional catch limits on the krill fishery. As a consequence of this lack of information on the biomass of krill in most of the Convention Area, CCAMLR in 2007 agreed that any krill fisheries proceeding in unsurveyed areas (the whole of Area 88, the Pacific sector, and Subareas 48.5 and 48.6 in the south-east Atlantic) would be viewed as exploratory fisheries (CCAMLR 2007). Such exploratory fisheries would have to be managed with a higher level of precaution compared to surveyed areas, and for the 2009/10 season, this would include: a general catch limit of 15 000 tonnes would apply, no more than 75% of the catch limit to be taken within 60 *n* miles of known breeding colonies of land-based krill-dependent predators, each vessel would carry at least one scientific observer, and there should be a detailed data collection plan (CCAMLR 2009). The data collection plan specifies the collection of considerable scientific data on operation of the fishing vessel and on the distribution, abundance and biology of krill.

The precautionary catch limits for Area 48 and for Division 58.4.2 incorporate 'trigger levels'. These are levels of fishing that cannot be exceeded until the overall catch limit is broken down into small-scale management units (SSMUs). In Area 48, the trigger level is set at 620 000 tonnes, and in Division 58.4.2, it is set at 260 000 tonnes west of 55°E and 192 000 tonnes east of 55°E. Trigger levels and SSMUs are designed to avoid the concentration of the fishing fleet in small areas with the consequent potential to have adverse ecosystem impacts. There has been considerable effort within CCAMLR devoted to the mechanism, whereby the catch limit can be subdivided amongst SSMUs, but there has been no agreement to date (Hewitt *et al.* 2004). In 2009, in recognition that even taking all of the 620 000 tonne trigger level from a small area could have serious consequences, there was agreement with an interim distribution of the overall trigger level between the four surveyed Subareas in the South Atlantic: 25% from Subarea 48.1, 45% from Subarea 48.2, 45% from Subarea 48.3 and 15% from Subarea 48.4 (CCAMLR 2009). Although these percentages total more than 100%, the overall cap of 620 000 tonnes remains in place. Significantly, in 2010, the krill fishery in Subarea 48.1 was closed when the catch approached the interim trigger level (155 000 tonnes) (CCAMLR 2010). This was the first time that the krill fishery had reached one of its catch limits and also represented the highest ever catch of krill from Subarea 48.1 (CCAMLR 2010). The requirement to closely monitor the catches and location of krill fishing activities to ensure that smaller-scale catch limits are not exceeded has resulted in CCAMLR changing its regulations regarding the frequency of reporting and the carriage of vessel monitoring systems in line with other fisheries in the Convention Area (CCAMLR 2010).

Observers

The *CCAMLR International Observer Scheme* is designed to play critical role in gathering and validating scientific information essential for assessing the population status of selected species and the impact of fishing on such populations, as well as those of related and dependent species (CCAMLR 2006). However, until recently, the krill fishery was the only fishery in the CCAMLR Area exempt from the mandatory implementation of the Scheme, and as a result, there has been a lack of consistency of data collection amongst the fishing fleets, between areas and throughout the fishing season (CCAMLR 2009).

The exemption from scientific observation has been defended because krill catches are small relative to the precautionary catch limits, there was no stated intention to increase krill catches dramatically, and there is a negligible by-catch (Kawaguchi and Nicol 2007). However, given the increasing number of nations showing renewed interest with increased notifications, and new fishing technologies such as the continuous pumping method with higher operating efficiency being introduced, and recent changes in the environment (e.g. sea-ice changes), this reasoning has been difficult to sustain (Kawaguchi and Nicol 2007). In 2007, CCAMLR agreed on 100% observer coverage for the Indian Ocean Sector (Division 58.4.2; CCAMLR 2007), but the current krill fishing grounds in the south-west Atlantic (Subareas 48.1, 48.2 and 48.3) still remain exempt from mandatory scientific observation.

The Scientific Committee has advised that 100% observer coverage is the best way to achieve systematic observer coverage, particularly in areas where low levels of observer coverage have occurred in the past (SC-CAMLR 2007). In 2009, as a first step, CCAMLR adopted a new Conservation Measure for krill observers that requires a target coverage rate of no less than 30% of vessels during the 2009/10 fishing season and no less than 50% of vessels during the 2010/11 fishing season. This coverage level was reviewed in 2010, and a scheme was agreed to achieve the required level of observer coverage of 50% of the vessels each year while maximizing seasonal coverage. The scheme was also designed ensure that all vessel would be observed at least once within the next 2-year period (CCAMLR 2010).

Industry initiatives

There has been considerable public controversy over the effects of the development of the krill fishery on the Antarctic ecosystem. This concern has led to a recent successful attempt to have one krill fishing company's operations certified as sustainable through the Marine Stewardship Council (MSC) in an effort to emphasize the sustainability of their operations (Anon 2010). In 2010, Aker Biomarine had their fishing operation certified despite their vessel being only one of ten vessels operating in the fishery. The certification of this vessel has in itself become controversial with suggestions that species being caught for fishmeal ought not to qualify for MSC certification and that the reported drop in krill biomass associated with a decline in sea-ice ought to disqualify krill from certification (Jacquet *et al.* 2010). It remains to be seen whether other companies will apply for MSC certification based on the sustainability of their operations, which is largely a reflection of CCAMLR's precautionary management regime.

At the 2010 meeting of CCAMLR, there was an announcement of the establishment of a krill fishery industry association that aims to support the scientific work of CCAMLR through the provision of data from the fishery to ensure a long-term sustainable harvest of krill. Although details of this association and its goals are not yet available (Even T. Remøy, Krillsea Group, personal communication), it may well herald a new and more co-operative approach towards managing krill harvesting than has been the case in the past.

The krill fishery and the environment

Fishing operations are now concentrated in the south-west Atlantic, where most of the krill stock is thought to reside (Atkinson *et al.* 2009), and there is a small number of fishing grounds that are frequented by vessels from all Nations fishing (Jones and Ramm 2004). Although the fishery has operated on a number of fishing grounds throughout the Area 48, there is considerable variation between years in the location of the maximal fishing effort. In some years, krill are scarce at South Georgia so little is caught in Subarea 48.3, and in other years, very large fishable concentrations are found in specific locations (e.g. the Bransfield Strait in 2009/10), and much of the catch is concentrated there. There is little agreement on the factors that result in differing sizes and locations of krill aggregations (Kawaguchi *et al.* 2006); however, information from an expanded fishing fleet may well reveal underlying patterns (Kawaguchi and Nicol 2007).

The krill fishery now mainly operates in late summer to mid-winter, and this has been made possible by the reductions in winter sea-ice around the Antarctic Peninsula as a result of climate change. Although sea-ice plays a number of ecological roles in the Southern Ocean that may affect krill stocks, it has also had a significant direct effect on the krill fishery (Kawaguchi *et al.* 2009). The Antarctic Peninsula is one of the most rapidly warming places on Earth, and this has resulted in a considerable reduction in the extent of sea-ice in winter. A consequence of the lack of winter sea-ice in the south-west Atlantic has been that the krill fishing season has become extended, and in recent years, fishing fleets have been able to operate in southern waters in the winter (Kawaguchi *et al.* 2009). The fishery has traditionally operated in the ice-free waters around South Georgia during winter and further south during spring, summer and autumn (Jones and Ramm 2004), but the current pattern of fishing is for most of the fishing effort to be concentrated in the autumn and winter months (Fig. 5). The ice-covered winter would have provided the krill population a refuge from its predators (including the fishery), but reductions in sea-ice will remove this protection, and this may well affect the dynamics of the krill stocks.

Changes in krill stocks

The absence of long-term, systematically collected data on krill stocks have required that researchers have had to use ingenuity to determine whether there has been any change in the abundance of krill over the last century. The most ambitious of these examinations, which used all available data from scientific nets, concluded that there had been a contraction in the range of krill to the South and that this had been associated with a significant decline in krill density (Atkinson *et al.* 2004). The magnitude of the decline (between 38 and 80%) is somewhat contentious, and there is a lack of ancillary data that corroborates such a decline. If the most recent global biomass estimate of krill from net and acoustic surveys – 133 million tonnes (Atkinson *et al.* 2009) – is realistic, then the biomass of krill prior to the 1980s would have been approximately 665 million tonnes if the current level is only 20% of what it was in the past. An absence of 500 million tonnes of a keystone species ought to have had significant ecosystem ramifications, and these have not been consistently recorded. Concerns have been expressed that management of the krill fishery does not take the reported changes into account (Jacquet *et al.* 2010); however, the decline was suggested to have occurred in the 1980s, and the current catch limits were set by CCAMLR using data collected in 1996, 2000 and 2006 so the biomass levels on which they were based would incorporate the effects of any declines in abundance. There is a need, however, for CCAMLR to examine whether its management approaches are robust to the possibility of an earlier decline in krill stocks.

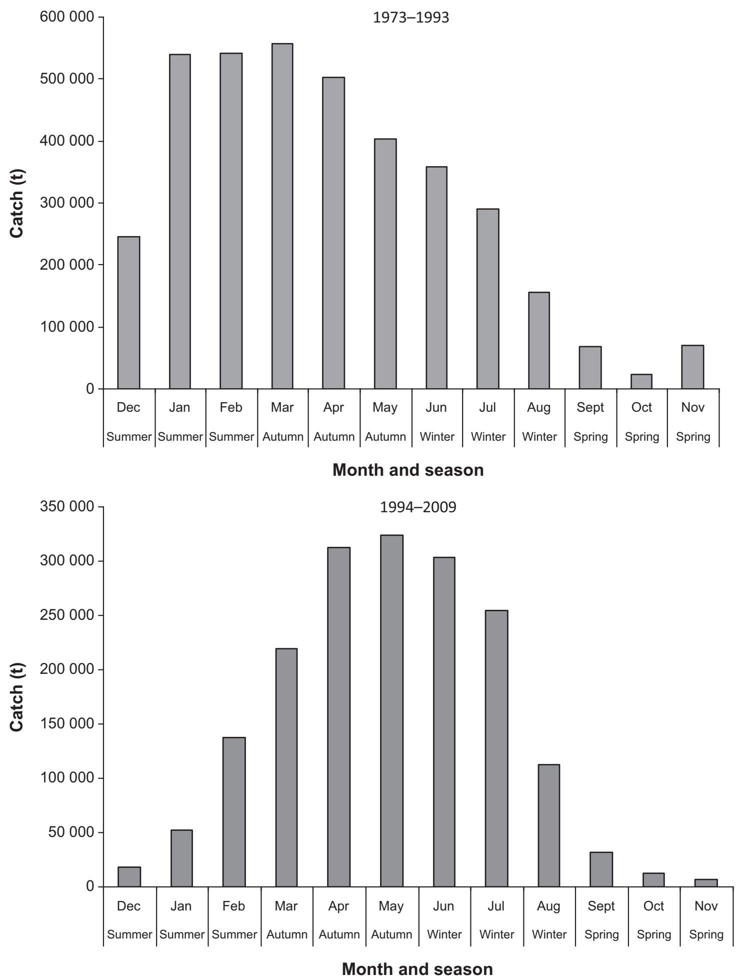

Figure 5 Seasonal distribution of the krill catch in its early development (1973–1993) compared to its recent history (1994–2010). Data from CCAMLR Statistical Bulletins.

Another important environmental issue emerging is the effect of ocean acidification. Southern Ocean ecosystems are expected to be rapidly affected by ocean acidification because of the higher solubilities of CO_2 and $CaCO_3$ in cold waters and because of the upwelling of deep seawater containing high CO_2 (Sabine *et al.* 2004). A recent study indicates negative impacts of acidification on krill early development and underlines the urgency of undertaking detailed studies on the sensitivity to ocean acidification across all life stages (Kawaguchi *et al.* 2010).

Environmental changes in the Southern Ocean are likely to impact on krill populations in a complex fashion, and data do not currently exist to make reliable predictions on the likely effects of predicted changes on the circumpolar krill stock. Consequently, management of the krill fishery will have to be suitably precautionary to account for an uncertain future.

Ecosystem effects of krill fisheries

There has been concern expressed about ‘fishing down marine food webs’, particularly in regard to the krill fishery (Pauly *et al.* 1998). Although krill may be considered to be towards the lower end of the trophic scale, they are omnivorous and occupy the niche of the pelagic schooling fish in the Southern Ocean, so they do not strictly replicate the situation in many other oceans where there has been a systematic movement of fisheries from higher to lower trophic levels. Certainly, the initial harvesting in the Southern Ocean focussed on seals and whales, but exploratory fisheries for fish and krill began almost simultaneously in the 1960s. Stocks of fish around Antarctica were always small, despite some large early catches, and it was the obvious abundance of krill, which had supported the vast populations of seals and whales, that attracted most attention.

There are 85 species of krill found throughout the world's oceans, and many of them are extremely abundant. Krill fisheries in the northern hemisphere that have developed or have been proposed are either highly restricted or have been banned, so the only substantial source of krill in future is likely to be from Antarctic waters. A recent California bill prohibits taking or landing of krill genera *Thysanoessa* or *Euphausia*, for commercial purposes and in 2009, NOAA's prohibited krill harvesting in federal waters (3–200 mile Economic Zone) off the coasts of California, Oregon and Washington (Department of Commerce 2009). Although there is a small krill fishery off British Columbia and several medium-sized fisheries off Japan, it is unlikely that major krill fisheries will develop in the northern hemisphere because of concerns over environmental effects and competition with existing fisheries (Nicol and Endo 1999). These sensitivities are likely to focus interest in the development of krill products towards the Southern Ocean where an existing sustainable management regime is in place.

Conclusions

The krill fishery is in a period of flux with a range of developments that are either affecting the industry, its management or the krill stock itself. Although CCAMLR has a precautionary and ecosystem-based approach to the management of the fishery, this has not yet been tested because of the low level of interest in the fishery in recent years. Before the fishery becomes fully developed, there are a number of additional measures of precaution that need to be taken to ensure the conservation of the Antarctic ecosystem. These measures include subdivision of all the catch limits into smaller management units, ensuring that adequate information is being supplied on the operation of the fishery and its drivers, directly incorporating the needs of krill-dependent predators into management approaches, including monitoring, and developing a management procedure that incorporates adequate feedbacks from the ecosystem (Nicol and de la Mare 1993). These measures need to occur before the fishery expands much more, and CCAMLR will need to ensure that the fishery does not expand more rapidly than the organization's ability to mange it.

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