Antarctic Krill:
a case study on the
ecosystem implications of fishing

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Antarctic krill Ecosystem implications of fishing

Antarctic krill *(Euphausia superba)* is central in the Antarctic food chain. The different components of the Antarctic marine ecosystem are made up of predators that rely, directly or indirectly, upon the health of the krill populations. Antarctic krill has a circumpolar distribution and is very abundant in the Southern Ocean.

The Antarctic krill fishery has been the largest fishery in the Southern Ocean since the late 1970s (Croxall & Nicol 2004). In most recent years, almost all krill fishing vessels have been operating in coastal areas of the South West Atlantic region, where the catch rate has historically been higher. This fishery is the largest crustacean fishery in the world and it has prospects for becoming the largest global fishery (Nicol & Endo 1997). There is potential for a rapid expansion of the fishery in future years, as krill-processing technology develops and demand for krill products increases. This raises concerns about the future of the vulnerable and still little understood Antarctic marine ecosystem.

Perception of massive abundance of krill stocks might trigger greater investments and it is slowing down policy progress to control the fishery. This is particularly important, taking into account the history of over-exploitation of marine species in the Southern Ocean. This pattern has included seals in the 19th century, the great whales in the middle of the 20th century, the marbled rockcod (*Notothenia rosii*) in the early 1970s and, most recently, some populations of Patagonian toothfish (*Dissostichus eleginoides*).

The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) is the international regime responsible for managing Antarctic krill stocks in the Southern Ocean. CCAMLR was negotiated in the framework of the Antarctic Treaty and the conservation of Antarctic krill stocks was a major factor in its inception. The Convention was pioneer in formulating the need to take into account the ecosystem as a whole in fisheries management.

Although krill catches in the Southern Ocean are currently well below CCAMLR catch limits, there is a risk of localized, excessive fishing effort that might impact on species that depend on krill for food, particularly during the breeding season. Considerable overlapping exists between the krill fishery and breeding areas for penguins and seals in the South Atlantic Ocean (Constable & Nicol 2002). Little is still known of feeding areas and consumption rates of other seals, whales, dolphins, fish, squid, or flying seabirds.

CCAMLR has made significant progress in the formulation and development of the precautionary principle and an ecosystem-based approach to the management of marine resources, but the full implementation of these principles in the Southern Ocean is still at an incipient stage. This situation is well illustrated by the case of Antarctic krill. Although the needs of krill-dependent species are taken into account for the setting up of krill fishing quotas for big areas of the Southern Ocean, CCAMLR still needs to subdivide the overall catch limit into smaller units, so as to distribute the effort geographically in a way that takes into account the relationships between krill and its predators, which occurs at a much smaller scales.

CCAMLR also needs to undertake reforms that strengthen the monitoring and controls applicable to the Antarctic krill fishery. In spite of its magnitude and importance, this fishery is still exempted from most monitoring and control measures applicable to other Southern Ocean fisheries.

I. About Antarctic krill

"Krill" is a term applied to describe over 80 species of open-ocean crustaceans known as Euphausiids, most of which are planktonic (Everson 2000a).

The following species of euphausiid crustaceans commonly occur in the Southern Ocean: *Euphausia superba*, *E. vallentini*, *E. triacantha*, *E. frigida*, *E. crystallorophias*, *Thysanoessa vicina* and *T. macrura*. Only two of them regularly occur in dense swarms and are of particular interest to commercial fisheries: *E. superba* and *E. crystallorophias*. All the Southern Ocean euphausiids have a circumpolar distribution and are broadly separated by their latitudinal ranges (Everson 2000a).

E. superba is the species commonly referred to as "Antarctic krill" and it is a widespread species, which is subject to significant commercial fishing (Everson 2000a). The Antarctic Convergence – that is the circumpolar front where the cold Antarctic surface water submerges below the warmer subantarctic waters - generally defines the northern limit of its distribution. High concentrations exist in the South Atlantic (Scotia Arc) and in some regions close to the Antarctic continent in the Indian Ocean. The total surface of the distribution of Antarctic krill is approximately 36 millions square kilometres – which represents for example, four and a half times the area of Australia.

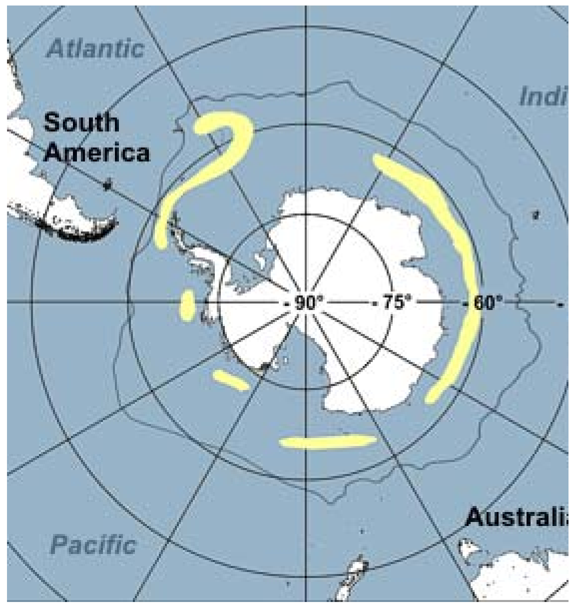


Fig. 1 - Large-scale distribution of Antarctic krill (based on surveys and commercial fishing). Extracted from Everson 2000c.

Antarctic krill is one of the most abundant and successful animal species on Earth. The biomass of Antarctic krill may be the largest of any multi-cellular animal species on the planet (Nicol 2004). Krill are also recorded as forming the largest aggregation of marine life (Macauley *et al.* 1984) and they have the most powerful proteolytic enzymes yet found (Anheller *et al.* 1989).

Antarctic krill are mainly herbivorous. In summer they feed on the phytoplankton (microscopic suspended plants such as flagellates and diatoms) of the Southern Ocean while in winter they feed largely on ice algae from the under-surface of ice flows. It is believed that planktonic animals (zooplankton) may also form a part of their diet.

Krill may live for six to seven years and attain sexual maturity at two (females) and three (males) years of age (Siegel 2000). Mating behaviour begins up to 1-2 months prior to spawning (in November). As krill mature and become adult they begin to aggregate into huge schools or swarms, with many thousands of krill packed into each cubic metre of water turning the water red or orange. These krill concentrations can be dense and compact through large layers, aggregation or deep scattering layers that may be kilometres in horizontal extent. This swarming behaviour is what makes krill attractive to commercial harvesting. However, most of the time krill swarms or schools remain at depth, unseen, during daylight hours, and only rise to the surface at night. This diurnal vertical migration is behaviour adopted by a variety of aquatic animals but is perhaps exhibited in its most spectacular appearance by Antarctic krill. As soon as they arrive at the surface, they become prey for surface feeding predators such as seabirds, seals, squid, fish or baleen whales (Nicol 2004).

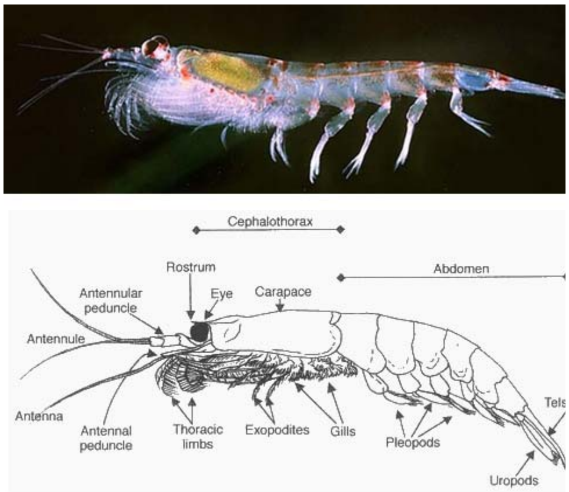


Fig. 2 – General view of krill showing main morphological features. Extracted from Everson 2000a.

It is still unknown how krill survive the Antarctic winter. They do not seem to build up large fat reserves, so must either use some food available under the ice, such as the algae which grows on the underside of the pack ice, detritus on the sea-floor, other animals in the water, or utilize some internal store other than fat. Evidence for the latter comes from laboratory studies in which Antarctic krill were found to be able to withstand long periods (up to 200 days) of starvation. They do this by shrinking, using up the very material of their body to meet their metabolic needs (Nicol 2004). This finding has led to the assumption that reducing its metabolic rate may also allow krill to survive the winter without feeding (Quetin and Ross 1991). Krill, like all crustaceans grow by moulting; that is, they cast off the old confining shell and expand in size while the new one is still soft. What seems to be unique in krill is the ability to use this

Der Riesensturmvogel (Macronectes giganteus) gehört zu den Hauptarten unter den Sturmvögeln, die auf Krill als Nahrung angewiesen sind. Foto: © Claudio Suter.

process in reverse (in other words, to shrink) when food is absent (Nicol 2004).

Estimates of krill abundance made in the 1960s, based on the amount of krill freed up by the removal of the baleen whales from the Southern Ocean, suggested that a huge sustainable krill harvest might be possible (Ichii 2000). More recent acoustic surveys have estimated the circumpolar biomass of Antarctic krill to be from 60 to 155 million tonnes (Nicol *et al*. 2000). Because of its abundance and position in the food web between the microscopic phytoplankton and the large vertebrate predators, krill is considered the key species in the Seasonal Pack-ice Zone and parts of the Ice-free and High-latitude Antarctic Zones (www.ccamlr.org).

To put the abundance of krill (60-150 million tonnes) into perspective, it is important to mention that less than 100 million tonnes of all species of fish and shellfish are currently harvested from the oceans of the world each year. Indeed, the biomass of Antarctic krill may be the largest of any multi-cellular animal species on the planet (Nicol 2004).

II. Role of krill in the Antarctic food web

The Antarctic marine ecosystem is largely dependent on Antarctic krill as the key prey item. Most species in the Antarctic are one or two trophic levels away from krill. Antarctic krill is a major component of the diet for a variety of species, and many rely on krill almost entirely (Alonzo et al. 2003).

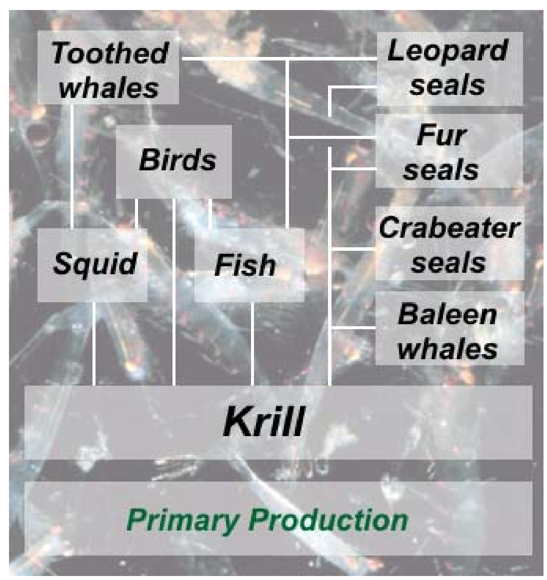


Fig. 3 - A simplified representation of the Southern Ocean food web linkages that are centred around krill as presented in Everson, 2000b

For many marine mammals and sea birds, particularly in the South Atlantic, krill is the most abundant food source. Areas of highest krill concentration are often close to the land-based breeding colonies of krill-eating birds and seals (Croxall 2003). These predators depend on krill being within reach of their colonies in order to feed and rear their offspring during the Antarctic summer. For example, there are clear links between krill abundance and the reproduction and survival of penguins in Antarctica (Alonzo et al. 2003).

Key species that directly depend upon krill for food

Seabirds: In general, seabirds are significant consumers of krill. The differences in the annual amount of krill taken differ between species and specific locations.

The following penguin species are dependent to a great extent on Antarctic krill (Croxall 1984): Adelie Penguin (Pygoscelis adeliae); Chinstrap Penguin (Pygoscelis antarctica); Macaroni Penguin (Eudyptes chrysolophus); Gentoo Penguin (Pygoscelis papua).

Three species of albatrosses feed on krill, although the percentage of contribution of krill to their diets differs between species. These species are as follows: Black-browed Albatross (*Diomedea melanophris*); Light-mantled Albatross (*Phoebretia palpebrata*); Grey-headed Albatross (*Diomedea chrysostoma*).

Three species of albatrosses feed on krill, including the Black-browed Albatross (Diomedea melanophris). Photo: © Claudio Suter.

Petrels in general, feed extensively on Antarctic krill. The contribution percentage of krill to their diet varies depending on the species, but seems to be very high in smaller petrel species (Everson 2000b). The main species of petrels dependent on krill for food are: Southern Giant Petrel (*Macronectes giganteus*); Northern Giant Petrel (*Macronectes halli*); Antarctic Petrel (*Thalassoica antarctica*); Cape Petrel (*Daption capense*); Snow Petrel (*Pagodroma nivea*); Diving Petrel (*Pelecanoides* spp); White-chinned Petrel (*Procellaria aequinoctialis*).

The smaller storm petrels (*Oceanites* spp) and prions (*Pachyptila* spp) feed on a wider range of crustaceans, including krill, although the emphasis of their diet is towards copepods (Prince and Morgan 1987).

Seals. All species of Antarctic seals, besides the Southern Elephant Seal (*Mirounga leonina*), feed to some extent on krill (Laws 1984). These species are: Crabeater Seal (*Lobodon carcinophagus*); Leopard Seal (*Hydrurga leptonix*); Weddell Seal (*Leptonychotes weddelli*); Ross Seal (*Ommatophoca rossi*); Antarctic Fur Seal (*Arctocephalus gazella*).

The Gentoo Penguin (Pygoscelis papua) is very vulnerable to changes in krill availability. Photo: © Claudio Suter.

Whales. The main whale species that feed predominantly on krill are the following (Everson 2000b): Minke Whale (*Balaenoptera acutorostrata*); Blue Whale *(Balaenoptera musculus)*; Fin Whale *(Balaenoptera physalus);* Sei Whale *(Balaenoptera borealis);* Humpback Whale *(Megaptera novaeangliae).*

The Crabeater Seal (Lobodon carcinophagus) is one of the Antarctic seals that have krill as part of their diet. - Photo: © Claudio Suter.

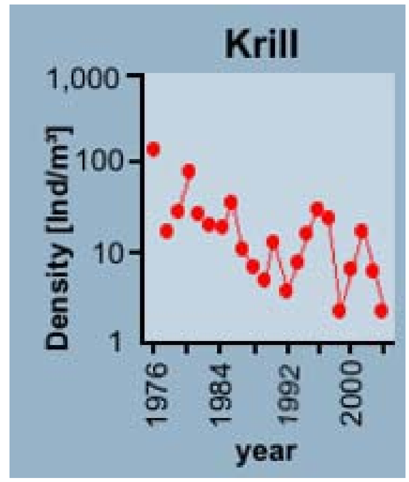
Fish. There is good evidence of several species of fish that feed on krill in the Southern Ocean (Kock 1992). The high concentrations of some fish species in certain areas might have a local impact on krill populations. In spite of this, the overall consumption of krill by fish in the Southern Ocean is unlikely to have a significant impact compared to the consumption incurred by whales, seals and birds (Everson 2000b).

Squid. Some species of squid, also present in the Southern Ocean, are known to feed on krill. Although it is estimated that the amount of squid in the Southern Ocean might be very large, accurate data on the current population size of squid are not available (Everson 2000b). This precludes any conclusion in regards to the impact of squid on krill stocks.

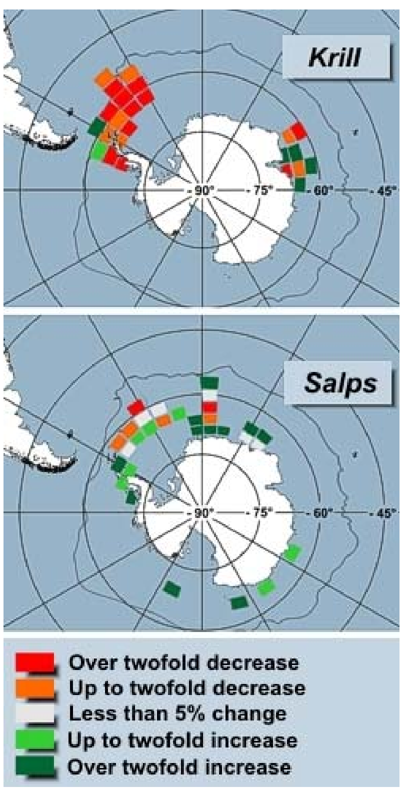
III. Effects of environmental conditions on Antarctic krill stocks

Antarctic krill has shown low recruitment rates in recent years, which is regarded with concern. In addition, possible long-term changes like global warming or ozone depletion could have significant effects at the individual or population level of euphausiid species.

In the case of Antarctic krill, the observed increase in air temperature in the Southern Ocean, affecting sea surface temperature and sea-ice conditions, could affect krill recruitment and krill stock size in the long term. Ultraviolet-B radiation is another variable that might affect near-surface krill concentrations and increase mortality rates, leading to a reduction in recruitment success and overall krill biomass (Siegel 2000).



Krill density in the SW Atlantic sector (4,948 stations in years with more than 50 stations). Extracted from Atkinson et al. 2004.



Temporal change of krill and salps above: temporal trends include post-1976 krill data from scientific trawls below: 1926–2003 circumpolar salp data south of the Southern Boundary of the Antarctic Circumpolar Current. Extracted from Atkinson et al. 2004.

A relationship has been found between krill recruitment and sea-ice conditions in the physical environment. Long sea-ice cover and a large spatial extent of it during winter are favourable conditions for an early onset of the spawning season. Generally, favourable sea-ice conditions allow for an early reproduction that leads to a successful spawning event in the summer. This is probably due to the availability of ice-algae as a feeding resource for larva/juvenile krill during the end of the winter and early spring. Ice-algae are algal communities encountered under the ice cover, and play an important role in primary production. Krill can scrape off the green lawn of ice algae from the underside of the pack ice. The ice-algae resource during this time of the year might be essential for adult krill to gain enough energy for an early onset of the reproduction process, which would favour the larval survivorship (Siegel and Loeb 1995).

Decline in krill density

A recent study conducted in relation to the southwest Atlantic - which contains more than 50% of the Southern

Ocean krill stocks - has found a significant decline in krill density in this area since the 1970s. The results of the study show that summer krill densities correlate to both the duration and the extent of sea ice the previous winter. It was found that sufficient winter ice in the Antarctic Peninsula and Southern Scotia Arc, which are major spawning and nursery areas, affects krill density across a whole ocean basin, including areas north of the Seasonal Ice Zone (Atkinson et al. 2004).

The Western Antarctic Peninsula is one of the world's fastest warming areas, and winter sea-ice duration is shortening in this area. Consequently, a significant finding is that key spawning and nursery areas of krill are located in a region that is particularly sensitive to environmental change. Changes in krill density, affecting a wide extent of the Southern Ocean, are thought to have profound implications for the Southern Ocean food web and predator balance (Atkinson et al. 2004).

The cumulative impacts of climate change and resource extraction need to be carefully considered when developing management models for krill, and speak in favour of keeping a strong focus on precautionary decisions, in view of the degree of uncertainty involved.

IV. About the Antarctic krill fishery

The krill fishery has been the largest fishery in the Southern Ocean since the late 1970s and has prospects for becoming the largest global fishery (Nicol & Endo 1997); (Croxall & Nicol 2004).

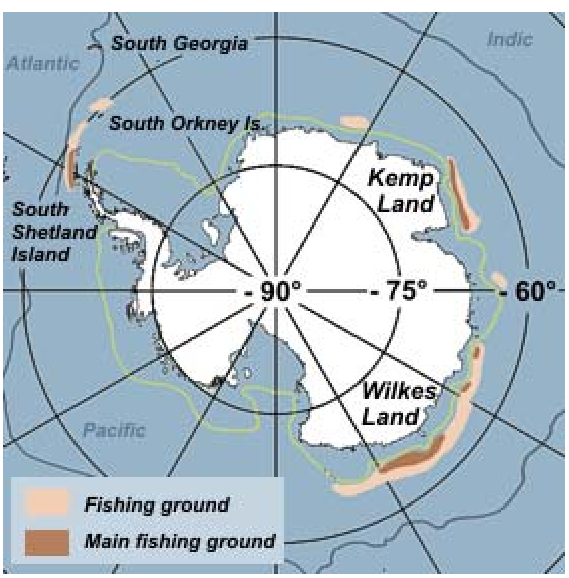


Fig. 5 - Distribution of Antarctic krill fishing grounds in relation to continental and insular shelves, and pack-ice edge, during the austral summer in the Antarctic (extracted from Ichii 2000).

The Southern Ocean contains the largest stocks of krill in the world. This factor, together with Antarctic krill's tendency to aggregate into large concentrations represented by swarms, makes the Antarctic krill fishery particularly attractive. Normally, vessels target krill concentrations located in limited areas. Good fishing grounds are usually found in ice-free continental and insular shelf break-slope areas.

Practically the entire Antarctic krill fishery seems to occur within the Area of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), where three main geographical regions of historical krill harvesting have been identified: off Kemp Land; off Wilkes Land; on the southwest Atlantic (Ichii 2000). The fishery has recently concentrated in the Atlantic Sector of the Southern Ocean, where the most predictable concentrations of krill are to be found (Miller & Agnew 2000).

Fishing strategies. Antarctic krill is harvested in mid-water with fine-mesh trawl nets. A relatively large vessel is required to enable the installation on board of at least three peelers and to allow for the production of additional (compared to regular needs) 10-12 tonnes of freshwater per day for processing purposes.

One of the most important problems in the Antarctic krill fishery is a logistic one, due to the fishery's remote location - far from major ports – and the very inhospitable waters where it takes place. For this reason, in spite of krill's circumpolar distribution, the fishery has tended to concentrate in areas closer to other fisheries, mainly off South America. This allows krill vessels to target other species, like squid and finfish, when krill fishing is less profitable (Ichii 2000).

Detection of krill swarms. One of the clearer attractions of the main Antarctic krill fishing grounds is that fishable concentrations of krill can reliably be found there each year. To detect krill concentrations, vessels utilise a range of information, being the historical record of good harvesting areas the most important indicator. Surface water temperatures are also monitored in an effort to identify oceanographic fronts, where krill tend to aggregate for prolonged periods.

Una captura de krill es izada a bordo de un arrastrero.
Photo: CCAMLR

In fishing grounds, sonar and echo-sounder are used to detect krill aggregations. Although an echo-sounder is especially suited to detect swarms at most depths immediately below the fishing vessel, it has a very limited horizontal range (normally, no more than the vessel width). On the other hand, the sonar has an effective horizontal detection range and a limited vertical range.

In general, krill trawlers target large and dense swarms. After being detected, swarms are intercepted by trawlers, using sonar to make adjustments as to optimise the operation.

Further adjustments in regards to the trawl depth are done following the swarm depth by using the echo-sounder and a net sounder. The latter indicates the net depth in relation to the surface, and also the quantity of krill that has entered the net (Ichii 2000).

Catching techniques. During fishing, trawlers usually travel at a speed of two knots. In most cases, catch rates are not limited by krill availability but by processing on board and by the need to overcome quality concerns. When trawling, towing duration during hauls is generally adapted to reduce product deterioration. Krill catches in each haul also limited to prevent the product being crushed and to allow processing when the catch is still fresh (normally 2-3 hours). Towing and processing operations are conducted continuously throughout day and night (Ichii 2000).

The use of new technologies to catch and process krill has been reported at the last CCAMLR Meetings (SC-CAMLR 2004). Under this new technology, krill is being caught using a pumping system that allows for higher catch rates and reduces product deterioration. CCAMLR's scientific body has recognized that this could be an indication that new economic and technological drivers are in place, which might significantly transform the fishery in the near future. Lack of comprehensive information about the characteristics and use of these harvesting methods is hampering relevant CCAMLR bodies from assessing the potential effects of these developments on the Southern Ocean marine ecosystem.

Catch selection. An important concern for Antarctic krill fishers is quality, and the linked commercial value of the catch. In general, Antarctic krill products are graded by body size and body colour.

In relation to body colour, the term "green" krill is applied to individuals that have been feeding intensively on phytoplankton. Green krill are normally found in the early austral summer (December-January). "Green" krill are avoided when fresh frozen or boiled frozen krill are produced, as it lowers the quality of the products due to a dirtier appearance, a poor smell, and inferior taste (Ichii 2000). "White" krill is the term used to refer to transparent krill, of higher commercial value due to its firm and attractive appearance. "White" krill is more frequent from late in the austral summer. Furthermore, "pink" krill refers to krill of a red/pink colour, flaccid and very crushable, of less value than white.

Krill size is generally used as grading criteria: "LL" refers to krill larger than 45 mm, easier to peel and of higher value, for human consumption and sport fishing uses. On the other hand, "L" is applied to individuals of 35 - 45 mm, and "M" is used for krill below 35 mm. These last two sizes are also in demand for sport fishing and aquaculture feed (Ichii 2000).

V. History of krill fishery

Interest in krill fisheries began in the 1960s, when a total catch of more than 150 million tonnes was projected, representing the so-called "krill surplus" caused by the great reduction in baleen whale stocks (Ichii 2000). Another important factor in the development of the krill fishery was the declaration of 200-mile Exclusive Economic Zones (EEZs) in the late 1970s, as a result of which distant water fishing nations turned to international waters for new fishing grounds (Nicol & Endo 1999).

Table 1: Antarctic krill catches (tonnes) in the CCAMLR Area (1993/94-2002/03), by country Fuente: CCAMLR. 2005. Boletín Estadístico, Vol. 17 (Versión electrónica). www.ccamlr.org

	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03
Argentina	-	-	-	-	-	6.524	-	-	-	-
Chile	3.834	-	-	-	-	-	-	-	-	-
United Kingdom	-	-	-	308	634		-	-	-	-
India	-	-	6	-	-	-	-	-	-	-
Japan	61.097	63.377	58.769	60.937	67.481	66.076	80.602	67.377	51.079	59.682
Korea	-	-	-	-	2.849	27	7.233	7.525	14.353	21.276
Panama	-	637	-	-	-	-	-	-	-	-
Poland	7.997	12.521	22.104	14.408	19.133	19.167	20.049	13.696	16.365	8.905
Russia	-	-	-	-	-	-	-	-	-	-
Ukraine	12.613	59.150	10.277	-	-	6.719	-	14.023	32.015	17.715
Uruguay	-	-	-	-	-	3.444	6.477	-	-	-
USA	-	-	-	-	-	-	70	1.561	12.175	10.150
Vanuatu	-	-	-	-	-	-	-	-	-	-
South Africa	3	-	-	-	-	-	-	-	-	-
TOTAL	**85.544**	**135.686**	**91.156**	**75.653**	**90.098**	**101.957**	**114.430**	**104.182**	**125.987**	**117.728**

In the 1970s, the development of the commercial krill fishery was facilitated by heavy fishing subsidies by the USSR, which became the most important krill-fishing nation in that decade. The highest krill catches occurred in the early 1980s, reaching over half a million tonnes. Problems in krill processing and rising interest in finfish caused a considerable decline in krill catches in the 1982/83 and 1983/84 seasons. From 1986 to 1991, annual catches stabilised at around 350,000 to 400,000 tonnes. In the following seasons, catches dropped again due to the break-up of the Soviet Union, which forced this fleet to cease operations (Ichii 2000). Although the Antarctic krill fishery has been stable for the last decade with catches around 100,000 tonnes, an increasing trend is clearly observed if multi-year trends are analysed (table 1).

For the last three years, catches have been around 120,000 tones. Based on reports on intentions of krill harvesting submitted by fishing nations, relevant bodies of the

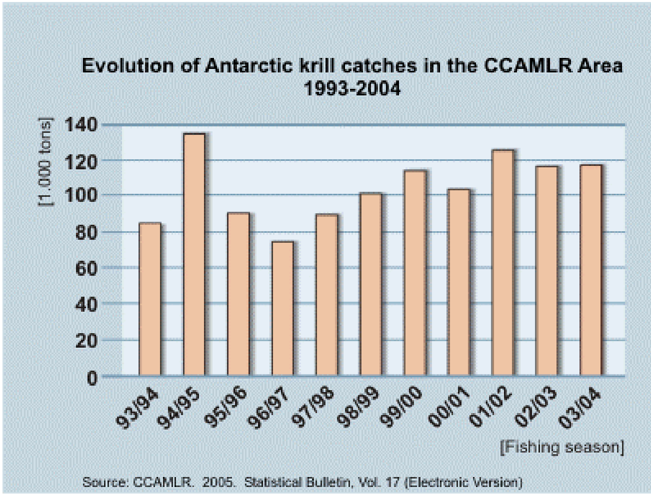


Fig. 6 - Evolution of Antarctic krill catches in the CCAMLR Area 1993-2004. Source: CCAMLR. 2005. Statistical Bulletin, Vol. 17 (Electronic Version). www.ccamlr.org

Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) have estimated the projected catch for the 2004/05 season to be in the region of 160,000 tonnes, a significant increase from previous years. Most importantly, the fact that the fishery is operated from a larger number of countries (including non-CCAMLR members) is considered as a signal of greater international interest in krill harvesting (SC-CAMLR 2004).

New developments in the aquaculture industry and improvements in the catching and processing techniques are fuelling a renewed interest from the fishing industry in exploiting large quantities of krill in the Southern Ocean. The challenge is now for CCAMLR to put in place precautionary catch limits throughout the Southern Ocean that are capable of avoiding the risk of fishery-related impacts on Antarctic marine species before the fishery expands.

VI. Management of the Antarctic krill: the precautionary and ecosystem approaches in practice

The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), which came into force in 1982 as part of the Antarctic Treaty System, was negotiated by the Antarctic Treaty Consultative Parties with the aim of regulating the harvesting of marine species in the Southern Ocean with the exception of whales and seals. The major factor that prompted the negotiation of CCAMLR was precisely the need to respond to the rapid expansion of the krill fishery in the 1970's and the related concerns over the possible impacts that krill fishing might have on the Antarctic marine environment (www.ccamlr.org). It was also the extended distribution of krill that was behind the designation of the management area for CCAMLR.

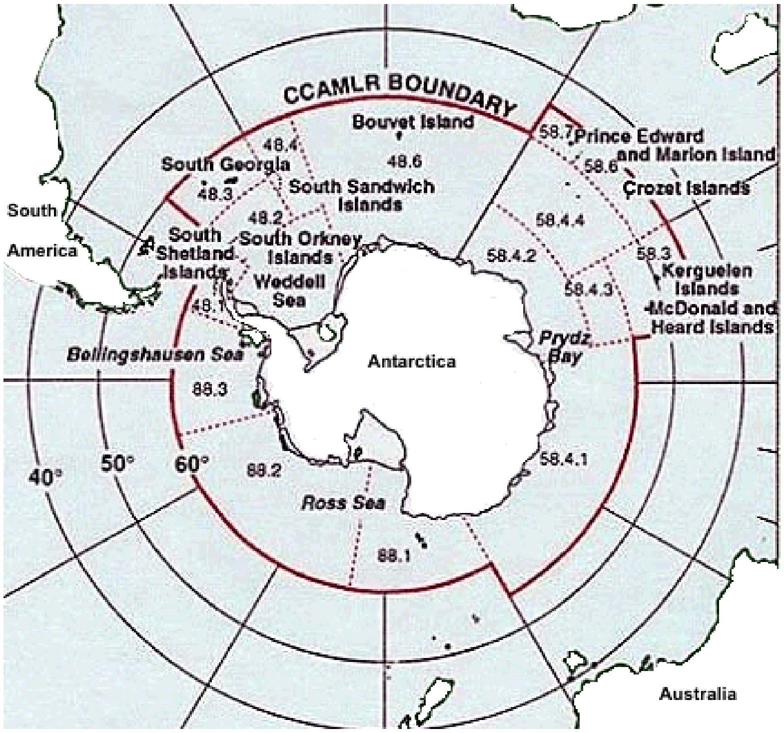


Fig. 7 - Map of the CCAMLR Area showing statistical areas, subareas and divisions used by CCAMLR for the reporting of fisheries catch data. Source: CCAMLR. 2005. Statistical Bulletin, Vol. 17 (Electronic Version). www.ccamlr.org

Krill's key role in the ecosystem was very important for the formulation of CCAMLR's basic principles. According to Article II, the objective of the Convention is the conservation of Antarctic marine living resources, including their rational use. CCAMLR was the first international fisheries arrangement to incorporate the ecosystem and precautionary approaches as basic principles.

An ecosystem approach concentrates not only on harvested species, but also requires that management take into account the ecological inter-relationships between harvested and non-harvested species, in order to minimize fisheries impact on dependent and related species, and on the ecosystem as a whole.

The most widely accepted and cited version of the precautionary approach in the environmental context is Principle 15 of the Rio Declaration (1992), which states: "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation".

In the context of CCAMLR (signed in 1980), the precautionary approach was formulated as a mandate to prevent or minimise the risk of changes in the marine ecosystem, which are not potentially reversible over two or three decades -Article II (c).

CCAMLR has a decision-making body, the Commission, composed by its 24 Members, which take all management decisions on the basis of consensus. Management rules take the form of conservation measures applicable to the different fisheries occurring in the

Convention Area. The Commission takes management advice from the Scientific Committee, which in turn is assisted by several working groups. The Working Group on Ecosystem Monitoring and Management (WG-EMM) takes on all relevant technical work in relation to the krill fishery, and is in charge of assessing relevant data in relation to the so-called the "krill-centric ecosystem".

Development of an effective system

The first challenge faced by CCAMLR at its entry into force in 1982, was to develop an effective system to accomplish the Convention's basic principles, at a time when a rapid expansion of krill fishing levels was anticipated. Since the early years it became clear that the traditional approaches to fisheries management were not appropriate for krill. Consequently, to adequately consider the needs of krill-dependent species, more conservative reference points than the ones commonly applied in a single-species fisheries management were adopted (Miller & Agnew 2000).

CCAMLR's Scientific Committee spent considerable effort in determining appropriate harvesting levels for krill using a simulation model, called KYM (Krill Yield Model). The KYM was developed on the basis of estimates of the initial, unexploited, biomass of the krill stock in the area that resulted from an international research program (Biological Investigations of Marine Antarctic Systems and Stocks or BIOMASS) coordinated in the early 1980s to investigate krill stocks in the Antarctic (Croxall & Nicol 2004).

The sighting of a whale defecating can help identify feeding areas for pelagic predators of krill. The Blue Whale (Balaenoptera musculus) is one of the cetaceans that feed predominantly on krill.

Photo: © Elsa Cabrera/Centro de Conser-vación Cetácea.

CCAMLR attempted to integrate the ecosystem approach into its management of the Antarctic krill fishery, by developing decision rules to determine the proportion of krill biomass that can be harvested each year that take into account krill's role in the ecosystem. For example, the requirements of predators of krill are incorporated by establishing a level of krill escapement of 75% of the pre-exploitation biomass, instead of the 50% level, normally used in single-species management.

Although CCAMLR's management of krill represents an important innovation in fisheries management, it is still far from fully implementing the ecosystem approach (Croxall & Nicol 2004). It is key for CCAMLR to develop a "feedback management" procedure for krill that incorporates new information from the Antarctic ecosystem –as it becomes available-, particularly on the potential effects of krill fishing on predator populations.

CEMP: Ecosystem Monitoring Programme

An assessment of the impact of krill fishing on dependent species is one of the main tasks of CCAMLR's Ecosystem Monitoring Programme (CEMP), designed to detect and record significant changes in the critical components of the ecosystem. CEMP findings are to be integrated into long-term management procedures, to allow relevant management measures to be adjusted to new information on the Antarctic ecosystem.

The Adelie Penguin (Pygoscelis adeliae) is greatly dependent on krill for food and is currently being monitored by CCAMLR's Ecosystem Monitoring Program. Photo: © Claudio Suter.

Catch limits for krill in Statistical Area 48 (South Atlantic), where the current fishery primarily operates, has been set in 4 million tones, subdivided into four Subareas: 48.1 (1,008 million tones); 48.2 (1,104 million tones); 48.3 (1,056 million tones); and 48.4 (0,832 million ones). Although the current fishery is only taking a small proportion of this quota -around 100,000-160,000 tones are being harvested annually- it is important to take into account that catch limits for krill are established for large areas of the Southern Ocean, while the krill fishery (and the krill resource) are in fact taking place at much smaller scales. For example, in the southwest Atlantic, this fishery operates in less than 20% of the area. Most importantly, in many areas, fishing grounds overlap with feeding areas of krill predators. This poses a risk that high krill quantities being removed locally could have an impact on these predators. It is therefore necessary to manage the krill fishery at much smaller scales, developing a model that adequately takes into account the relations between predators and their prey (Croxall & Nicol 2004).

In 2002, CCAMLR started this process by defining 15 "Small-scale Management Units" (SSMUs) for the management of the krill fishery in the South Atlantic. The current challenge is to set catch limits for each of these areas that adequately take into account the needs of krill-dependent species. At this stage, management decisions in this direction need to deal with considerable uncertainty until more information is available that allows to: calculate how much krill is required by fisheries and predators in certain areas and times of the year; to estimate the main fluxes of krill into and out of these areas; and to evaluate the nature of potential competition between predators and fisheries. In the interim, CCAMLR needs to start testing precautionary management approaches aimed at minimizing potential risks on the ecosystem (Croxall & Nicol 2004).

VII. Ecological concerns

The central role of krill in the Antarctic marine ecosystem poses some key questions in relation to the potential impact of krill harvesting, particularly on those species that have krill as an essential component of their diets. According to the information currently available, the Antarctic krill fishery occurs almost entirely within the foraging ranges of land-based krill predators such as penguins and seals (Constable & Nicol 2002).

The impact of high krill catches taken in a small area, close to land-based predator colonies, like this Gentoo Penguin colony (Pygoscelis papua), needs to be carefully taken into account when managing the krill fishery. Photo: © Claudio Suter

There is evidence that competition for krill between fishing vessels and krill predators already exists in some areas. This evidence is especially based on consumption rates in local areas and at particularly critical times of the year for predators (SC-CCAMLR WG-EMM 2003).

In addition, recent research has shown that demand for krill has begun to exceed supply in some areas of the southwest Atlantic. As a result, it is thought that penguins and albatrosses might be having difficulties in rearing offspring successfully. Twenty years of long-term monitoring of seabirds and seals on South Georgia has revealed an increase in the frequency of years when there is insufficient krill to feed seal pups and seabird chicks. This discovery is now putting into question the apparent super-abundance of krill over all of the Southern Ocean and reinforces the need to manage the krill fishery in a way that takes into account the needs of predators in different Antarctic areas (British Antarctic Survey 2002).

The impact of high krill catches taken in a small area, close to land-based predator colonies, also needs to be considered in relation to breeding times. Concentrated fishing may have its maximum impact on predator breeding success, when fishing takes place on the immediate foraging area and at the critical breeding time. For example, in the Antarctic Peninsula, the summer fishery takes place at the same time and in the same areas where penguins and seals are foraging to rear their young.

CCAMLR has attempted to consider the needs of krill predators at the time of establishing decision rules for setting up catch limits for the krill fishery. These rules allow fishing quotas to be set at lower levels in order to secure more quantities of krill be left for predators than if single-stock management principles were applied. In spite of this innovative approach, current management of Antarctic krill is still occurring on the basis of large sections of the Southern Ocean. These sections have been identified as "harvesting units", and have been described as large-scale areas circumscribing the managed population of the harvested species –for example, Antarctic krill is commonly assessed at the scale of the South Atlantic. Harvesting units are likely to comprise a number of fishing grounds and are usually adequate for the management of target stocks when a single species management is considered. This type of management does not take into account complex predator-prey-fishery interactions, which occur at much smaller scales (Constable & Nicol 2002).

At the level of harvesting units, CCAMLR has been applying the Statistical Subareas defined by FAO, in the same way as it is done with other Antarctic fisheries. In 2000, CCAMLR adopted a subdivision of the krill catch limit in Area 48, pending a further review of catch quotas in localized areas. In the case of krill, there is a particularly imperative need to identify a different type of management unit, since a harvesting unit will inevitably include a number of foraging areas of krill predators. In order to ensure the application of an ecosystem-based management, it is important to identify predator-prey-fishery systems, relatively independent from each other. These have been referred to as "predator units" (Constable & Nicol 2002).

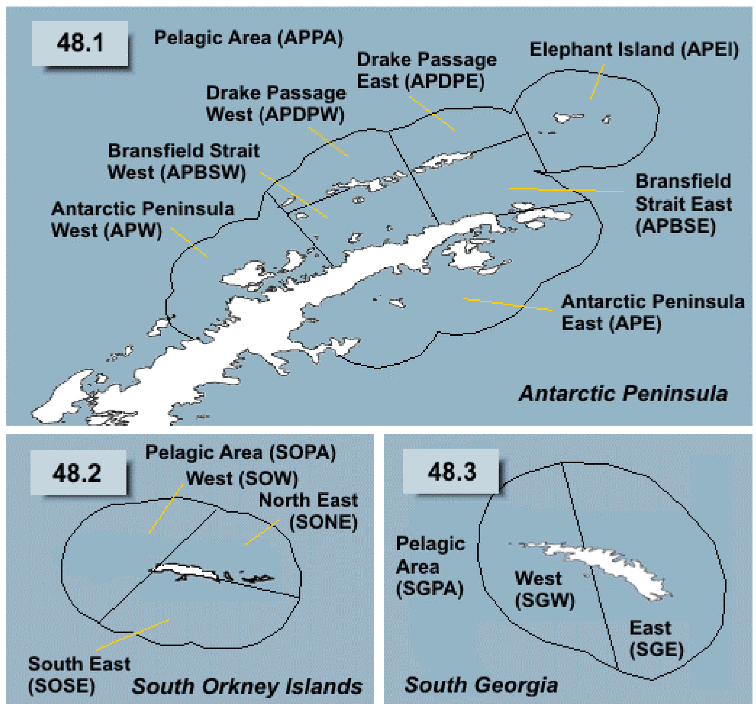


Fig. 8 - Location of SSMUs. Top: Subarea 48.1: Antarctic Peninsula; Bottom left: Subarea 48.2: South Orkney Islands; Bottom right: Subarea 48.3: South Georgia Islands. Extracted from WG-EMM 2003.

It has been acknowledged that the current management that sets limits for harvesting units involves a great potential for localised impacts on krill-dependent predators (Constable & Nicol 2002). This impact is more likely to occur if large portions of the actual quota are taken within a small portion of a Subarea. It is important to highlight that an important portion of the historical krill harvest has been taken from a small number of areas, which coincidently also concentrate a high percentage of the estimated predator demand for krill in the Southern Ocean (Hewitt *et al.* 2004).

CCAMLR has responded to the risk of competition between krill fisheries and predators by sub-diving the Subareas in the South Atlantic into 15 SSMUs ("Small-scale Management Units") that respond to the concept of predator units. The delimitation of these SSMUs was the result of a process in which land-based predator foraging areas, krill distribution, and the behaviour of the fishery were considered (Hewitt *et al.* 2004). The next challenge for CCAMLR is to subdivide the current catch limits applicable to Area 48 among the SSMUs, in order to avoid excessive localised effort that could affect krill availability in predator foraging areas. Another measure taken by CCAMLR to avoid this type of localised impact is the requirement that the total catch in the South Atlantic should not exceed 620,000 tonnes until this subdivision has been completed.

VIII. Surveillance, control and monitoring: the need for stronger regulations of the Antarctic krill fishery

Although krill is recognized as a key resource in the Southern Ocean, the Antarctic krill fishery still constitutes an exception in regards to most of the basic regulatory requirements applicable to other Southern Ocean fisheries. This applies to several aspects of the fishery, such as reporting requirements, notification of fishing plans, and monitoring and surveillance measures.

Prior to 2002, the krill fishery was the only CCAMLR fishery that did not require mandatory submission of detailed catch and effort data. In 2002, CCAMLR adopted rules that established a data reporting system for krill fisheries, according to which, krill catches are to be reported to the Commission on a monthly basis (CCAMLR 2002). Despite these new reporting requirements, more detailed information on the krill fishery is still needed. CCAMLR scientific bodies have repeatedly highlighted the need to receive haul-by-haul data from the fishery in order to examine trends in krill distribution abundance, and to estimate the degree of overlap between the fishing fleets and the foraging ranges of krill predators, which are essential for adequately managing the fishery (CCAMLR 1992; 1998). Currently, submission of fine-scale data on a haul-by-haul basis is required for most of CCAMLR fisheries but not for krill.

There are CCAMLR rules in place that require the notification of intended entrance into a number of Southern Ocean fisheries, but these do not apply to krill (Croxall & Nicol 2004). The absence of complete and reliable information on future krill fishing plans is precluding

CCAMLR bodies from predicting trends in the krill fishery, which would be key for management decisions (SC-CCAMLR WG-EMM 2003).

Perhaps the most important regulatory gaps with respect to the Antarctic krill fishery are the absence of required vessel monitoring devices and scientific observers on board. In relation to vessel monitoring, CCAMLR requires states to monitor the position of all of its fishing vessels licensed to fish in the Convention Area through an automated satellite-linked Vessel Monitoring System (VMS). This requirement is applicable to all CCAMLR fishing vessels except for krill.

Management of the krill fishery need to take full account of potential impacts on krill-dependent species such as the Macaroni Penguin (Eudyptes chrysolophus) - Photo: © Claudio Suter.

VMS is a basic regulatory tool that allows states to verify that fishing operations comply with the conditions of the fishing licence and that fishing in non-authorised areas does not occur. VMS is also important for an accurate evaluation of the operation of the fishery. At its 2004 meeting, CCAMLR strengthened the system by establishing a centralised VMS, by which flag states are to transmit the position of the vessels to the CCAMLR Secretariat, to allow for independent verification of vessel positioning data. The fact that krill vessels are not subject to VMS makes this fishery poorly regulated and difficult to monitor.

Similar comments can be made in relation to the requirement of observers on board. It is widely acknowledged that the presence of scientific observers on board of all fishing vessels is necessary for the gathering of relevant data on different aspects of the fishery, which are key for adequate management. Surprisingly, CCAMLR does not currently require the presence of scientific observers on vessels fishing for krill in the Convention Area. Although CCAMLR has designed a “Scheme of International Scientific Observation”, there is no conservation measure making it compulsory for krill fishing. CCAMLR conservation measures require the presence of scientific observers on board of vessels participating in other fisheries, but the krill fishery constitutes an exception to this rule.

IX. Market for Antarctic krill products

There are no recent studies on the economics of krill fisheries, although it is known that high costs are generally associated to fishing for krill. More information needs to be developed on the current and potential markets for krill products in order to better understand future trends in the krill fishery (CCAMLR 2002).

There is an increasing demand for Antarctic krill as aquaculture feed, particularly for salmon farms, like Loch Eriboll fish farm, North Sutherland. Photo: © The Salmon Farm Protest Group. (www.salmonfarmmonitor.org)

Recent analysis of the fishery and the market for krill products has detected signals that an expansion of the Antarctic krill fishery might be about to happen. The main driving factor is an expected increase in the demand for krill products, particularly for aquaculture feeds but also for pharmaceutical uses (Nicol & Foster 2003).

The development of krill products for aquaculture and medical uses present the greatest increases in later years, an indication that demand for these products is increasing. For example, 87.5% of krill patents for medical products have been filed after 1988 (Nicol & Foster 2003).

Antarctic krill is also used in the production of food for human consumption, although it has been noted that information on this kind of products from nations other than Japan is not generally available. Approximately 40% of the Japanese Antarctic krill catch is processed for human consumption as boiled frozen krill or peeled krill tail frozen in blocks on board. In the past, canned tail meat was also produced from the Japanese catch but not any longer (Nicol *et al*. 2000).

The main krill product for human consumption is frozen krill tail meat, which consists of the cooked and peeled tail meat of krill, frozen at sea. It has been marketed as a very nutritional organic seafood product with a mild taste, similar to lobster, rich in Omega 3 oils, vitamins, minerals and antioxidants. It can be used in pizzas, seafood salads, soups, and restaurant entrees (Sclabos 2003). There have also been some reports on the marketing of "Antarctic Krill Concentrate" as health food supplement prepared from peeled, freeze-dried tail meat (Nicol *et al*. 2000).

A steady development of krill products for non-nutritional uses -such as pharmaceutical and industrial uses - has been documented. Main applications are the production of chitin and chitosan from krill shells and krill enzymes for pharmaceutical and other purposes. Chitin and its substance-derived chitosan have a wide variety of current and potential uses, from loudspeakers membranes to cholesterol lowering products. Krill oils have also been described as an expanding market in the lucrative nutriceutical, cosmetic and pharmaceutical fields (Nicol & Foster 2003).

Krill's powerful hydrolytic enzymes have an interesting potential for pharmaceutical uses, such as the production of chemonucleolytic agents or debriding agents for the treatment of necrotic wounds. Research programs have succeeded in the identification of a single enzyme from krill, which may lay the basis for the development of drugs for the treatment of several types of infections. Moreover, krill enzymes may also be used in the restoration of works of art, which adds up to the potential of krill-derived high-value products (Nicol *et al*. 2000).

There is an increasing demand for Antarctic krill as aquaculture feed, particularly for salmon farms.

There is a view that demand for these products may not develop to the point where they become a major economic justification for krill fishing, even though they might result in high-value by-products that contribute to the profitability of the fishery (Nicol *et al.* 2000).

The use of krill for aquaculture feed seems to be the most important market development that is triggering investments in krill harvesting. Aquaculture, especially salmon farming, lacks sufficient feed supply. The fish farming industry already uses up around 75% of the world's fish oil and around 40% of the world's fish meal. By 2010, these figures might go up to 90% and 56% respectively, according to predictions by the International Fish Meal and Fish Oil Manufacturers Association (IFOMA). FAO has indicated that by 2010, farmed salmon and trout alone could consume 620,000 tonnes of fish oil (Staniford 2002). With demand exceeding supply and rising prices, fish oil has been labelled "the new blue gold" (Staniford 2001).

This lack of supply, along with increasing concerns over contaminants in aquaculture feeds, is leading the industry to urgently seek feeding alternatives. Krill demand is likely to increase due to its excellent value as nutrient source for farmed fish and crustaceans (protein, energy, essential amino acids). Other outstanding properties of krill are its natural pigment content (particularly appropriate for salmon farming), its palatability, its low content of pollutants, and its likely improvement of larval fish survival. These attributes make krill a more attractive feed than potential competitors such as squid meal, clam meal, artemia soluble, and fish soluble (Sclabos 2003).

Another attribute that is likely to increase krill's potential is its high concentration of Omega 3 fatty acid, which increases the natural Omega 3 content of farmed fish fed with diets containing krill (Sclabos and Toro 2003).

In summary, the demand for high quality aquaculture feeds, and in particular as a protein source for salmon farms, might raise the profitability of krill fishing considerably. Furthermore, increasing restrictions to access to krill fisheries in the Northern Hemisphere –fuelled by opposition to expanding krill fishing from local fishing industries, fishery managers and conservation groups- is very likely to intensify pressure on Southern Ocean krill stocks. Antarctic waters are the most obvious source for krill (Nicol & Foster 2003). In light of these developments, an expansion of the Antarctic krill fishery seems inevitable.

X. New developments in the krill fishery: prospects of expansion

There are strong indications that interest in the Antarctic krill fishery is rapidly increasing, as the market for krill products expands. The perceived massive abundance of krill stocks in the Southern Ocean and increasing restrictions to access to krill fisheries in the Northern Hemisphere are elements that may intensify pressure on Southern Ocean krill stocks in the short term (Nicol & Foster 2003).

After a period of highly subsidised krill fishing, particularly by the former Soviet Union, when krill catches reached their peak (around 5000,000 tones in the early 1980's), krill catches dropped due to lack of economic incentives and problems encountered in krill processing (Ichii 2000). A "new generation" of krill fishing resumed in the 90's, with increased interest from the fishing sector in several industrialised countries due to the emergence of a potentially rewarding market of krill products as aquaculture feed. Although reported krill catches have stabilised around 100,000 tones during the last decade –around 120,000 in most recent years-, reports of fishing plans by krill-fishing nations to the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) indicate that catches might go up to 160,000 tones in the 2004/05 season (SC-CAMLR 2004).

A new interest in krill fishing as a profitable, promising industry is observed internationally. The Norwegian fishing industry might become a major player in this new generation of krill fishers, by deploying large, modern, highly efficient factory vessels to the remote waters of the Southern Ocean to harvest what is perceived as an "enormous resource" (NRK 2005). For example, the Norwegian-owned multi-national *Aker Seafood* started harvesting krill in the Southern Ocean during the 2003/04 season, using the *Atlantic Navigator*, a factory super trawler, under the flag of Vanuatu (AKER ASA 2004).

At the CCAMLR XXIII meeting (2004), it was manifest that the *Atlantic Navigator* had failed to comply with relevant CCAMLR conservation measures, such as the timely and complete submission of catch data (CCAMLR 2004). In spite of this, Vanuatu notified its plans of catching 60,000 tonnes of krill in the 2004/05 season. Vanuatu's krill fishing raised serious concerns within the Commission related to the high level of intended catch, doubts over the capacity of this state to exercise proper flag jurisdiction, and reports that the Vanuatu-flagged vessel was using new technologies about which CCAMLR bodies had no detailed knowledge.

The *Atlantic Navigator* is a large, modern factory trawler -built in 1996-, regarded as the most advanced vessel of its kind, and one of the most disputed ships in the world. It triggered notable controversy in the mid 1990's while fishing in Alaska under the name *American Monarch*, and promted opposition from environmental groups again when it was deployed to enter the already over-exploited fishing grounds of Southern Chile to fish for southern blue whiting and hoki (Patagonian grenadier). At that time, this vessel was reported to be capable of fishing and processing up to 1,200 tonnes of fish each day - more than any other fishing vessel in the world (Greenpeace 1997).

These Norwegian-owned krill fishing operations will be probably flying the Norwegian flag hereafter. Investments are coupled with the use of new technologies to catch and process krill that might increase the profitability of the operations in a significant way. As reported at the CCAMLR meeting in 2004, the new technology involves pumping the krill constantly from the trawl (CCAMLR 2004). This avoids rapid deterioration of the krill, one of the main factors that have limited the catching capacity of krill trawlers until now. As a result, the catching and processing capacity of krill harvesting fleets might expand dramatically in the short-term. This could stimulate a rapid growth of Antarctic krill fishery with irreversible impacts on krill-dependent species in the Southern Ocean, unless appropriate precautionary management procedures are developed early enough.

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