

Review

Krill fisheries: Development, management and ecosystem implications

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Abstract – There are currently at least six commercial fisheries harvesting six different species of euphausiid, or krill: Antarctic krill (*Euphausia superba*), fished in the Antarctic; North Pacific krill (*Euphausia pacifica*), fished off Japan and off western Canada; *Euphausia nana*, fished off the coast of Japan; *Thysanoessa inermis*, fished off the coast of Japan and off eastern Canada; and *Thysanoessa raschii* and *Meganyctiphanes norvegica* which have been experimentally harvested off eastern Canada. The current world catch of all species of krill is over 150 000 tonnes per annum but few fisheries are being exploited to their maximum theoretical potential. The size of the world krill harvest is currently limited by lack of demand, although some fisheries are being deliberately managed at low levels because of ecological concerns. We have outlined the history of these krill fisheries to determine where there are common trends and issues which will affect their future development. Krill products are currently mostly used for the aquaculture and sport fishing market but considerable effort has also been put into developing products for human consumption, particularly from Antarctic krill. The future development of krill fisheries is examined in the light of information on trends in krill products which include pharmaceutical and industrial uses in addition to nutritional products. Because of the central ecological role of krill in many marine ecosystems, the subject of krill harvesting is a sensitive issue and krill fisheries require careful management. This requirement has spawned an innovative international management regime in the Antarctic – the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) – which has developed procedures for managing the harvest of Antarctic krill that may be applicable to other fisheries. The common problems of managing krill fisheries are outlined particularly those relating to the role of krill in many coastal ecosystems, and as prey for many other species which are commercially fished. © Ifremer/Cnrs/Inra/Ird/Cemagref/Elsevier, Paris

Krill / euphausiid / fisheries / ecosystem management

Résumé – Le krill : développement et gestion de la pêche et conséquences sur l'écosystème. Il y a au moins six pêcheries de krill récoltant six espèces différentes d'Euphausiacés ou krill : le krill de l'Antarctique (*Euphausia superba*), capturé en Antarctique, le krill du Pacifique nord (*Euphausia pacifica*), capturé dans les eaux du Japon et de l'est canadien, et enfin, *Thysanoessa raschii* et *Meganyctiphanes norvegica* qui sont récoltés de façon expérimentale dans les eaux de l'Est canadien. Les captures mondiales de krill, toutes espèces confondues, sont de 150 000 tonnes par an mais peu de pêcheries sont exploitées au maximum de leur potentialité théorique. L'importance des captures est actuellement limitée par le manque de demande, bien que certaines pêcheries soient délibérément gérées à de faibles niveaux pour des raisons écologiques. Nous avons mis en évidence l'histoire de ces pêcheries de krill afin de déterminer les tendances communes et leur développement futur. Les produits du krill sont pour la plupart utilisés en aquaculture et pour les pêches sportives, mais des efforts considérables sont déployés dans le développement de la consommation humaine, en particulier à base de krill de l'Antarctique. Le développement futur des pêcheries de krill est examiné en regard de l'information sur les tendances des produits pharmaceutiques et industriels, issus du krill, et aussi de la nutrition humaine. En raison du rôle écologique central du krill dans de nombreux écosystèmes marins, les pêches de krill demande une gestion attentive. Cette nécessité a conduit à un régime de gestion internationale innovant en Antarctique, la « Convention pour la conservation des ressources vivantes marines de l'Antarctique » (CCAMLR), et cela a permis de développer des procédures pour gérer les pêches de krill de l'Antarctique qui pourraient être appliquées à d'autres pêches. Les problèmes communs des pêches de krill sont soulignés, en particulier, ceux qui sont liés au rôle du krill dans de nombreux écosystèmes côtiers, et en tant que proie de nombreuses autres espèces pêchées commercialement. © Ifremer/Cnrs/Inra/Ird/Cemagref/Elsevier, Paris

Krill / Euphausiacés / pêche / gestion des écosystèmes

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1. INTRODUCTION

Krill is the common term for euphausiids, a world-wide family of pelagic marine crustaceans [76]. The 85 species of krill range in size from a few millimetres in length to deep sea species which can reach 15 cm in length [9]. Krill are planktonic when young but become less so as they grow and adult krill are generally considered as micro-nektonic.

Many species of krill are found in pelagic swarms or schools which makes them attractive to both natural predators and to commercial fisheries. The density of krill in swarms can be extremely high with biomasses up to 35 kg·m⁻³ and densities of over one million animals per cubic metre of seawater (e.g. [94]). Swarms can cover large areas, particularly in the Antarctic where swarms of Antarctic krill have been measured covering an area of 450 km² and have been estimated to contain over two million tonnes of krill [68].

Despite the widespread distribution of euphausiids and their great abundance, they have only been harvested in large quantities in two areas: Antarctic waters and the coastal waters off Japan. Krill have been harvested since at least the 19th century and possibly earlier [39] but large scale commercial harvesting of krill has only occurred in the last 50 years. In the 1960s and early 1970s, there was considerable speculation about the potential of harvesting krill, particularly from the Antarctic, and the role that such fisheries might have on the world's projected protein shortage [102, 104]. The huge krill fisheries initially proposed have not yet eventuated but krill fisheries in a number of areas have developed and have progressed beyond the experimental stages. Six species of krill are currently harvested (table I) and of these fisheries, that for Antarctic krill is the only one which has been well documented [1, 79, 80, 84], although there has been considerable research into the Japanese krill fisheries which until recently has only been locally published [93]. This review examines the prospects for the expansion of krill fisheries based on developments to date.

2. ANTARCTIC KRILL (*EUPHAUSIA SUPERBA*)

2.1. Distribution

E. superba has a circumpolar distribution, and is generally found close to the continental shelf or associated with the island groups of the Weddell-Scotia arc (figure 1). Its distribution is largely known from studies in summer when the sea ice has retreated. Its exact winter distribution is uncertain but most of the population probably remains under the seasonal pack ice. Localised studies are beginning to reveal the complex relationship between the oceanography, the bathymetry and the behaviour of krill [55], but regional differences in krill abundance are less well understood. There are areas around the coast of the Antarctic and the subantarctic islands where krill are perennially abundant [69] and initial studies suggested that these large scale concentrations of krill did not constitute biological stocks [38]. Recently, more sensitive genetic tests are beginning to show evidence of separate krill stocks [139] which may be of use in managing the fishery on a more ecological basis.

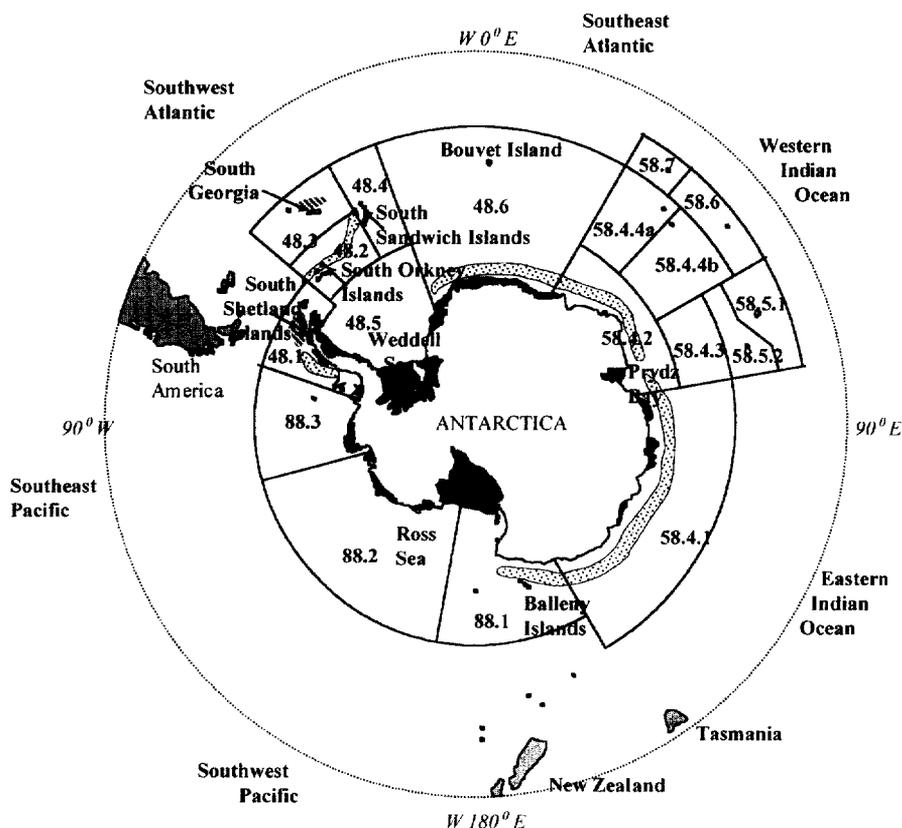
Antarctic krill are usually found aggregated in the top 200 m of the water column, but there are many records of the presence of surface swarms of krill [74] and of aggregations of krill near the bottom at up to 480 m [47]. Antarctic krill, like many species of euphausiid, may undergo diel vertical migrations, although *E. superba* does not exhibit this behaviour in a routinely predictable fashion [83].

There is considerable intra- and inter-annual variation in the abundance of Antarctic krill in particular areas and some evidence of krill being absent from large areas in certain years [53]. There is also some suggestion of long-term declines in krill abundance and recruitment, particularly in the South Atlantic [67, 121]. Few estimates of the global abundance of krill have been attempted recently but most authorities cite a figure of around 500 million tonnes as the krill standing stock size [109].

Table I. Biological information on species of krill that are commercially harvested or which have been proposed as harvested species.

Species	Common names	Maximum weight (g)	Maximum length (mm)	Estimated life span (year)	Depth distribution	Where commercially fished
<i>Euphausia superba</i>	Antarctic krill	2	65	5-7	Surface to 500 m	Antarctic
<i>Euphausia pacifica</i>	North Pacific krill	0.1	20	1-2	Surface to 300 m	Japan, British Columbia
	<i>Isada</i>					
<i>Euphausia nana</i>	<i>Ami-ebi</i>	0.01	10	< 1	Surface to 300 m	Japan
<i>Thysanoessa inermis</i>	smaa krill	0.15	32	2	Surface to 300 m	Japan, Gulf of St. Lawrence
<i>Thysanoessa raschii</i>	smaa krill	0.13	30	2	Surface to 300 m	Gulf of St. Lawrence
<i>Meganyctiphanes norvegica</i>	North Atlantic krill	0.5	40	2+	Surface to 300 m	Gulf of St. Lawrence, Mediterranean, Scotian Shelf (proposed)
<i>Nyctiphanes australis</i>	<i>stor krill</i> <i>suil dhu</i> Brit	0.02	17	1	Surface to 150 m	Tasmania, Australia (proposed)

Figure 1. CCAMLR statistical reporting areas in Antarctic waters (numbering derived from the FAO STATLANT system) and the location of existing and past Antarctic krill (*Euphausia superba*) catches. ■, Ice shelves and fast ice in summer.



2.2. Fishery

The development of the Antarctic krill fishery has been well documented [13, 80, 84, 113]. Full statistics on all Antarctic fisheries are available from the CCAMLR Secretariat¹ in the form of Statistical Bulletins [20].

The great abundance of krill led to early speculation that it might become commercially fished [74]. The immense potential for a krill fishery was highlighted by the 'surplus' krill hypothesis which suggested that the 150 million tonnes of krill that would have been consumed annually by baleen whales prior to their exploitation might be available for harvesting [66]. With the depletion of many traditional fisheries, including whales in the Antarctic, and the declaration of 200 mile EEZs by many countries in the late 1970s, fishing nations looked elsewhere for new species. Krill appeared to offer a potential for a large fishery in international waters [80].

Exploratory fishing expeditions first harvested Antarctic krill in 1961/62 and full-scale commercial operations were underway by the mid 1970s [80]. The major krill fishing nations have been Japan and the Soviet Union, and later the Russian Federation and the

Ukraine; currently vessels from four nations are involved in the fishery for Antarctic krill: Japan (62 233 tonnes), Poland (15 312 tonnes), the Republic of Korea (1 623 tonnes) and the United Kingdom (632 tonnes) (1997/98 data). The catches of krill have been unevenly distributed between Antarctic regions with total cumulative catches of krill of: 4.7 million tonnes from Area 48 (the South Atlantic), 750 000 tonnes from Area 58 (the South Indian Ocean), and 40 000 tonnes from Area 88 (the South Pacific). The fishery in the South Atlantic, from where all the current catch is taken, operates in both the summer and winter; catches in the South Georgia area (subarea 48.3) reach their peak in the winter months [35], whereas catches in subareas 48.2 and 48.1 peak in the summer months (December–March).

The annual catch of Antarctic krill reached a peak in 1982 when 528 201 tonnes were landed (figure 2), 93 % of this was taken by the Soviet Union. The krill catch underwent a poorly understood decline in 1983–1985. A second major decline in the krill fishery accompanied the political break-up of the Soviet Union in 1991. Currently 78 % of the krill caught in the CCAMLR Convention area is caught by Japanese vessels and the level of Japanese catch has been relatively stable for a number of years. The low level of the fishery at present seems to be dictated by lack of demand rather than by difficulties of supply in the Antarctic, although companies from a number of coun-

¹ CCAMLR Secretariat, PO Box 213, North Hobart, Tasmania, 7002, Australia.

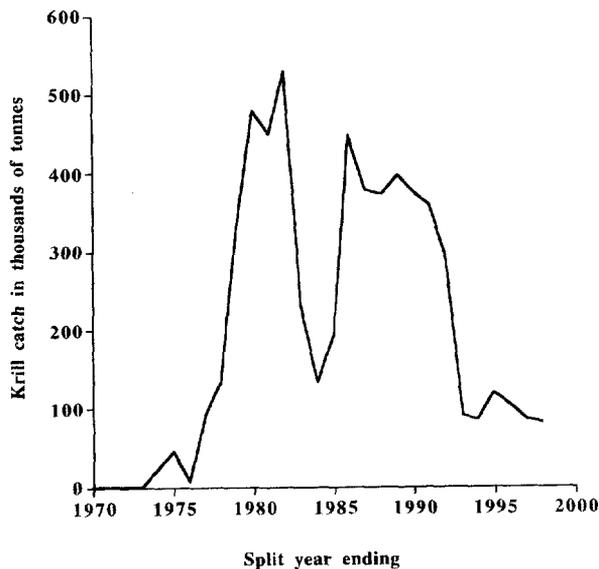


Figure 2. Annual catches of Antarctic krill (*Euphausia superba*) reported to CCAMLR. Catches are reported for the period 1st of July one year to 30th of June the next, known as the split year.

tries have recently expressed interest in exploiting Antarctic krill [8, 132].

2.3. Management

Harvesting of all marine living resources (other than whales and seals) in Antarctic waters is regulated by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) which was negotiated by the Antarctic Treaty nations in the late 1970s [29], was ratified in 1980, and came into force in 1982 when the Commission for the Conservation of Antarctic Marine Living Resources (also referred to as CCAMLR) first met. There are 23 full members of CCAMLR, and the Convention has been acceded to by 29 nations² and the European Union.

The Convention applies to an area of approximately 32.9 million km². The subdivision of this region into statistical areas was based on the Food and Agriculture Organisation of the United Nations (FAO) statistical reporting system for fisheries (*figure 1*). The Convention adopted an 'ecosystem approach' to management in recognition of the profound effects that harvesting krill might have on the other elements of the ecosystem [78].

There was an early recognition within CCAMLR that regular stock surveys for Antarctic krill were

impractical and early attempts to examine management options for the krill fishery focused on the potential of using catch per unit effort (CPUE) data from the fishery as a measure of krill abundance [14, 71, 84]. The Scientific Committee of CCAMLR subsequently concluded that because of the highly aggregated nature of krill, CPUE alone was unlikely to be useful in managing the krill fishery. Efforts have continued to develop a 'composite index' of krill abundance, incorporating CPUE and searching time, which might be used in management models [72].

In the absence of information about biologically constituted stocks [38], CCAMLR concentrated on developing management measures for the existing statistical areas. Initially, the management measures utilised information from the extensive BIOMASS (Biological Investigation on Marine Antarctic Systems and Stocks) acoustic surveys for krill carried out in the early 1980s [36] but there has been a trend recently towards carrying out new surveys, using more advanced acoustic technology and specifically designed for the needs of CCAMLR [95]. Acoustic surveys for krill are carried out to a standardised design using standard frequencies (usually 120 kHz, but often alongside 38 and 200 kHz) [118, 119].

In the early 1990s, CCAMLR began the process of instituting precautionary management measures for the krill fishery [15, 26, 90, 91]. Precautionary limits are currently calculated using an initial estimate of the total biomass of the krill stock in an area, an estimate of the rate of natural mortality (which includes natural predation), a model of how individual krill grow in weight during their lives, and an estimate of the inter-annual variability in recruitment [16, 21, 22].

Precautionary catch limits have now been adopted in three areas (*table II*) which cover just over 51 % of the CCAMLR area including most of the area that has been commercially fished. A conservation measure subdividing the catch of krill in subarea 48 was adopted in 1992 but lapsed in 1994 when CCAMLR was unable to agree on an acceptable mechanism for subdividing the catch.

Questions have been raised on the use of krill biomass data from the early 1980s following recent advances in

Table II. Precautionary catch limits set by CCAMLR (Convention for the Conservation of Antarctic marine Living Resources) on the Antarctic krill fishery for the South Atlantic and South Indian oceans.

Statistical area (area in million km ²)	Biomass estimate (millions of tonnes)	Precautionary limit, tonnes per year (date adopted)
Area 48 (11.4)	34.5	1 500 000 (1991)
Division 58.4.2 (1.04)	3.9	450 000* (1995)
Division 58.4.1 (4.68)	6.67	775 000* (1996)

* Based on a revised acoustic target strength value for krill.

² Current Members of CCAMLR, as of January 1999, are: Argentina, Australia, Belgium, Brazil, Chile, European Union, France, Germany, India, Italy, Japan, Republic of Korea, New Zealand, Norway, Poland, Russian Federation, South Africa, Spain, Sweden, Ukraine, United Kingdom, the United States and Uruguay. States which are party to the Convention but which are not members of the Commission are: Bulgaria, Canada, Finland, Greece, Netherlands and Peru.

acoustic techniques [33] and as a result of evidence suggesting that there may have been changes in the krill populations in the South Atlantic over the last decade and a half [67]. There are also substantial mismatches between the abundance of krill estimated from acoustic surveys and that estimated from predator demand [34]. Accordingly, there are plans to conduct a new international multi-ship acoustic survey of the South Atlantic in the Austral summer of 1999/2000 [19].

2.4. Ecosystem interactions

Vertebrates and squid are estimated to consume between 150–300 million tonnes of krill annually [83]. Potential competition between the krill fishery and vertebrate predators which are restricted to land-based breeding sites during the summer has been a major concern to CCAMLR [25]. In areas where there is some overlap between fishing areas and zones of highest predation, the fishery currently takes much less krill than predators [2, 56]. In the South Shetland Islands, there is conflicting information on the potential for competition between the krill feeding predators and the fishery [23, 56]. Additionally, modelling studies have shown that land based krill-predator performance could be critically affected by the level of catch and the length of the fishing season [73]. Further consequences of increased levels of fishing in currently exploited areas are dependent on the poorly understood functional interaction between the predators, the krill stock and the fishery [25]. It has been assumed that highly mobile predators, such as whales, would be less impacted by a localised krill fishery; however, this assumption has not been investigated.

In 1985, CCAMLR initiated a programme to monitor the performance of critical ecosystem components, the CCAMLR Ecosystem Monitoring Programme (CEMP) [3], using a number of key indicator species including: Adélie penguins, chinstrap penguins, macaroni penguins, gentoo penguins, black-browed albatross and Antarctic fur seal. The CEMP monitors indices of predator status and breeding success at a number of sites around the Antarctic [3] and attempts to relate changes in these indices to krill availability, and to distinguish between changes that result from commercial harvesting and those that are a result of natural fluctuations in the biological and physical environment [24]. There are CEMP sites in the Ross Sea, in the Antarctic Peninsula region, on South Georgia and in the Indian Ocean sector [17] and data from these sites are submitted to CCAMLR each year. Attempts are now being made to incorporate CEMP data into management models [34].

2.5. By-catch

It is uncertain whether fish by-catch is a major problem for the krill fishery [37, 103, 107]. Fisheries operators reportedly avoid areas where there is likely to be a contaminating catch of fish, and large krill aggregations tend to be monospecific. There are also some sugges-

tions that by-catch is more significant in the Indian ocean sector than in the South Atlantic [136]. Potential problems with catching juvenile and larval fish could be avoided if the krill fishery moved off the continental shelf into more oceanic areas [37, 103], but this could affect the viability of the krill fishery. The CCAMLR scheme of scientific observation has quantification of fish by-catch as one of its research priorities [18].

3. NORTH PACIFIC KRILL (*EUPHAUSIA PACIFICA*)

Euphausia pacifica ('Isada') has been fished commercially in the waters off Japan, and off British Columbia.

3.1. Japan

E. pacifica is fished in the Pacific region of the Japanese coastline between 36° and 40° N (figure 3) [59]. *E. pacifica* is considered as a key species in Sanriku waters, the sea area off north-eastern Japan, and many endemic and migrant predators including pelagic and demersal fishes, marine mammals, seabirds and benthic organisms depend on this species for food.

3.1.1. Distribution

E. pacifica is distributed in the whole area of the Japan Sea up to the southern part of the Gulf of Tartary [60, 106], and in the south-western area of the Okhotsk Sea [100]. Off Japan, *E. pacifica* is found in surface swarms [31], in benthopelagic swarms and in midwater aggregations. Off Ibaraki prefecture, in the southern part of its distributional range, surface swarms appear to be formed in the years when cold water (5–7 °C) prevails from the surface to the bottom, whereas benthopelagic swarms occur when the water column is stratified with warmer water (> 10 °C) at the surface above thick, cold (6–9 °C) deeper layers [86]. When the water column is stratified with a shallow cold surface layer, surface swarms and benthopelagic swarms are absent. Off Onagawa, in the central part of its range, the daytime benthopelagic krill biomass is greatest in June (2 g·m⁻² at 300 m depth) and lowest in February and April (0.02 g·m⁻² at 300 m depth) [129]. In April, benthopelagic krill are relatively abundant at 150 m; offshore, they occur at depths of 200–300 m in all seasons.

3.1.2. Fishery

The average annual catch of *E. pacifica* over the last 10 years has been 60 427 tonnes with an average annual value of 1.5–3.6 billion yen making it one of the most important Japanese coastal fisheries. The total annual catch of *E. pacifica* has increased steadily over the last 20 years (figure 3) exceeding 40 000 tonnes in 1978, 80 000 tonnes in 1987 and 100 000 tonnes in 1992. This increase was facilitated by the introduction of plastic storage containers in 1975 and fish pumps in

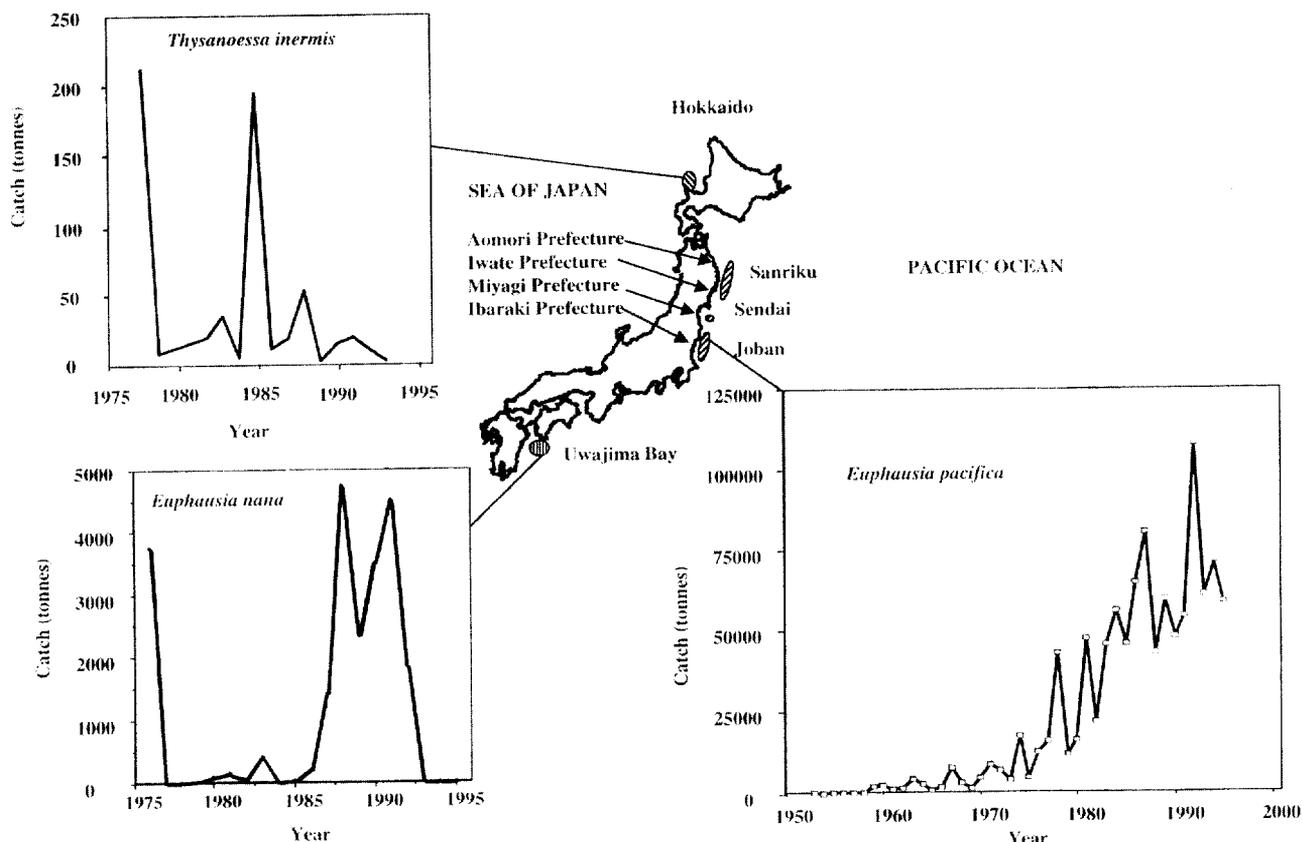


Figure 3. Krill fishery locations off the Japanese coast with regions mentioned in the text and annual catches of *Euphausia pacifica*, *Thysanoessa inermis* and *Euphausia nana*.

the 1980s [64]. In 1993, the total catch decreased to 60 881 tonnes, when catch regulations were imposed in Miyagi and Iwate prefectures in order to avoid price declines.

The largest catch in the 1970s was landed in Miyagi prefecture. In the early to mid-1980s, Ibaraki prefecture expanded its catch to 60% of the total; since 1988, Iwate and Miyagi prefectures have been the main fishing prefectures [64, 97, 99]. Fishery statistics for *E. pacifica* from Onagawa Fish Market have been available since 1953, but fishermen report that the fishery began earlier. The fishery expanded to the northern as well as the southern coasts of Miyagi prefecture, then into Ibaraki prefecture in 1972, followed by Fukushima prefecture in 1974 and Iwate prefecture in 1975 driven by increasing requirements for food for sea bream culture and for bait for sport fishing.

A small-scale fishery for *E. pacifica* has also been conducted along the Japan Sea coast over the last 20 years [65]; however, there is currently little catch from this area.

Off Sanriku, sand lance, *Ammodytes personatus*, have been caught using a bow-mounted trawl for over 100 years [96] and this method was applied to *E. pacifica* in the mid 1940s. The fishery currently involves boats less than 20 tonnes, mostly one- or two-boat

seines, but in Miyagi prefecture, both one-boat seines and bow-mounted trawls are also still used [65]. Bow-mounted trawls can only catch swarms within 8 m of the surface whereas one- and two-boat seines can catch subsurface swarms as deep as 150 m using echosounders to detect the swarms. Several hundred fishing boats are involved from each prefecture with a total of around 1 500 vessels participating in the *E. pacifica* fishery.

The fishing period generally extends from February–July, but varies from area to area and from year to year [93]. The fishing grounds are on the continental shelf (< 200 m) within 10–20 nm from shore. The fishing depth is less than 50 m in Sanriku waters, but deeper (0–150 m) in the Joban coastal area.

3.1.3. Management

The *Euphausia pacifica* fishery is categorised as a Licensed Fishery, therefore, vessels require a license from a Prefectural Governor. Fishery regulations are set separately for each prefecture. The license issued by the Prefectural Governor defines the fishing period, the operation time, fishing area, boat size and other factors. Other regulations include total catch limit per season, and maximum number of plastic containers per boat per day. Fishermen regulate catches in order to

keep the price high and to avoid over-fishing, collaborating with their counterparts in adjacent prefectures [93]. To date, there have been no biomass surveys, nor any attempt to use biological information to manage the fishery.

3.1.4. Ecosystem interactions

E. pacifica is preyed upon by almost all the commercially important fish species in Japanese waters [30, 137]. These species include Pacific cod, *Gadus macrocephalus*, walleye pollack, *Theragra chalcogramma*, Japanese chub mackerel, *Scomber japonicus* and sand lance, *Ammodytes personatus* [93]. *E. pacifica* may be most important as food for demersal fish in the upper slope region, where the abundance of demersal fish is highest but the species diversity is low, compared with continental shelf and deeper waters [41].

Demersal fish species are key predators of *E. pacifica* in the area from Aomori to Ibaraki prefectures consuming approximately 1 000 000 tonnes-year⁻¹ [57]. Off Miyagi and Fukushima prefectures, annual consumption of *E. pacifica* by demersal fish was estimated to be between 15.4 and 63.8 % of the annual tonnage of krill landed off the coast of Japan [138]. The high proportion of krill in the diet of demersal fish and the change in operational mode of the krill fishery, from surface to demersal fishing, was seen to potentially have a negative impact on demersal fish stocks.

Pelagic fishes such as sardines, Japanese chub mackerel, *Scomber japonicus*, and Japanese flying squid, *Todarodes pacificus*, also migrate in large numbers into this area in May–January. Their total biomass is estimated to be more than 1 000 000 tonnes [57]. These pelagic species probably also consume a considerable biomass of *E. pacifica*.

During the fishing season sand lance, black-tailed gull, *Larus crassirostris*, and rhinoceros auklet, *Cerorhinca monocerata*, feed intensively on *E. pacifica* [58]. Other seabirds which feed on euphausiids in Sanriku waters include: sooty shearwater, *Puffinus griseus*, and the slender-billed shearwater, *P. tenuirostris*, [98]. Although seabird observations during winter are rare, thick-billed murre, *Uria lomvia*, common murre, *U. aalge*, rhinoceros auklet, crested auklet, *Aethia cristatella*, and ancient murrelet, *Synthliboramphus antiquum*, are common in Sanriku waters and are thought to feed mainly on euphausiids [98]. There have been no systematic studies of the interaction between the fishery and seabirds and other predators.

3.1.5. Other species of krill harvested in Japanese waters

3.1.5.1. *Thysanoessa inermis*

Thysanoessa inermis has been commercially exploited since the early 1970s in the inshore waters of Shakotan Peninsula and Yagishiri Island, the western coast of Hokkaido [49, 61] (figure 3). Surface swarms

of this species are fished in the daytime usually in early March to early April; the swarms are composed of fully mature individuals engaged in reproductive activities [49]. A spoon net, with a diameter of 2 m and a 3–4-m handle, is used to catch *T. inermis* swarms. The price varies from 75 to more than 3 000 yen per kg. The yearly catch varies from several tonnes to 200 tonnes (figure 3). The *T. inermis* fishery is categorised as a ‘recognised fishery’ by the Fisheries Regulation Committee of Ishikari-Shiribeshi waters. There are no fishery regulations such as catch limits, but the fishing period is limited to February–June. There have been no substantial catch reported recently and the ecosystem implications of this fishery have not been studied.

3.1.5.2. *Euphausia nana*

‘Ami-ebi’ or *E. nana* has been commercially exploited for 20 years in Uwajima Bay, Ehime prefecture, Shikoku [54] (figure 3). The distribution of this neritic species is from the southern Japanese coasts to the East China Sea and Taiwanese waters. This species seems to migrate seasonally into Uwajima Bay and the fishing season is restricted to the March–July period. The adults perform diel vertical migration with daytime depth of 300–400 m in Sagami Bay [54].

E. nana swarms are harvested either by groups of vessels operated at night with a netting boat, a transport-boat, and up to three light-boats using fish gathering lamps, or by groups operating in the daytime with two netting boats, a boat with a fish finder (with three frequencies of 50, 200 and 400 kHz) and a transport-boat. Catches have at times been relatively high but because the fishery is dependent on a migratory species the landings have fluctuated (figure 3). *E. nana* are used as aquaculture feed for red sea bream. There are no catch regulation on the *E. nana* fishery and the ecosystem implications of this fishery have not been studied.

3.2. Canada

A fishery on *E. pacifica* has been operating in the waters off British Columbia, Canada since 1970; however, little published information on this fishery has been available [42, 52]. More recently, a more general account of this fishery was published [48] and, in 1995, a workshop was held on krill harvesting [105].

E. pacifica is one of the dominant species of krill off British Columbia and accounts for over 70 % of the euphausiid biomass in the Strait of Georgia where the fishery occurs and is the only species targeted [42] (figure 4). Commercial concentrations of euphausiids have been identified on the west coast of Vancouver Island and near the southern end of the Queen Charlotte Islands [42, 52]. Intermittent surveys of the overall area have been accompanied by regular monitoring of krill stocks in Jervis Inlet since 1990 [43, 108, 124].

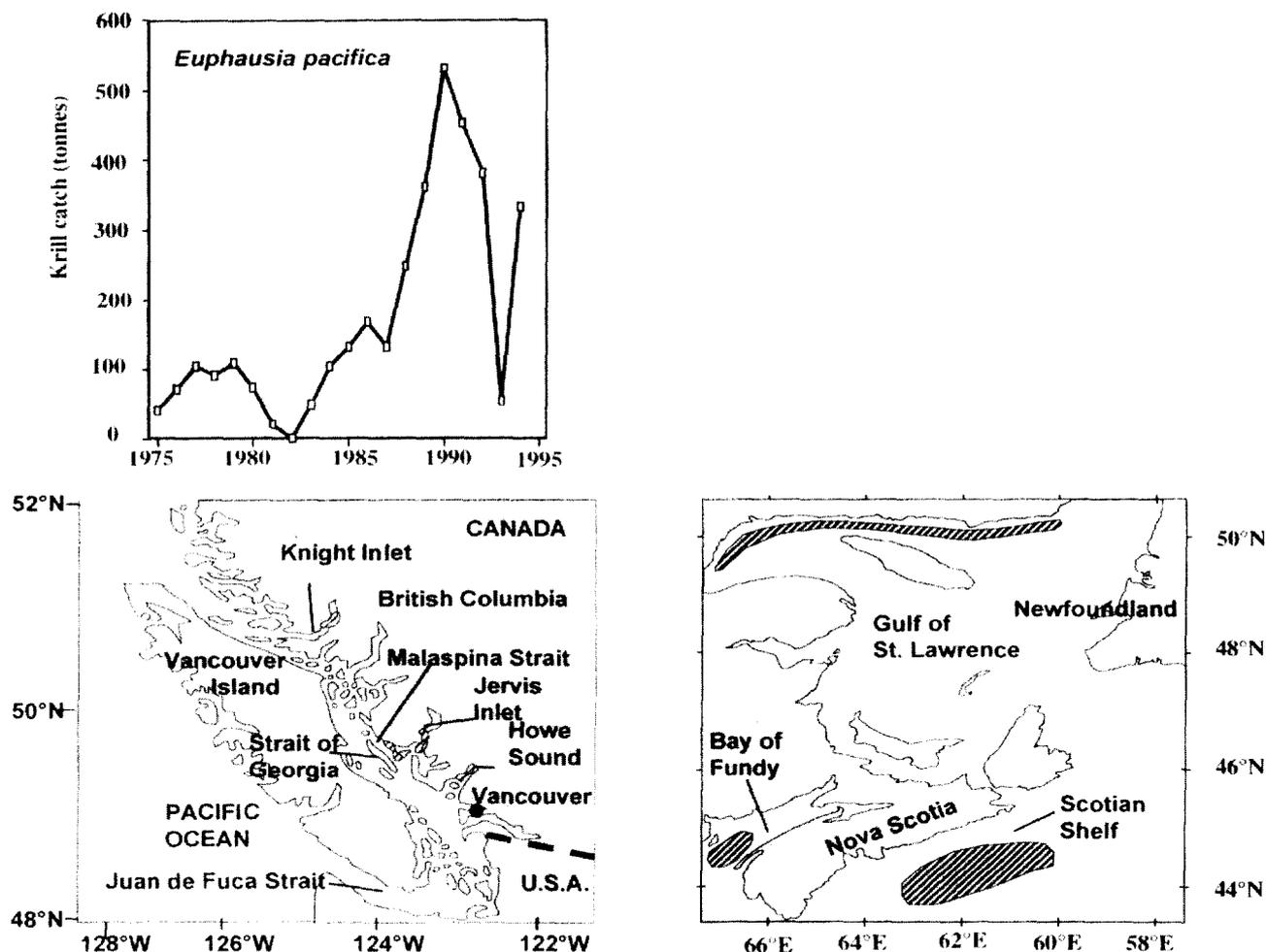


Figure 4. Areas off the west and east coasts of Canada where krill fisheries occur, or have been proposed, and annual catches of *Euphausia pacifica* from the British Columbia fishery.

3.2.1. Fishery

The commercial fishery for *E. pacifica* began in about 1970 on an experimental basis and was confined to the Strait of Georgia and the east coast of Vancouver Island (figure 4). Until 1985, annual landings were less than 200 tonnes (figure 4), with fishing concentrated initially in Saanich Inlet, then Howe Sound and more recently in Jervis Inlet [7].

During 1992, some poor quality krill reached the market and in 1993, demand for British Columbia krill was depressed, and landings were low. Landings reported for 1994 were in excess of 300 tonnes, with a value of Can\$ 259 000 [85] as markets recovered.

The fishery is carried out by small freezer vessels with a limited freezing capacity of 5–6 tonnes of krill a day, and larger vessels which land large quantities of euphausiids for onshore processing and freezing [48]. The fishing season can be as short as 20 d and individual vessels may land as little as 32 tonnes in a season.

Fishing is carried out close to the surface (< 20 m) on moonless nights when the krill rise to the surface. Krill are found in layers less than 10 m in vertical extent which are located by echosounders. Larger vessels use a seine nets and are usually out-of-season salmon fishing boats, smaller vessels use midwater trawls with mouth areas of around 80 m². The presence of these vessels in the fishery is usually dependent on the success of the salmon fishery. If there has been a bad salmon catch, then krill are fished to increase revenues.

Catch per unit effort (kg·h⁻¹) has remained relatively constant since 1986 at approximately 300–400 kg·h⁻¹. As with other species of krill, CPUE is not thought of as a reliable index of krill abundance and some operators have resorted to sophisticated scientific echosounder systems to make independent stock assessments [48].

3.2.2. Management

Quotas were established in 1976 for the British Columbia *E. pacifica* fishery in response to concerns

about harvesting a species upon which salmon and other commercially important finfish depend [6]. The annual catch was set at 500 tonnes with an open season from November–March to minimise the incidental catch of larval and juvenile fish. This quota was derived from an estimate of the annual consumption of euphausiids by all predator species in the Strait of Georgia. The quota was set at 3 % of this estimate. Subsequently, there have been real and seasonal modifications to the quota system.

The Regional Executive Committee of the Canadian Department of Fisheries and Oceans has stated that as a matter of policy the region is not prepared to support developmental fisheries on forage species such as krill. The 500 tonne quota for the Strait of Georgia and mainland inlets will, therefore, remain fixed for the foreseeable future [85].

3.2.3. Ecosystem interactions

Concerns on ecosystem interactions in the British Columbia krill fishery have concentrated on the potential for this fishery to impact on other commercial species. Recent studies have shown that offshore euphausiids are a major food source for offshore stocks of Pacific hake, Pacific herring, dogfish, sablefish, [130] as well as Pacific halibut and chinook and coho salmon. *E. pacifica* is also known to be an important dietary item for many bird species in British Columbia including Cassin's auklet (*Ptychoramphus aleuticus*) [133] and ancient murrelet (*Synthliboramphus antiquum*) [120]. Detailed studies on the interactions between krill dependent species and the fishery have not been reported.

4. KRILL IN THE NORTH ATLANTIC

Meganyctiphanes norvegica, *Thysanoessa raschii* and *Thysanoessa inermis* are often found in similar areas in the North Atlantic and fisheries have been proposed that would target all three species (figure 4)

4.1. Distribution

4.1.1. *Meganyctiphanes norvegica*

M. norvegica lives in water depths down to 300 m, the adults inhabiting water deeper than 200 m whereas the younger stages may be found in shallower waters. They undergo diel vertical migrations, and they also form benthopelagic aggregations [46] and surface swarms [77]. Detailed investigations of surface swarms have been carried out in the Bay of Fundy [12, 88] and in the Gulf of St. Lawrence [11]. Sub-surface layers of *M. norvegica* off the east coast of Canada have been shown to have densities up to 1 000 krill·m⁻³ from net sampling and acoustic studies [114] and can extend for tens of kilometres [117]. In the Gulf of Maine, near-bottom concentrations of *M. norvegica* have been estimated to contain densities of greater than

1 000 krill·m⁻³ using acoustic techniques [46]. Surface swarms have been estimated to contain higher densities; up to 770 000 krill·m⁻³ (154 kg·m⁻³), and individual surface swarms can be 30 m long, can cover an area of 111 m², and contain up to 2.2 tonnes of krill [88].

4.1.2. *Thysanoessa raschii*

T. raschii is usually found in water depths greater than 100 m. They perform diel vertical migrations in the summer months and are thought to form benthopelagic aggregations in winter [75, 141]. They have been known to form surface swarms [140].

4.1.3. *Thysanoessa inermis*

T. inermis is predominantly an arctic or subarctic species of krill found in shelf waters [62]. Like *T. raschii*, they perform diurnal vertical migrations in the summer months and are thought to form near bottom aggregations in winter [116]. Surface swarming has also been reported in this species in the North Atlantic [126].

4.2. Gulf of St. Lawrence

A research programme was started in 1972 to locate harvestable concentrations of krill in the Gulf of St. Lawrence [112]. Three species are commonly found in the Gulf: *Meganyctiphanes norvegica*, *Thysanoessa raschii* and *Thysanoessa inermis* [123]. The estimated biomass of krill in two areas of the Gulf where krill are most concentrated was 75 000 tonnes [115] and an estimated catch rate for trawlers fishing a 100-m² mouth opening trawl was estimated to be 379 kg·h⁻¹ based on a biomass estimate of 1 g·m⁻³. The estimated potential for harvesting of all three krill species in the Gulf, based on an exploitation rate of 50 % of the biomass, was 37 500 tonnes; estimated in 1975 to be worth Can\$ 3.75 million [115]. More recent studies have used acoustics to determine the abundance of krill in the Gulf of St. Lawrence [122-124] and acoustic estimates of krill biomass for krill in the Gulf range from 400 000 tonnes to 1 million tonnes.

In 1991, DFO Canada (the Canadian Department of Fisheries and Oceans) issued a scientific permit to fish zooplankton in order to study the quality of zooplankton in the Gulf of St. Lawrence [111]. An exploratory fishery for krill and the copepod *Calanus finmarchicus* subsequently took place in the Laurentian Channel. The permit was renewed in 1994 with a 'preventative' TAC of 100 tonnes for krill and 50 tonnes for *Calanus*. The fishery took place in November when 6.3 tonnes of krill and 0.4 tonnes of *Calanus* were harvested [111].

One 119-foot fishing boat has been involved in this fishery. The Gulf fishery produces: frozen krill and freeze-dried krill for ornamental fishes and for public aquaria and freeze-dried krill as an ingredient in salmon feed and as a flavouring for food for human consumption. Krill fishing in the Gulf of St. Lawrence appears to have stopped recently because quotas could not be reached and fishing is not economically viable [51].

4.2.1. Management

The Gulf of St. Lawrence krill fishery is managed by DFO, Laurentian region, and permits to enter the fishery are issued on the basis of policy guidelines developed by DFO Eastern Canada regions [44]. The fishery in this region is still deemed experimental or pre-commercial [111] and is managed using the DFO policy for under-utilised species which requires: the preparation of a management plan, interaction between management, industry and scientists, acquisition of basic biological data and formal financial commitment to support necessary science.

It has been assumed that the catch level ~0.5 % of the minimum estimate of the available biomass would have a negligible effect on the krill populations and on the populations of natural predators dependent on krill and TACs for this region have been set on this basis. Factors that have been taken into account when designing management strategies for krill in this region include: the problems of taking the whole of the catch from a restricted area, the effect on the populations of whales that feed in the area, and the incidental by-catch, particularly of juvenile fish [111].

4.2.2. Ecosystem interactions

Krill in the Gulf of St. Lawrence are prey for a variety of fish: capelin, herring, sand lance, mackerel, cod, redfish and flatfishes. They are also the prey of whales—particularly blue, fin, minke and humpback and a variety of seabirds [122]. There is particular concern that any development of the krill fishery in this area should not interfere with the local whale-watching industry (Y. Simard, pers. comm.)

4.3. Scotian shelf

A permit to fish 1 000 tonnes of krill (primarily *M. norvegica*) on the Scotian Shelf and Gulf of Maine, off Nova Scotia, Canada, was applied for in 1995. The krill would be used to produce a product to coat fish pellets to be fed to young salmon in fish farming [50]. To date no license has been issued.

On the Scotian Shelf, there are concerns about the effect of the proposed krill fishery on the fish species of the region which have a major portion of krill in their diet [51]. There is also considerable concern about the possibility of a significant by-catch of larval and juvenile forms of other commercial species that could be taken with the krill catch, and about possible adverse interactions with populations of the endangered right whale off Nova Scotia [50].

5. KRILL PRODUCTS

The development of products from the Antarctic krill fishery has been reviewed a number of times [13, 28, 32, 45, 93, 127, 128]. Despite the large tonnages that could be caught in the Antarctic, there have been a

number of factors that have slowed down the rate at which the krill fishery has developed. These include: the rapid spoiling of the catch due to enzymatic action, the high fluoride concentration of the exoskeleton and the difficulty of producing acceptable items that can justify the expense of fishing [13] – all of these factors also apply to other species of krill. Some of these problems have been overcome recently by the production of low-fluoride products [131], better utilisation of krill waste products such as the shell [4] and liquid waste [27], the production of valuable pharmaceuticals from krill [81] and an enhanced focus on krill as an aquaculture feed [125] where high fluoride levels are not a problem.

There has been considerable effort expended in developing Antarctic krill products for human consumption; however, most of the krill catch has been used for domestic animal feed, particularly in recent years for aquaculture feed. The Japanese Antarctic krill fishery, which takes most of the current catch, produces four types of product: fresh frozen (46 % of the catch), boiled-frozen (10 % of the catch), peeled krill meat (10 % of the catch) and meal (34 % of the catch). Yields in the manufacture of these products are: 80–90 % for fresh-frozen and boiled-frozen, 8–17 % for peeled krill and 10–15 % for meal. These products are used for aquaculture and aquarium feed (43 % of the catch), for sport fishing bait (~45 % of the catch), and Antarctic krill are also used for human consumption (~12 % of the catch) (1999 figures, T. Ichii, Japan National Research Institute of Far Seas Fisheries, pers. comm.).

E. pacifica caught off Japan is used for sport fishing (~50 % of the catch), feed for fish culture, particularly as a reddening agent, and a small amount is used for human consumption [63]. Most of the *E. pacifica* from the Canadian fishery is frozen for export to the US, where it is used in the production of fish feed or pet food [48].

The development of krill products for human consumption has been a focus of the fishery in the past but it seems likely that products for aquaculture will dominate in the near future. Demand for quality aquaculture feed is growing and supplies are uncertain [110] and krill of all species appear to have a number of features that make them an attractive aquaculture feed [5]. In particular, krill hydrolysates appear to have the ability to make other feeds more palatable [40] so they can be mixed with cheaper grains and fishmeal to enhance fish production [101]. The existing or proposed coastal krill fisheries in the northern hemisphere have been developed to provide local sources of feed for aquaculture and there have been similar proposals in other areas, e.g. *Nyctiphanes australis* in South Eastern Australian waters [134, 135]. It seems likely that stocks of other species of krill will also be investigated once krill become a more established aquaculture feed.

There has been a steady development of krill products for non-nutritional uses such as pharmaceuticals and industrial uses [93]. These include the production of chitin and chitosan from krill shells and the utilisation of krill enzymes for pharmaceutical [81, 82] and other purposes [70]. These demands may not develop to the point where they become a major economic justification for krill fishing but they may be instrumental in putting the fishery on a sound economic footing.

6. SCIENTIFIC, TECHNOLOGICAL AND MANAGEMENT ISSUES

Over the last 20 years, krill fisheries have developed from experimental to full-scale commercial fisheries and are of considerable regional importance. There is a resurgence in interest in krill, particularly in its use as an aquaculture feed [132], and this has resulted in proposals to establish or expand krill fisheries in temperate coastal waters closer to sites of aquaculture developments. These developments have highlighted issues which face all emerging and existing krill fisheries.

It is unlikely that future krill fisheries will be allowed to develop in the absence of scientifically-based management plans. These will require a basic level of scientific knowledge on the species being considered, including biomass, stock identity and life-history parameters. The methodology for acoustic estimation of krill abundance is now refined and applicable to most species that might be fished commercially. Unfortunately, very little is known on the local or global biomass of krill in areas other than the Antarctic and even less is known on the inter-annual variability of these populations. Within species, there is little information on stock identity and this information may be critical in some areas, such as the North Pacific, where fisheries are being prosecuted and managed independently in both the west and the east. The life history of most species is poorly known; the exception again is Antarctic krill. Experience with this species has shown that historical information on life history parameters, such as age-classes and longevity, has proved misleading following experimental investigation [89]. Few experimental investigations have been carried out into other species of krill.

Krill are, generally, smaller organisms than have been fished traditionally and this has a number of real and perceived problems. The technological problems with catching and processing such small animals have largely been overcome, but the issue of by-catch in fine mesh nets is yet to be resolved. Their small size has, however, been correlated with their trophic level and severe reservations have been raised concerning the harvesting of organisms that are perceived to be so close to the base of the food chain. These reservations come despite the long history of fishing larger pelagic species such as anchovies which occupy an analogous trophic level in other ecosystems and benthic crustaceans [87] which share many characteristics with krill.

The perception that krill are plankton rather than micro-nekton, and are herbivores – when many species are carnivorous or omnivorous [10] – has further highlighted the perceived novelty of establishing krill fisheries. The lack of available information on the longer-established krill fisheries off Japan and British Columbia [93] has meant that newer proposals have not been viewed in the light of the experience gained in other areas. The best documented fishery is that for Antarctic krill and this has a number of features that sets it aside from other existing or potential fisheries. It occurs largely in waters which do not fall under recognised Economic Zones of any nation. It has an international management body (CCAMLR) which was designed with the krill fishery in mind which has adopted an ecosystem approach specifically to cope with the issues of krill fishing [92]. There are no established competing fisheries and the krill fishery has consistently been the largest in the Antarctic region. It also occurs in distant waters and has proceeded in relative obscurity for much of its existence. Nonetheless, the Antarctic krill fishery is affected by many of the same issues that temperate krill fisheries face. Krill is central to the Southern Ocean ecosystem and is prey for a large number of species of high conservation value. The Antarctic region itself is of high conservation value and is becoming more the focus of environmental concern. The management of the krill fishery has forced the development of new management approaches [34].

A major expansion of coastal krill fisheries away from the Antarctic seems unlikely because of concerns of conservationists, who fear for the livelihood of other species which depend on krill, of fishers, to whom krill is novel risky and prey for their preferred species, and of scientists and managers who would have to manage any krill fishery in a multi-species context under conditions of great uncertainty [51]. Restricting access to coastal temperate krill fisheries in the face of demand for krill from aquaculture may increase pressure on the Antarctic region where krill stocks are greatest. Currently, the precautionary limits on the Antarctic krill fishery set by CCAMLR are 2.7 million tonnes compared to the catch which is only 80 802 tonnes per year so there is considerable scope for expansion. The key factor in the further development of the Antarctic fishery is, however, likely to be ‘where?’ rather than ‘how much?’. The fishery is seasonally constrained by ice. In summer, the fishery can spread out around the Antarctic continent and many of the subantarctic islands and thus localised fishing pressure can be minimised. In winter, however, the fishery is restricted to a number of small areas in the South Atlantic, most notably around South Georgia, where waters are generally ice-free. If the fishery requires a year-round operation to maintain its viability then it may be that the sustainable limit of winter catches in the South Georgia area will be the factor that sets the overall constraints on the size of the fishery.

7. CONCLUSION

The Antarctic krill fishery is currently held in check by economic and marketing factors rather than by stock size or management limitations; other krill fisheries are being managed at their current levels. As conventional wild fisheries decline and as aquaculture continues to grow in scope, there will be a greater emphasis on harvesting hitherto under-utilised species such as krill. Increased successful use of Antarctic krill as an aquaculture feed may lead to an increase in demand and thus an incentive to develop krill fisheries in temperate and sub-tropical waters. Krill fisheries in temperate and subtropical waters may be limited because of their relatively small stock sizes and because of perceived deleterious interactions with other fisheries and with species of high conservation values. Any increase in demand, thus will in all proba-

bility lead to a greater pressure on the largest known krill stock – in the Antarctic.

Harvesting krill brings with it the potential for ecological problems because there is little experience in managing fisheries on such species. A precautionary approach, such as that adopted by CCAMLR, is an appropriate way to proceed when managing fisheries which are surrounded by more than normal levels of uncertainty. Krill fisheries have a great potential to increase the world's harvest from the oceans, particularly in an era when fisheries for so many conventional species are in decline, but they also have considerable potential for causing unpredictable harm to marine ecosystems. Development of krill fisheries must be accompanied or preceded by effective management so that the benefits are maximised and the ecological costs are minimised.

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