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An appraisal of the commercial fishery potential of krill *Nyctiphanes australis* Sars, in Tasmanian waters

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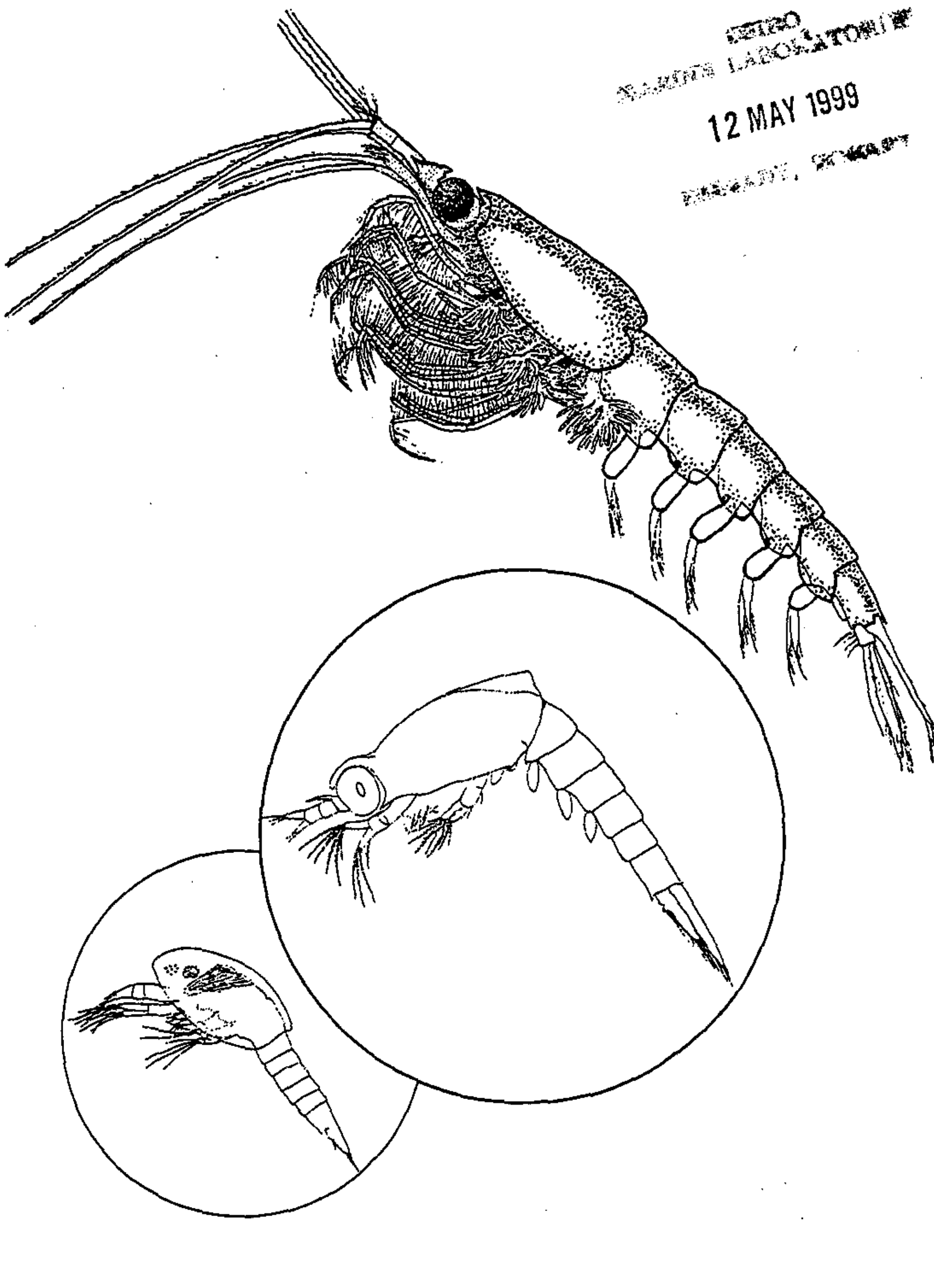

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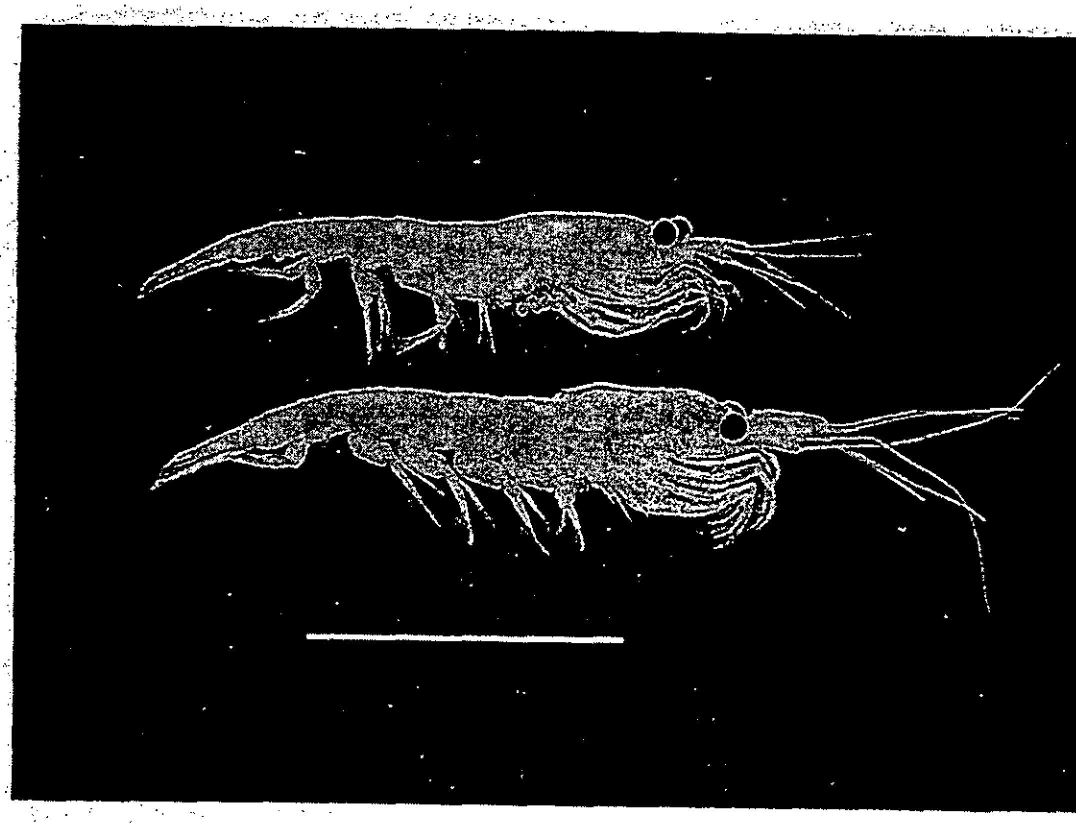

Nycytiphanes australis: mature female (top) carrying eggs and mature male (scale = 10 mm)

Abstract

Although the euphausiid krill *Nyctiphanes australis* is abundant in Tasmanian waters, it has never been commercially exploited. In this report we evaluate possible commercial uses for it, with particular emphasis on its potential as a component of aquaculture feeds. Some relevant behavioural, distributional and biochemical features of the species are described. To provide examples of how such a fishery might operate, we describe two temperate-zone nearshore krill fisheries in the north Pacific. We conclude that *N. australis* in Tasmanian waters has a number of attractive characteristics as an ingredient in feed for the culture of salmonids and other marine and freshwater species, and has several other possible commercial uses. But a satisfactory appraisal of its commercial potential requires a better understanding of temporal and spatial variations in its catchability, as well as an estimate of how much might be harvested without affecting wild populations of marine animals for whom this species is an important food.

1. INTRODUCTION

Commercial fishing for pelagic crustaceans is not, as sometimes assumed, limited to large, expeditionary factory vessels operating in Antarctic waters. Nearshore, small-vessel, day-trip fisheries for various euphausiid (krill) species or other planktonic crustaceans exist in various parts of the world (for brief reviews see Parsons 1972, Omori 1978). The krill *Nyctiphanes australis* is abundant in the waters of the continental shelf off southeast Australia (Blackburn 1980, Ritz and Hosie 1982). Its biomass is not known, but it is almost certainly substantial (see below). Could it, too, support a commercial fishery? Here we examine the available information.

A Tasmanian fishery and associated markets for *N. australis*, if they eventuated, would have much less in common with the Antarctic krill fishery than with temperate zone, near-shore krill fisheries. To provide some indications of how a Tasmanian krill fishery might be developed, we therefore describe features of two such fisheries. We also review relevant biological and biochemical research on *N. australis*.

Analysing the economic factors that influence the commercial potential of krill is beyond the scope of this report. But it is worth noting that in the early 1990s the global supply of fishmeal available for aquaculture feed was shrinking while the demand for it was rapidly increasing. Both trends are expected to continue, and fishmeal prices are expected, accordingly, to "increase dramatically" unless cheap substitutes are found (*e.g.* Rumney 1993). It is thus possible that the market price obtainable for krill, which (as discussed below) can be a high-quality component of aquaculture feeds, will increase significantly in future years.

It is useful to calculate roughly how much krill the Tasmanian aquaculture industry could use. If krill were used as a supplement for improving growth performance and various quality characteristics in salmon feeds in Tasmania as well as to provide 10% of the total protein intake, the projected sustained level of production of 3,000 tonnes of cultured salmon per year would require roughly 2,100 tonnes (landed weight) of krill. An additional 1,000 tonnes might be used to supplement feed for pen-cultured rainbow trout.

2. BIOLOGY OF *NYCTIPHANES AUSTRALIS* IN TASMANIAN WATERS

2.1 Distribution and abundance

N. australis is the principal species of euphausiid in southeastern Australian and New Zealand continental shelf waters, where it often forms dense surface and subsurface swarms. As with many krill species, this feature of its behaviour should help facilitate its harvesting in large quantities. In Tasmania one unusually large swarm was reported by O'Brien (1988) to cover an area of 0.42 km^2, although these swarms are generally less than 10 m in diameter. Swarms occur throughout the day and the year, but are most common during summer and at night (O'Brien 1988).

Although *N. australis* is typically present in Tasmanian coastal waters year round, Ritz and Hosie (1982) and Young *et al.* (1993) reported seasonal cycles in its abundance. It is found to a maximum depth of 400 m (Blackburn 1980), but is generally found between 200 m and the surface. There is some evidence that *N. australis* spends a portion of its time near, or even on, the bottom (Blackburn 1980).

According to Bartle (1976), this species migrates vertically from below 150 m to the uppermost 100 m at night. However, we found no significant difference in krill density between simultaneous surface and deep tows in shelf waters of eastern Tasmania (Young *et al.* 1993). Furthermore, surface swarms have been reported at all times of the day and at all seasons, which does not support the argument for vertical migration. Swarming has been documented in Bass Straight and in waters off east and southeast Tasmanian (*e.g.* Blackburn 1980, Montague *et al.* 1986, O'Brien 1988).

There is no published information on *N. australis* in waters off southwestern Tasmania. But large windrows of the species have been found washed up on the beaches there (R. J., pers. observ.) and fishers report commonly seeing swarms in nearby waters (J. Y., pers. observ.). Flocks, sometimes thousands-strong, of short-tailed shearwaters feed heavily on *N. australis* in Tasmanian waters.

The optimal temperature for the species is between 12 and 18°C, although adults can tolerate 11 to 22°C (Sheard, 1953). It has been observed in water of salinities ranging from 32 to 35.09 ⁰/oo (Hosie 1982, O'Brien *et al.* 1986).

2.2 Trophic links

N. australis is a major link to higher trophic levels in Tasmanian waters. During a 19 month study, *N. australis* constituted 99.9% by weight of the stomach contents of jack mackerel *Trachurus declivis* seined off the east coast of Tasmania (Webb 1976). More recent studies of jack mackerel feeding support this result (Young *et al.* 1993). Pelagic fish the size of jack mackerel require at least ten times their weight in food per year. Enough krill to support the feeding for a year of the average annual catch of jack mackerel in these waters would therefore run to several hundred thousand tonnes. Juvenile *N. australis* are also an important food for jack mackerel larvae (Young and Davis 1992).

In addition, *N. australis* is one of the most important single foods in Tasmania for a variety of other abundant fish and seabird species. It is the main food in Tasmania of adults and chicks of short-tailed shearwater *Puffinus tenuirostrus,* whose adult population numbers roughly nineteen million (Skira 1986). It is also the main food of the fairy prion *Pachyptila turtur* (O'Brien 1988). It is the principal food in these waters of Australian salmon *Arripes trutta* (Malcolm 1959) and skipjack tuna *Katsuwonis pelamis*, (Blackburn and Serventy 1981), as well as a large component of the food of tiger flathead *Platycephalus richardsoni*, barracouta *Leonura atun* (Blackburn 1957), slender tuna *Allothunnus fallai* (Wolfe and Webb 1975) and other common or abundant fishes and seabirds (O'Brien 1988).

N. australis is omnivorous, eating detritus, dinoflagellates, diatoms, copepods, bryozoans and inorganic particles (*e.g.* Dalley and McClatchie 1989, Ritz *et al.* 1990).

2.3 Life history

In Storm Bay, southeast Tasmania, *N. australis* spawns from August through March and possibly April (Ritz and Hosie 1982) while it occurs throughout the year off the east coast (Young *et al.* 1993). Sexual maturity is reached after 3–4 months and females are capable of producing multiple generations (Hosie 1982). The animals live for about 1 year, and can grow to about 20 mm (Fenton 1981, Ritz and Hosie 1982). Sheard (1953) and Palmer (1978) describe the anatomy and developmental stages of N. australis.

2.4 Comparisons with *Euphausia pacifica*, a commercial species in the northern hemisphere

Comparing it with similar species of krill that are commercially harvested can give an indication of the commercial viability of *N. australis*. The main species of a similar size harvested elsewhere is the northern hemisphere species *Euphausia pacifica*. Table 1 compares the main biological characteristics of *N. australis* with those of *E. pacifica*. A more thorough examination of the *E. pacifica* fishery is documented below. However, a number of similarities, at least in the biology of these species, are worth highlighting here. For example, these two species are of similar size, have similar life spans, and have extended spawning periods, high production to biomass ratios and comparable densities. Both are swarming species. Their biochemical composition (*e.g.* W3 fatty acids ~ 40% in both species) also appears to be very similar. Such similar characteristics would indicate that a fishery for *N. australis* could be modelled upon the established fisheries for *E. pacifica* in the northern hemisphere.

3. COMMERCIAL USES OF KRILL

3.1 Aquaculture feeds

Krill of all species are of high nutritional value as components of aquaculture feed (*e.g.* Storebakken 1988, Shimizu *et al.* 1990). Several characteristics make them attractive for this purpose. Because Tasmania supports an important aquaculture industry for Atlantic salmon and rainbow trout, we will emphasise salmonid aquaculture in the following discussion.

3.1.1 High fatty acid and carotenoid content

One of the most important biochemical characteristics of krill as fish feed is its typically high concentrations of the polyunsaturated fatty acids (PUFAs). These compounds are essential in the diet of various commercially raised fish and shellfish (Watanabe 1982, Storebakken 1988, Takeuchi *et al.* 1990), including salmonids (*e.g.* Lall 1991) and prawns (*e.g.* Millamena 1989). Fatty acids of the n-3 group, such as C20:5 or eicosapentaenoic acid (EPA), and C22:6 or docosapentaenoic acid (DHA), are especially important in this regard.

EPA and DHA are a major constituent of the fatty acids in *N. australis*, ranging from 11.3-36.5% and 10.8–24.4% respectively (Virtue *et al.* 1995). The fatty acid profile was markedly unsaturated, with the total w3 fatty acid mean being 47.5 ± 1.48% (n = 20), which is close to double that of *Euphausia superba*. However, the total lipid because of the public's growing preference for natural ingredients, industry would prefer natural sources of pigmentation if they could be substituted economically. The economic consideration is not trivial: feed costs, which average about 50% of the total cost of farming salmon, are increased by around 10–15% by synthetic carotenoid supplementation (Torrissen *et al.* 1989).

Although astaxanthin is the main pigment in zooplankton from which salmonids in the wild get their colour, the major synthetic pigment used in feeds has been canthaxanthin because of the lower cost of its manufacture. However, salmonids both absorb and retain astaxanthin considerably more efficiently than canthaxanthin (*e.g.* Choubert and Storebakken 1989).

Rainbow trout take up the astaxanthin in Artemia faster than they do the crystalline synthetic form (Long and Haard 1988). Torrissen *et al.* (1989) cites other research indicating that astaxanthin in crustaceans seems to be a more efficient pigment source than free astaxanthin. Virtue *et al.* (1994) found that *N. australis* contained astaxanthin at concentrations of 32–70 ug/g. This is close to the range of concentrations of 15 – 77 ug/g reported for *E. superba* (Storrebakken 1988). In short, astaxanthin has important benefits as a feed ingredient for salmonids and other cultured marine species, and it is present in *N. australis,* as in other krill, in high concentrations.

3.1.2 Improved Palatability and digestibility of Feed

The amount of food eaten by farmed fish depends in part upon its palatability. Feeding trials indicate that krill species are exceptionally palatable to fish. This makes them valuable in so-called "starter" diets to induce fish to begin feeding after yolk-sac absorption, which is sometimes difficult with farmed fish. Atlantic salmon fry, for example, can be difficult to induce to feed, with consequent high mortalities (*e.g.* Holm 1986, Lemm and Hendrix 1981).

Palatability is also important when temperatures are suboptimal and feeding rates drop (see Peterson and Martin-Robichaud, [1989] for a discussion of this in relation to Atlantic salmon) or when fish are sick and they must be enticed to ingest medicine. A number of researchers have reported that krill stimulate feeding in a variety of fish species (*e.g.* Allahpichay and Shimizu 1985, Shimizu *et al.* 1990, Ikeda *et al.* 1988).

Foster (1992), researching the Tasmanian salmonid culture industry, stated "extra costs for ingredients that may improve the feed intake by increasing the digestibility are worth the expense in some cases, because extra feed intake from increased palatability may mean the different between having or not having a saleable product. Materials that increase palatability . . . can make a marked difference in the growth rate. This is particularly true of salmon and trout fry, and of salmon greater than 1 kg in weight living at low water temperatures (<10°C)".

The guts of some very young fishes, including Atlantic salmon, are deficient in the production of digestive enzymes (*e.g.* Hansen and Torrisen 1985, Walford and Lam 1993). Whereas the animals that such fish eat in nature will provide an exogenous source of digestive enzymes as they autolyse in the gut, such enzymes are destroyed during the processing of heat-treating of artificial foods. These foods are thus poorly digested by very young fish (de Verga and Böhm 1992).

There is a need, therefore, to provide such fish with exogenous proteolytic enzymes in their feed until their own capacity to secrete digestive enzymes is adequate. This entails feeding them, or incorporating into their feed, animal material that is either alive or that has been frozen and to maintain its proteolytic activity.

Krill are well known for the exceptionally high levels of proteolytic enzymes they contain (*e.g.* Budzinski *et al.* 1985). This, then, is a second reason why frozen or freeze-dried krill can be a valuable component of food for very young fish. Live krill would probably be even better, because they would not lose essential ingredients through leaching as frozen or freeze-dried krill do when placed in feeding tanks. But the logistic problems of delivering live krill from fishing ground to fish farm seem to preclude this approach.

3.1.3 Improved Growth

Because feed for marine farms comprise 40–60% of the total cost of production, feed-to-flesh conversion rates should be high. The inclusion of *E. superba* in feed is reported to result in increased growth efficiencies for some fish species as well as increased growth rates (Allahpichay and Shimizu 1985).[2] Feeding trials with salmonids and other cultured fishes suggest that *E. superba* contains a growth factor, thought to be a steroid (Akiyama *et al.* 1984; Allahpichay and Shimizu 1985).

3.1.4 Improved Hatching Success

Feeding Red Sea bream *Pagrus major* on raw *E. superba* shortly before spawning resulted in higher hatching rates of eggs (Watanabe et al 1985)

3.1.5 Improved Flavour to Consumer of Salmon fed on Krill

The flavour of rainbow trout raised on feeds containing *E. pacifica* has been judged superior to those on control feeds by taste panels in the United States (Spinelli 1979). Similarly, a Japanese salmon farmer told me that consumers rate highly the flavour of coho salmon fed on *E. pacifica.*

3.2 OTHER COMMERCIAL USES OF KRILL

3.2.1 Aquarium fishfood

Krill (*E. superba* and *E. pacifica)* are used widely in fish feeds in commercial public aquaria and private hobby aquaria. The Shedd Public Aquarium in Chicago, for example, uses almost three tonnes of frozen krill per year in its feeds (Gordon 1988).

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2 Some early studies did not demonstrate this effect, but poor-quality krill meal is thought to have been used (Akiyama *et al.* 1984).

In North America the total market for feed of all kinds for the aquarium trade reportedly amounts to hundreds of millions of dollars per year, but we have been unable to find reliable figures on what fraction is made up of krill. A krill wholesaler in Vancouver told one of us (R. J.) that he was offered a standing order of 200 tonnes of *E. pacifica* per year (which he could not supply because of the limited catch in British Columbia; see below) by one American manufacturer of aquarium feeds.

The ornamental fish industry in Australia is worth an estimated 300 to 400 million dollars per year and dried crustacean-based[3] flaked, pelleted or powdered feeds are in widespread use. At present, in Australia imports almost all of these products from overseas. Here, then, is a possible opportunity for import replacement with *N. australis*.

3.2.2 Proteolytic Enzymes

Recent research has shown that extracts of the protein-digesting (proteolytic) enzymes of Antarctic krill were more effective as debriding (wound-cleansing) agents than commercially available products (Campbell *et al.* 1987, Anheller *et al.* 1989). In 1989 a Swedish pharmaceutical company contacted an Australian exporter, seeking 420 tonnes per month of high-quality krill for the production of a commercial wound-cleansing product (G. Boothby, pers. comm.).

Proteolytic enzymes have many other commercial applications. One example is their use in fish processing to remove the skins or scales of fish that are difficult to skin or scale by mechanical means. They can also be used to hydrolyse the supporting tissue surrounding trout and salmon roe being prepared as "caviar" (Infofish International 1992(6) p. 53; Fish Farming International (1992) 17(8): p. 71).

3.2.3 Krill oil

Krill oil, which contains high concentrations of astaxanthin, is effective in pigmenting salmonids (Arai *et al.* 1987). It is produced commercially in Japan and British Columbia.

3.2.4 Krill for Human Consumption

Part of the catch of Antarctic krill *Euphausia superba* is processed into products for human consumption after machine separation of the tail meat. *N. australis* is a much smaller species, with an adult fresh weight of about 40 mg, or only about 4% of the adult weight of *E. superba*. It is unlikely that the tail meat of *N. australis* could be processed economically as human food[4].

A small portion of the commercial catch of a similar-sized species, *E. pacifica*, is used in Japan to make a dried appetiser of the whole animal. But this is a specialty food for which the market in Australia would be minuscule.

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3 Made from *Artemia salina* and *Euphausia superba*.

4 Indeed, processing even *E. superba* into human food at acceptable cost remains problematic after several decades of research by Russians, Poles, Germans and Japanese (*e.g.* Nicol 1991).

Chitosan

Chitin, the main constituent of crustacean shells, can be converted chemically into chitosan, a molecule that is thought to have a bright commercial future with many developing applications (*e.g.* Sjak-Braek *et al.* 1989). It has been suggested that krill could be a source of the necessary chitin (*e.g.* Nicol 1991). But it seems unlikely that a *N. australis* fishery would be an economically competitive source, given other much larger sources of chitin, such as prawn shells and Antarctic krill.

Berley

Thousands of tons of frozen *E. pacifica* are sold each year to recreational fishers for use as berley (chum) in Japan (see below). No information was found on its use for this purpose outside of Japan.

4. TWO EXISTING NEARSHORE SMALL-VESSEL KRILL FISHERIES

To obtain information on existing krill fisheries operating under conditions similar to those presented by *N. australis* one of us (R. J.) visited two such fisheries in Japan and British Columbia in April-May, 1989. Much of the catch of both these nearshore, temperate zone fisheries is used in aquaculture feeds.[5]

4.1 The Japanese Fishery

4.1.1 Background

Since about 1945 a nearshore day fishery for *E. pacifica,* a euphausiid similar to *N. australis* in size and in a number of relevant biological characteristics, has operated north of Tokyo off the northeast coast of Honshu Island, between 36° and 40°N. An average of 60,300 tonnes was landed annually between 1983 and 1992 (Food Chain Section 1992). To put this number in perspective, the largest-ever annual catch in Australia's largest single-species fishery, the Tasmanian jack mackerel fishery, was 41,000 tonnes.

Statistics for the fishery began to be collected in 1953[6]. For the first few years of the fishery the catch, which amounted to less than 1,000 tonnes annually, was boiled, dried, salted and used exclusively for human consumption as a savoury. Demand increased from 1970 when a market developed for the use of frozen krill as berley (chum) in the recreational line fishery. The krill fishery expanded accordingly; between 1976 and 1983 the mean annual catch was 26,500 tonnes (Odate 1991).

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5 Some video footage, photographs and descriptions of selected Japanese and British Columbian krill fishing gears are available for inspection at the CSIRO Marine Laboratories in Hobart.

6 Much of the information on the development of this krill fishery was provided by Mrs Kasuko Odate and other staff members at the Tohoku Regional Fisheries Research Laboratory in Shiogama, Dr Yoshinari Endo of the Far Seas Fisheries Research Laboratory in Shmizu, and Mr Kitaro Abe, a krill fisherman and coho salmon farmer from Izushima Island in Miyagi Prefectures. We are extremely grateful for the unstinting hospitality these people showed R. E. J. and for the comprehensive assistance Dr. Endo gave R. E. J. during his visit to the Japan.

In 1975, frozen *E. pacifica* was in demand as an ingredient in feed for cultured salmonids, especially coho salmon *Oncorhynchus kisutch*. It also began to be used in feed for cultured yellowtail *Seriola quinqueradiata*, and Red Sea bream *Pagrus major*, to brighten skin pigmentation (Fujita *et al.* 1983). Between 1983 and 1987 the mean catch was 56,000 tonnes. In 1983 the average daily catch per boat was reportedly about 3 tonnes (Hanamura *et al.* 1984).

By 1987 about half the catch was used as berley and half used in aquaculture feeds. Small amounts of frozen krill were marketed as food for ornamental aquarium fish.

Published details on the fishery are sparse. It originated in Miyagi Prefecture, but spread to Fukushima, Iwate and Ibaraki Prefectures in the 1970s when the berley market greatly increased demand. The fishery was independently regulated in each prefecture (with significant differences in boat and gear restrictions). The information given here pertains mainly to the fishery that lands catches at the coastal village of Onagawa in Miyagi Prefecture, the most important single landing site for *E. pacifica*.

4.1.2 Fishing technology

The original fishing gear, which was still used by much of the fishing fleet in 1988, was an unusual bow-mounted trawl (Fig. 1). It consisted of two fibreglass poles between which the trawl net (0.35 mm mesh aperture) was suspended. The poles were crossed and lowered from the bow of the fishing vessel, and fished from the surface to depths of about 8 m. Krill were caught only when swarming at or near the surface, which happens mainly during the day (Endo 1984). Swarms are typically found in these waters from February through May.

Swarms were located either by noting the behaviour of auklets, especially *Aethia cristatella*, and seagulls, especially *Larus crassirostris*, which feed on swarming krill, or by the reddish colour of surface swarms, or by the use of echo sounders. Swarms were said by fishers to be less dense on cloudy days. The fishing boats had high wheelhouses to facilitate spotting.

Recently developed seines for one or two boats are also used to catch *E. pacifica*. They enable fishers to catch krill in less dense aggregations in commercial quantities and now dominate the fishery. They also enable fishers to target krill that are not at the surface, the aggregations being detectable by colour echo sounders at 50 or 200 KHz. Three to four people crew the single-boat seining operation. When a krill swarm is located, a buoy attached to the rope of the seine is dropped. The boat moves downstream, then makes a right-angle turn while releasing the net. The boat then returns upstream past the swarm and retrieves the net. The operation takes 15–20 minutes. One- and two-boat seines can be deployed as deep as 120 m, and some are even said to fish as deep as 200 m.

Boats using a bow-mounted trawl vary considerably in size, from 14 to 40 t. The average in 1989 was 17 t, with a mean length of 20 m. The largest catch in a single trawl is up to 3 tonnes and boat storage capacities range from 3 to 6 tonnes. Crew numbers range from three to six. The boat owner gets half the profits, as well as one crewman's share if he participates actively in the fishing. The crew divide their profits equally.

In the early years, the krill was stored on deck until the vessel reached port. Product quality was poor because krill deteriorate very rapidly if not frozen soon after they are caught (see below).

The catch is now stored in refrigerated holds. Immediately upon reaching port, fishers pack the catch in 30 kg capacity stackable plastic trays. On some boats the krill is simply shovelled into the trays, but other boats have pumps to suck the krill from the hold and distribute them more quickly into the trays.

When the krill are landed they are chilled but not yet frozen. Seawater is added to the trays (4–5 l per 10 kg of krill) and the catch placed in a deep freeze facility. Fishers said that krill must be frozen within 5–6 hours of being caught to prevent significant deterioration. From Onagawa several dozen regular buyers distribute the catch.

4.1.3 The Catch

Catches fluctuate from year to year because of variability in krill abundance. The highest catches have been made in years when the nutrient-rich waters of the southerly Oyashio Current, in which *E. pacifica* is endemic[7], moved strongly into coastal waters in the fishing area. Odate (1979) reported a significant correlation ($r = 0.93$) between the catch and the extension of cold waters (i.e. below 5°C at a depth of 100 m, in the area between 35°N and 42°N west of 145°E). Typically the season has extended from late February through May although it has varied in duration from year to year.

Harvestable shoals of *E. pacifica* have often been found near the boundaries between cold and coastal waters (Odate 1979). Swarms first appear with the arrival of cold water of about 7°C and disappear when the temperature exceeds 16°C (Komaki, 1967).

The catch was poor in 1988 (about 43,000 tonnes — down on the 80,000 tonnes caught the previous year) because a warm core eddy tended to block the inshore movement of Oyashio waters (Y. Endo, pers. comm.).

As these krill are of oceanic origin, the catch is assumed to constitute a minor fraction of the total stock. The size-distribution of krill in catches varies erratically during the season, suggesting that different populations are involved as the season progresses. Accordingly, no biological limits are set on the catch.

In order to prevent gluts and falling prices at times when catches are high, fisheries cooperative association authorities keep in touch with the fleet by radio and call them into port as early as noon if catches threaten to exceed desired levels. There has been no limit to the number of boats allowed in the Miyagi Prefecture. There is a limit,

7 *E. pacifica* lives in the subarctic and transition zones of the North Pacific. Its crescent-shaped distribution extends further south near Asian and North American continental margins (*e.g.* Brinton 1962; Komaki 1967).

however, on the number of boats registered in other prefectures and allowed to fish for krill in Miyagi Prefecture waters[8].

The average gross income per boat from krill fishing alone was ¥4,400,000 in 1988, whereas in the previous season with a catch almost twice as great, the average gross income per boat was ¥8,800,000.

Uncertainty about the availability of krill from year to year and during the season was said by fishers to be a major concern. As a result some fishers switched in the 1980s to raising coho salmon. In 1988 there were 348 local bow-mounted trawl boats in the Miyagi Prefecture fishery; numbers had been declining gradually since a high of 573 in 1984.

Some salmon farmers continued catching krill part-time to feed their salmon stock, even installing food grinders on the decks of their vessels. On arriving at their salmon pens, they fed frozen krill, frozen fish (cod and sardines) and dried fishmeal components (including vitamins, antibiotics, canthaxanthin pigment and binders, as well as some dried Antarctic euphausiid *E. superba*) through the grinders to produce moist pellets on the spot.

Krill was added in different proportions, or not at all, to the mix, depending on the salmon's growth stage. During the last 2–3 months before the salmon were killed and marketed, frozen *E. pacifica* constituted about 25% of the feed by weight. One of its main functions at this stage was to enhance the pink colour of the salmon flesh that is so important to consumers. Because the fishmeal component of the feed contained synthetic canthaxanthin and some residual astaxanthin from the dried Antarctic krill, the salmon had a light pinkish colour up to this stage. Adding krill to their diet also improved the flavour of the fish, according to fishers.

Krill for the berley market were distributed in 15 kg frozen blocks. These were sliced into smaller portions and sold out of machines resembling soft-drink dispensers, found commonly throughout Japan at fishing supply stores. In 1988 the price for such krill at ports in the vicinity of the fishing grounds ranged from ¥60 to ¥80 per 100 g. The price was only about ¥40 per 100 g the previous year when catches were higher.

Sellers said aquaculturists complained when prices rose, but recreational fishers seemed willing to pay whatever price was asked. The price of krill to fish farmers in Miyagi Prefecture in 1988 was ¥75 – ¥100 per kg.

The same vessels were also used to fish for sand lance *Ammodytes personatus*, using similar gear but with larger mesh netting. Annual catches of sand lance and krill fluctuate in parallel, both fisheries experiencing good years when the cold Oyashio Current moves strongly into coastal waters (Komaki 1967). Later in the year the boats were also used to fish for squid (*Stenoteuthis bartrami* and *Todarodes pacificus*) with automatic jigging machines and night-lights. Occasionally fishers found it possible to catch krill at night with bow-mounted trawls, using the same night-lights (10–12 halogen lamps of 1–3 kw) to attract them.

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8 Fishers, through their cooperatives, are given far more direct responsibility for managing their coastal fisheries in Japan than is the case in most western countries (*e.g.* Ruddle, 1990).

The Japanese mackerel *Scomber japonicus* feeds on swarms of *E. pacifica*. The availability of this fish in the local spring mackerel fishery appears to depend upon the abundance of these swarms (Komaki 1967). This parallels the situation in Eastern Tasmanian waters with regard to the jack mackerel *Trachurus declivis* and its main food, *N. australis* (Young *et al.* 1993).

The British Columbia Krill Fishery

4.2.1 Background

A small commercial fishery for *E. pacifica* has been working in inlets (fjords) in the Strait of Georgia in southern British Columbia since the early 1970s (Heath 1977, Sloan and Fulton 1987)[9]. Here, *E. pacifica* migrates close to the surface mainly at night (Bollens et al, 1992). The fishery, accordingly, takes place at night and the swarms are found with echo sounders (100 KHz or more).

The best catches are made on dark nights, according to fishers; krill do not come as close to the surface on moonlit nights. This means there are about 20 satisfactory fishing nights per month. Occasionally krill swarms come to the surface during the day, but usually only when driven there by feeding fish, one fisher said.

The early development of the fishery was described by Heath: "Operating from a small boat, the first Canadian commercial plankton fishers used a 10 m long square net (about 2 m x 2 m in the mouth), which was equipped with surface floats, bridle and horizontal bars. The mesh of the euphausiid net was 6 mm knotless nylon while the codend consisted of a plastic bucket which screwed onto a threaded section of plastic pipe on the cone of the net. The net was towed on a polyester warp about 100 m in length and was retrieved by hand. After draining, the catch was frozen on board in plastic bags" (Heath 1977).

4.2.2 Fishing technology

Heath (1977) described a modified Issacs-Kidd midwater trawl that was better for selecting fishing depth than the net with surface floats, and easier for emptying the catch through its zippered codend. Fishers adopted a version of this trawl with a 13 m^2 mouth area, using it from boats designed primarily for salmon trolling.

One fisher reported that, because the animals must be frozen quickly to maintain their quality, he packs them in the hold in trays about 4 cm deep, placing the trays in a frame designed to leave 4 cm space between them to allow cold air to circulate freely.

The fishery takes place in winter months when the boats, which are designed for salmon trolling, would otherwise be idle. They fish generally within the top 20 m of water (Sloan and Fulton 1987). From about March (early spring) phytoplankton blooms tend to clog the nets, making fishing difficult.

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9 Most of the uncited information provided in this section was provided by Mr Bill Crook of Murex Aquafoods, Vancouver, Mr David Saxby of Specialty Marine Feeds, Vancouver; and Mr. Ivan Tentschoff, a krill fishers of Gibsons Landing, B.C.. We are indebted to these people for their help.

A much cheaper possible alternative is to produce silage. Here material such as seafood by-products or krill is mixed either with acid (acid-based silage) or allowed to ferment (fermented silage) to produce a liquid that is useful ingredient in feeds for salmonids and other fish (*e.g.* Lall 1991).

Acid ensilage has been found not only to preserve astaxanthin, but also to improve its absorption from prawn waste by rainbow trout (Torrissen *et al.* 1981/82). Before krill could be used in this way research would be needed to determine the extent to which nutritionally important constituents such as PUFAs were preserved.

5.3 Bycatch

Contamination of krill catches with other crustacean plankters, such as copepods, would probably have no appreciable affect on the quality of the catch unless, perhaps, this contamination was severe. However, contamination of the catch with significant quantities of gelatinous zooplankters such as salps or jellyfish could cause problems. Salps sometimes dominate the catches made in plankton nets in southeastern Tasmania (*e.g.* Clementson *et al.* 1989), although not off Tasmania's east coast (J. Y., Pers. Observ.). Contamination is less likely to be a problem if surface swarms are targeted exclusively. In British Columbia contamination and clogging of krill nets with phytoplankton is a seasonal problem that sometimes results in premature termination of fishing late in the fishing.

5.4 Availability

Before a commercial krill fishery is attempted in Tasmanian waters, more information on the distribution and abundance of *N. australis* should be obtained. Further data is required not only on temporal (diurnal, seasonal and interannual) variations in this species but also on its spatial distribution.

Interannual variations in availability could, in particular, prove to be a significant impediment to a fishery. In 1989 *N. australis* almost disappeared from the water column in eastern and southeastern Tasmania (Young *et al.* 1993). This disappearance appears to be linked to the intrusion in that year of warm low-nutrient subtropical waters onto the shelf with an associated decrease in phytoplankton production. This, in turn, appeared to be linked to the large El Nino-Southern Oscillation event of 1988 (Harris *et al.* 1991).

N. australis is usually reported as being limited in its distribution to shelf waters. It is not known whether, in 1989, its east coast populations were swept off the shelf, starved due to insufficient food, or moved elsewhere. The answer has obvious bearing on its availability in such years.

Another important question is how often do these periods of the near-disappearance of *N. australis* from eastern and southeastern waters typically occur? Harris *et al.* (1988) noted water temperatures off eastern Tasmania were unusually high in 1957 and during several years in the late 1970s and early 1980s. These may have been times when subtropical waters moved onto the shelf, with consequent dramatic declines in krill numbers. No confirmatory information is available, however.

N. australis was still found on the southwest coast of Tasmania when it was absent in 1989 off the east coast (Young *et al.* 1993). But even if the species always remained available in these waters, its commercial potential is problematical. Not only are waters off the southwest coast particularly rough — which would make locating and netting of swarms difficult — but they are also a long way from any logical potential landing and processing site.

5.5 High Fluoride Content

Whole krill typically contain high concentrations of fluoride (*e.g.* Adelung *et al.* 1987) and for this reason are considered unsuitable for human consumption and stock feed. Krill tail meat is, however, safe for these uses since the bulk of the fluoride is in the exoskeleton. Like other krill *N. australis*, has very variable but generally high levels of fluoride, ranging from 530–3500 ug/gm dry wt. (Virtue *et al.* 1995).

For small krill such as *N. australis* it is not practical to separate flesh from exoskeleton so, as noted earlier, marketing this species for human consumption is not an option. However, whole krill with high fluoride levels are not precluded from use in aquaculture because ingested fluoride is found largely in the bones of cultured fish. Trout and salmon fed exclusively on krill for three years had lower fluoride levels in their muscle tissue than had wild Baltic fish from the same area (Grave 1981).

5.6 A Potentially Competitive Product

For several years research has been underway on farming zooplankton commercially in sewage ponds in Victoria and Tasmania. Anyone planning to harvest krill commercially in Australia should keep abreast of the developments in this potentially competitive endeavour.

Finally, as *N. australis* is the main source of food for a number of important fish and seabird species in Tasmanian waters, estimating how much krill could be harvested without affecting these species would be an essential step in planning for a commercial fishery.

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