University of the Highlands and Islands
Oilthigh na Gàidhealtachd agus nan Eilean

UHI Research Database pdf download summary

Krill as a source of aquafeeds

Wilding, Thomas

Publication date:
2007

Publisher rights:
© Queen's Printer for Scotland, 2007.
Published by The Crown Estate on behalf of The Marine Estate
This publication (excluding the logos) may be re-used free of charge in any format or medium. It may only be re-used accurately and not in a misleading context. The material must be acknowledged as Crown Estate copyright and use of it must give the title of the source publication. Where third party copyright material has been identified, further use of that material requires permission from the copyright holders concerned.

The re-use license for this item is:
Other

The Document Version you have downloaded here is:
Version created as part of publication process; publisher's layout; not normally made publicly available

Link to author version on UHI Research Database

Citation for published version (APA):
Wilding, T. (2007). *Krill as a source of aquafeeds*. (SAMS Internal reports; No. 263). Crown Estate.

General rights
Copyright and moral rights for the publications made accessible in the UHI Research Database are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights:

1) Users may download and print one copy of any publication from the UHI Research Database for the purpose of private study or research.
2) You may not further distribute the material or use it for any profit-making activity or commercial gain
3) You may freely distribute the URL identifying the publication in the UHI Research Database

Take down policy
If you believe that this document breaches copyright please contact us at RO@uhi.ac.uk providing details; we will remove access to the work immediately and investigate your claim.

Download date: 09. Aug. 2024

KRILL AS A SOURCE OF AQUAFEEDS

Contract reference: AQU/06/12

Technical Report
Version: Draft Final(2).
Aug 2007

by Thomas A. Wilding.
Scottish Association for Marine Science,
Dunstaffnage Marine Laboratory,
Oban, Argyll, Scotland. PA37 1QA

ADMINISTRATION PAGE

Contract reference: AQU/06/12, period: March – August 2007.
Report version: Draft2.
© Queen's Printer for Scotland, 2007. ISBN ?????.
Published by The Crown Estate on behalf of The Marine Estate.

Dissemination statement
This publication (excluding the logos) may be re-used free of charge in any format or medium. It may only be re-used accurately and not in a misleading context. The material must be acknowledged as Crown Estate copyright and use of it must give the title of the source publication. Where third party copyright material has been identified, further use of that material requires permission from the copyright holders concerned.
This report is available from The Crown Estate website www.crownestate.com
Suggested citation: Wilding, T. A.. (2007) Krill as a source of aquafeeds. The Crown Estate, ?? pages, July 2007. ISBN ???.

Contents

ADMINISTRATION PAGE ii
List of tables....iv
List of figures....iv
List of abbreviations and acronyms iv
EXECUTIVE SUMMARY v
Background....vi
1. Introduction....1
2. Biological overview....1
2.1. Reproduction....2
2.2. Growth and diet....2
2.3. Behaviour....3
3. Krill fisheries 4
3.1. The Antarctic fishery for E. superba....6
3.2. Canadian and Japanese E. pacifica fisheries....8
3.3. Other fisheries....8
4. The Capture and processing of krill....9
4.1. Fishing for krill 9
4.2. Product quality....10
4.3. Krill Products....10
4.4. Meal production....11
4.5. Expanding the krill fishery....11
5. krill fisheries – threats and consequences....11
5.1. Effects of climate change....12
5.2. By-catch....12
5.3. Response of non-governmental organisations 13
6. Krill composition and their potential for use in aquafeeds....13
6.1. Krill composition 14
6.1.1. Lipids....16
6.1.2. Proteins....19
6.1.3. Pigments....19
6.1.4. Chitin....22
6.1.5. Fluoride....22
6.2. Contaminants 23
6.2.1. Trace metals....24
6.2.2. Persistent organic pollutants....25
6.3. The potential for krill as an Aquafeed 27
7. Krill fishery economics....28
8. Data gaps....30
Environmental....30
Economic 31
Consumer....31
Regulatory....31
9. Realistic possibilities 31
10. conclusions....32
11. Recommendations for future resarch....33
12. Referenced literature and electronic sources 34
13. Appendices....40
Organisations providing information for this report....40

Summary of nutritive analyses (lipids, amino acids, carotenoids and seasonal variabilty)....................41
Summary of the use of krill in aquafeeds - feed trials....................41

LIST OF TABLES

Table 1 – Length, weight and lifespan of commercially relevant krill....................1
Table 2 – Krill diet as a function of species....................3
Table 3 - Swarm densities of various krill species....................4
Table 4 - Summary of main current krill fisheries....................5
Table 5 – Comparative information on the major current krill fisheries....................6
Table 6 – Crude compositions of various krill species....................15
Table 7 – Lipid characterisation in different krill species....................18
Table 8 – Essential amino acid content) in *E. superba* meal compared with fishmeal. 19
Table 9 - Pigment concentrations in various krill species....................22
Table 10 – Fluoride content of various krill species....................23
Table 11 – Trace metal concentrations (mg kg^{-1}) in krill and krill based feeds....................24
Table 12 – Level of POPs present in fish-oil, salmon feeds and krill....................27

LIST OF FIGURES

Figure 1 – Reported landings of Antarctic krill (*E. superba*) over the period 1970 – 2005 (source: FAO)....................7
Figure 2 – Price trends (June 2000 to December 2006) in fishmeal and fish-oil....................29

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
CCAMLR	Committee on the Conservation of Antarctic Living Resources
CPUE	Catch per unit effort
FAO	Food and Agriculture Organisation
FOB	Free On Board (seller pays for transportation of the goods to the port of shipment, plus loading costs. The buyer pays freight, insurance, unloading and transport costs).
IFFO	International Fishmeal and Fish-oil Organisation
NGO	Non-governmental organisation
POP	Persistent organic pollutant
TAC	Total allowable catch

EXECUTIVE SUMMARY

Aquaculture is a rapidly expanding industry that is currently highly dependent on limited supplies of fishmeal and fish-oil. There is a pressing need for the aquaculture sector to find alternatives to fishmeal and fish-oil which are both cost-effective and maintain product quality.

There are currently two substantial krill fisheries but only one, the Antarctic fishery, offers scope for the expansion necessary to make a significant contribution to global fishmeal and fish-oil supplies.

The following aspects of krill make them a potentially significant source of aquafeeds:

- Krill are a massive resource and consist of high quality protein and oil
- Krill can be used directly, or processed into products, that are ideal for use in a broad range of aquafeeds
- Salmon and cod grow at least as well on krill diets compared with traditional fish-based diets
- Krill can be used as an feed attractant, making highly vegetable substituted diets more acceptable to fish
- Krill contain high concentration of astaxanthins making them particularly useful in finishing (grow-out) diets
- Salmon and cod fed krill are highly agreeable to consumers, in terms of taste, smell, texture and colour.

The Antarctic fishery for *E. superba*, currently operates at 1/40th of the total allowable catch and considerable expansion of the fishery is possible.

However, there are a number of issues that need to be addressed before krill fisheries can develop. These include:

- The extent to which technological innovation will reduce krill fishing costs in the harsh operating conditions that characterise Antarctic fishing grounds
- The potential ecological implications of an expanding fishery, particularly in combination with other threats such as climate change
- The extent to which future market price for fishmeal and oil, and vegetable and fuel oil will determine krill fishery viability
- Consumer acceptability of fish fed krill substituted diets
- The potential for change in EU legislation with regard to animal feedstocks, that currently limit krill inclusion in aquafeeds.

Economic models, that test a range of likely scenarios, are urgently required to predict under what conditions the krill fishery will expand to make a substantive contribution to global aquafeed supplies.

BACKGROUND

Aquaculture is one of the fastest growing sectors of the global economy, an expansion associated with an increasing demand for protein and oil (Naylor et al. 2000). Many fish-feeds, particularly those for carnivorous species such as salmon, contain high concentrations of proteins and oils which are currently predominantly derived from forage fish (Naylor et al. 2000).

The following points summarise the current situation:

i. Demand for fish will grow as a consequence of a growing human population
ii. Given the overexploitation of wild fish stocks, increased supplies of fish can, in the long term, only come from aquaculture
iii. Increasing aquaculture production will increase demand for fish-feeds
iv. Fishmeal and fish-oil production has been static during the past decade and is unlikely to increase
v. The price of fishmeal is likely to continue to increase, possibly drastically as was seen in 2005/6
vi. The aquaculture industry must either reduce its reliance on fishmeal through finding marine or terrestrial alternatives

(New and Wijkstrom 2002).

Concerns with regard to the long-term supply of fishmeal and fish-oil led The Crown Estate to commission SAMS to conduct a review into ‘Alternative marine sources of protein and oil for aquaculture feeds’ (Wilding et al. 2006). That study identified krill as the most likely and economically viable alternative marine source of proteins and oils.

The current report sets out to review the potential of krill for use in aquafeeds through an evaluation of krill biology, fisheries (including environmental concerns), nutritional value and economics. Information for this report has been derived from both published research and through direct communication with industry and academia (correspondees are listed in 13.1.1.1)

PRACTICAL 1 INTRODUCTION

Krill are marine crustaceans (Class Malacostraca, Order Euphausiacea) consisting of approximately 80 species a majority of which are free swimming and considered plankton (Everson 2000). Krill are highly fecund (Ross and Quetin 2000), periodically found in very high densities and have a global distribution ranging from coastlines to the deep sea (Everson 2000). Krill range in size, the smallest (<10 mm) being tropical, to deep-sea species that reach 140 mm or more (AAD 2007). Krill sometimes form dense swarms that can extend over several square kilometres and represent a biomass of thousands or even millions of tonnes (Nicol and Endo 1999). Krill diet is varied, some species are obligate carnivores or herbivores whilst others are omnivorous and seasonally change their diet.

Krill contain high proportions of protein, lipid and pigments which, together with their high abundance, make them an attractive fishery. Krill have been harvested since the 19th century but it was only during the 1960s that commercial krill fisheries began in earnest (Beck et al. 1977; Rehbein 1981) following recognition of their potential for both direct human consumption and in agricultural feeds (Nicol and Endo 1999).

This review focuses on two species, *Euphausia superba* and *E. pacifica*, as these are the current main fishery species. However, other species such as *M. norvegica* (Northern krill), *Nyctiphanes australis*, *Thysanoessa inermis, T. raschii* and *E. nana* will also be considered as these are either currently fished, at small or experimental scales, or show some potential for becoming fishery species (Virtue et al. 1995; Nicol and Endo 1999). References to other species are made where they illustrate broader principles.

PRACTICAL 2 BIOLOGICAL OVERVIEW

Studying krill poses several challenges primarily because krill are small and have a characteristically highly variable distribution. This applies particularly to open/remote ocean species where direct sampling and/or observations are particularly difficult (Nicol 2003). However, the ecological importance of krill combined with their commercial potential has meant that they, particularly *E. superba* (Nicol 2006), have been extensively studied,

Among commercial species of krill there is considerable variability in their size and longevity (Table 1).

Table 1 – Length, weight and lifespan of commercially relevant krill.

Scientific and common name (where available)	Maximum size, weight and lifespan
E. superba (Antarctic krill)	65 mm, 2 g, 7 yrs
E. pacifica (North Pacific Krill)	20 mm, 0.1 g, 3 yrs
N. australis	17 mm, 0.02 g, 1 yr.
Euphausia nana	10 mm, 0.01 g, <1 yr

Thysanoessa inermis	32 mm, 0.15 g, 2 yrs.
Thysanoessa raschii	30 mm, 0.13 g, >2 yrs.
*Meganyctiphanes norvegica (*Northern Krill).	45 mm, 0.5 g, >2 yrs.

(Source: Nicol and Endo 1999)

Krill are often considered planktonic with their distribution being controlled by ocean currents (Nicol et al. 2000; Hofmann and Murphy 2004) yet many species are much larger than most plankton and show large vertical migrations (Nicol 2003) and possibly other non-passive movements (reviewed in Siegel 2005). Krill show a variable swarming behaviour which makes estimating their biomass difficult and, possibly, imprecise (Demer 2004).

2.1 REPRODUCTION

Krill, including those of commercial significance, are highly fecund, with hundreds or thousands of eggs (or larvae in the case of *N. australis*) being broadcast several times during the breeding season. In *E. superba*, both the males and females expend considerable energy in the production of gametes, and it seems likely that this applies to many species, particularly those found in high latitudes (Virtue et al. 1996; Ross and Quetin 2000). Once hatched juveniles go through several larval stages, via a series of moults, before becoming sexually mature. Krill typically reach reproductive maturity when they have attained half their maximum size and 30 – 60% of their life-span. Krill life-span and age-of-first-reproduction are not always the same for males and females and, where there is a difference, the male lifespan is generally shorter than the females (Ross and Quetin 2000).

In general the initiation of spawning follows the progression of the season meaning that, for example, northern populations of *E. superba* will begin spawning earlier (and finish later) than their more southern counterparts (Ross and Quetin 2000). This is driven primarily by seasonally available primary production (food), although this dependency is moderated, at least in some species, by the utilisation of storage lipids for reproduction, which differs between species and sex (Virtue et al. 1996; Ross and Quetin 2000) (see §6.1.1).

There remains considerable uncertainty as to the relative importance of egg production versus early larval mortality in determining year-class strength in many krill species and the factors determining the high interannual variability in the current main fishery species, *E. superba*, are still unclear (Hill et al. 2006).

2.2 GROWTH AND DIET

Growth rates, and times to maturity, are important factors in determining fecundity and subsequent recruitment in krill but, in terms of fishery potential, the role of diet in determining the composition of krill is of most interest.

Euphausia superba is omnivorous showing a seasonally adaptable diet. During the spring and summer *E. superba* constitutes one of the largest consumers of phytoplankton in the Antarctic (Atkinson et al. 2004). During the harsh Antarctic winter *E. superba* (including larvae) retreat under the ice sheet and adopt an omnivorous diet taking a broad range of items including ice-attached algae, other zooplankton (including krill), exoskeletons and faecal material (Mauchline 1980). In the absence of sufficient food to cover metabolic costs Antarctic krill survive, uniquely, by catabolysing body tissue (and subsequently shrinking between moults) and reversed gonad development (McGaffin et al. 2002).

Like *E. superba*, *E. pacifica* is omnivorous; larvae have been recorded as consuming organic detritus, at least in the Yellow Sea (East China Sea) (Suh et al. 1991). Other research has demonstrated that *E. pacifica* will ingest toxic algae indicating herbivory and, more importantly, their potential as a vector of algal toxins into the food-chain (Bargu et al. 2002).

Krill diets are summarized in Table 2.

Table 2 – Krill diet as a function of species.

Species	Diet type	Notes and reference
E. superba	Omnivorous	Intense summer feeding on phytoplankton, winter feeding on various (Mauchline 1980; Cripps and Atkinson 2000)
E. pacifica	Herbivorous (adult)	Possible vectoring algal toxins into the food chain (Bargu et al. 2002)
	Omnivorous (larval)	Organic detritus consumed by larval stages (Suh et al. 1991)
E. nana	Filter-feeder (unspecified).	Mauchline (1980)
T. inermis	Herbivorous	Falk-Petersen et al (2000)
T. raschii	Omnivorous	Mauchline (1980)
M. norvegica	Omnivorous	Copepods (frequently calanoid) (Falk-Petersen et al. 2000) during day time at depth, herbivorous at night (Mauchline 1980)
N. australis	Omnivorous	Mauchline (1980)

2.3 BEHAVIOUR

The aggregation of krill into swarms, a feature typifying the Euphausiids as a group, is the factor that makes them amenable to fishing (Watkins 2000). Daily migrations are also common within the Euphausiid group with about 75% of species, at least at some life stages (Mauchline 1980), exhibiting such behaviour.

In the case of *E. superba* larval stages perform pronounced vertical diel migrations while juveniles and adults are commonly found in the upper 30 m at flight, and may migrate within the upper 100 m layer in daytime or remain stationary throughout day and night demonstrating no clear diel pattern of vertical distribution (FAO 2007). The picture is quite different for *M. norvegica* where diel migration, probably in pursuit of food or avoiding predators, is common (Tarling et al. 2000).

Whilst there appears to be no common pattern in swarming or vertical migratory behaviour with different species behaving in different ways it is likely that all these migrations are involved with predator avoidance (Ritz 1994), the pursuit of prey (phyto- or zooplankton) (which may also show diurnal migrations, Tarling et al. 2000) or, in the case of swarming, because membership confers energetic advantages when maintaining position in the water column (Ritz 2000).

In some species diel migrations are associated with the formation and dissolution of swarms. For example, *E. superba* has been observed migrating to the surface during the night whereupon the swarm dissociates (Watkins 2000), presumably to re-form during the next day.

Swarms of krill form patches, the patterns of which operate at several different scales, both over time and space. Some compact swarms are only metres across while others extend for several kilometres in horizontal extent (Watkins 2000). Members of the same swarm tend to be of similar size, maturity or same stage in the moult cycle (Watkins 2000).

Swarming behaviour results in periodically very high densities of krill with recorded maxima ranging widely. Such variation, which may be a function of species (Table 3) makes biomass estimates difficult particularly given that a significant (perhaps a major) part of the krill population may occur in a solitary or dispersed stage (FAO 2007).

Table 3 - Swarm densities of various krill species

Species	Swarm density range (per m^3)
E. superba	20,000 – 60,000
E. pacifica	10,000 – 72,000
M. norvegica	9,000 – 770,000
N. australis	3,000 - 480,000

(Source: Watkins 2000)

Swarm size is very variable, for *E. superba* swarms of up to 150 km^2 have been recorded with a biomass of between 1 and 10 million tonnes (indicative of problems in estimating biomass from acoustic data) (Watkins 2000). Less is known about the extent to which krill exist in a dispersed (solitary) phase further compromising biomass estimates and the understanding of the role of krill in the Antarctic ecosystem (Watkins 2000).

Swarm characteristics also change with season, *E. superba* follows a cyclical pattern with swarming behaviour increasing over the spring and summer (from 20 – 100 g m^{-3} to 150 – 500 g m^{-3}) followed by a decrease through the autumn – winter to minima of around 10 g m^{-3} (Lascara et al. 1999).

PRACTICAL 3 KRILL FISHERIES

There are currently several active krill fisheries but these are dominated by two; one based in the Antarctic for *E. superba* and the other based predominantly in Japan (but also Canada) targeting *E. pacifica*. Together these two fisheries (*E. superba* and *E. pacifica*) represent at least 97% of the total krill landed (Table 4). These fisheries have the most relevance to addressing the UK aquafeed issue, either directly or indirectly, and form the main focus of the following section.

Table 4 - Summary of main current krill fisheries

Species	Distribution	Main use	Fishery location, tonnage and major fishing nation
E. superba	Antarctic ocean	Human consumption, aquafeeds and nutraceuticals	Southern ocean, particularly Antarctic convergence. Major fishing nations are Japan (70,000 t), Poland (18,000 t) (FAO, 1999)
E. pacifica	North Pacific Ocean	Aquafeeds, sport fishing bait, human consumption (7%)	Japanese east coast 60,000 tonnes (J. Morishita, personal communication, July 2007)
E. pacifica	Western Canada	Aquaculture and aquaria	Canadian catch, very variable tonnage: variable, few hundred t/yr. Max 500 t in 1985.
E. nana	Pacific	Aquafeed (red-seabream)	Japanese south-east coast, currently small landings variable, 0 - 5000 t (1985 – 1990)
T.inermis	Pacific and Atlantic	Not specified	Japanese north-west coast, ca. 200 t/yr (1985) (Japanese fishery). Also small fishery in the Gulf of St. Lawrence, Canada.

(Source: Nicol and Endo 1997; Nicol and Endo 1999; Ichii 2000)

The two main krill fisheries (targeting *E. superba* and *E. pacifica*) are exploited in different ways and at different times of year. The Antarctic, which is one of the hardest places in the world in which to operate a fishery, necessitates larger fishing vessels in order to process and store sufficient catch to make it economical (Table 5) whilst *E. pacifica* fisheries are targeted by smaller vessels supplying local markets and operating in less harsh conditions.

Table 5 – Comparative information on the major current krill fisheries

Location	Antarctic ocean	Off north-eastern Japan	Off western Canada
Species	*E. superba*	*E. pacifica*	*E. pacifica*
Ground	Vicinity of islands and continental shelf breaks/slopes	Ocean fronts	Inlets and straits
Season	Dec – Aug	Feb – May	Nov – Mar
Type of boat	Stern trawlers (4000 tonnes)	Small vessels (<20 t)	Small vessels
Number of boats	<10	>300	<20
Method	Mid-water trawl	Boat seine	Surface trawl
CPUE	100 t/vessel/day, 10 t per haul	5 t/vessel/day 1 t/day	3 t/vessel/day 0.5 t/haul
Quality issues	Large white (non-feeding) preferred for human consumption, no quality issues in relation to aquafeeds	Highly coloured (red) preferred	No quality aspect
Fishermen's concern	Targeting quality (rather than quantity)	Fishing condition, length of season	

(Source: Ichii 2000)

3.1 THE ANTARCTIC FISHERY FOR *E. SUPERBA*

The Antarctic fishery began in earnest in the mid 1970s and expanded rapidly with a bulk of the fishery being exploited by a subsidised Soviet fleet (Ichii 2000). Over the period 1975 – 1985 the fishery increased 10 fold from approximately 50,000 to 500,000 tonnes per annum. However, following the discovery, in the mid 1980s, of very high concentrations of fluoride in krill products (see §6.1.5) the fishery declined to just over 100,000 tonnes per annum. The subsequent development of effective peeling machines allowed the industry to re-establish to a level of around 400,000 tonnes per annum (Figure 1). This fishery continued until the break-up of the USSR and the removal of subsidies from the Soviet fleet following which landings decreased to about 80,000 tonnes per year in 1993 (Figure 1) from a non-subsidised (mostly Japanese) fishery. Since then the fishery has been stable at about 100,000 tonnes per annum with an assortment of nations, led by Japan (landing about 30,000 tonnes per annum by one trawler; J. Morishita, personal communication, July 2007) but including South Korea, Poland and the Ukraine, currently exploiting the fishery (AAD 2007).

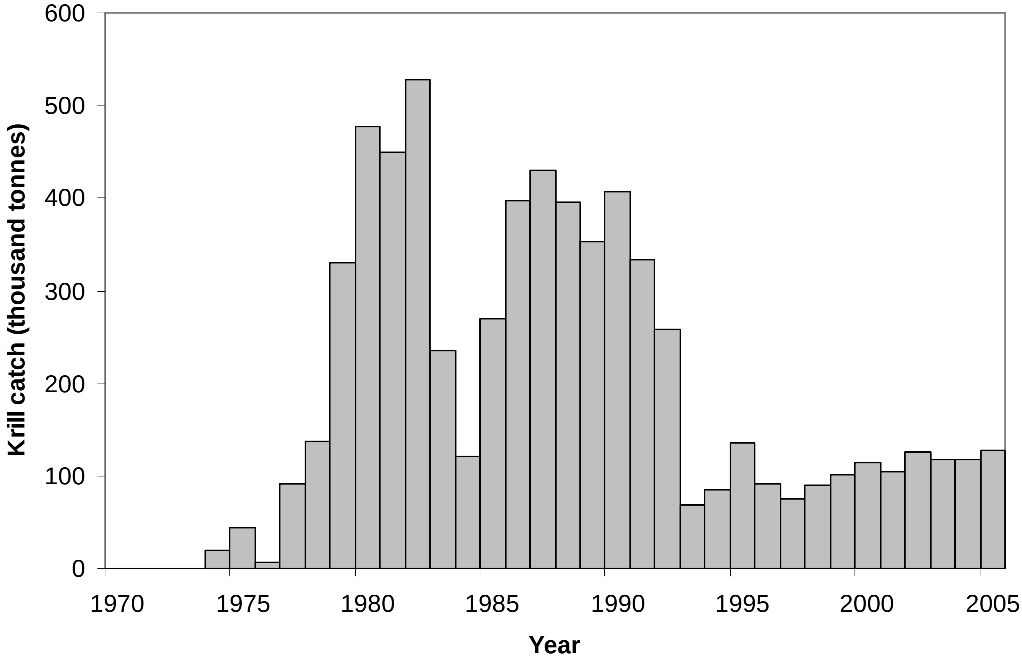

Figure 1 – Reported landings of Antarctic krill (*E. superba*) over the period 1970 – 2005 (source: FAO).

Antarctic krill occurs throughout most of the waters south of the Antarctic Convergence but is most abundant closer to the Antarctic continent and around some of the Antarctic and subantarctic islands. The current fishery concentrates in the South Atlantic with summer fisheries along the Antarctic Peninsula and winter fisheries around South Georgia (Nicol and Endo 1997) for logistical (re-supply) reasons. The northward extent of the fishery, during the winter, depends on the extent of winter ice (Clarke et al. 2007; Ducklow et al. 2007; Murphy et al. 2007).

The massive increase in the unregulated Antarctic fishery, seen in the late 1970s, caused considerable international concern with respect to the Antarctic environment and ecosystem and initiated the formation of the Committee on the Conservation of Antarctic Living Resources (CCAMLR). This organisation is charged with balancing harvesting and conservation, protecting the needs of dependent species, and aims to avoid ecosystem changes that are irreversible in 20-30 years (Croxall and Nicol 2004). There are several factors which make CCAMLR unique including being underpinned by a widely adopted international agreement and an extensive research base. CCAMLR has pioneered ecosystem approaches to fishery and environmental management and currently set limits on the size of the Antarctic fishery and licence exploitation by area to ensure that local depletion of stocks does not occur (Constable and Nicol 2002; Croxall and Nicol 2004; Hill et al. 2006). The current total allowable catch (TAC) is approximately 4 million tonnes, based on a standing-stock estimate of 44 million tonnes (e.g. Hill et al. 2006). The current fishery, at approximately 100,000 tonnes, therefore represents just 1/40th of what is available and considerable expansion of the fishery is possible. Whilst CCAMLR is considered an exemplary system of fishery management, it remains to be seen whether the management provisions will work in a quota limited fishery (also see §5.3).

3.2 CANADIAN AND JAPANESE *E. PACIFICA* FISHERIES

The *E. pacifica* fishery is split between Canada and Japan with the vast majority being landed by the Japanese (Table 4).

The Japanese fishery has been stable at about 60,000 tonnes per annum for the last decade (Table 4), a situation considered likely to continue (J. Morishita, personal communication, July 2007). Krill are landed by numerous predominantly small vessels (<20 tonnes) on a daily basis for processing into commodities including a sport fishing bait and aquaculture feed (red seabream) (Ichii 2000). The seasonal onset of the fishery depends on highly variable oceanographic conditions resulting in highly variable catches; *E. pacifica* is occasionally absent and fishermen, therefore, only use the krill fishery as part of their strategy of diversification. The Japanese *E. pacifica* fishery is regulated and managed at the prefectural level on the basis of catch and catch per unit effort (Ichii 2000) but as these are both determined by the industry this is considered inadequate (Ichii 2000).

The Canadian krill fishery is comparatively small with a total catch of up to 400 tonnes per annum. The fishery is spatially limited (Staits on the landward side of Vancouver Island) and there are ecosystem concerns, in particular in relation to the subsequent effects on other fisheries and, subsequently, the fishery is highly regulated (Ichii 2000). In addition, following a glut in 1993, which overstretched shore-based processing facilities, spoiled catch entered the market and resulted in a decrease in demand/price and fishermen now limit catches to maintain price. The krill product is mostly used as an aquafeed or pet-food and is exported to the US. The Canadian west-coast krill fishery, like its Japanese counterparts, is exploited for a limited season (November to March), and it is used as part of fishery diversification, particularly when salmon fishing is poor. However, unlike the Japanese fishery, both small and large boats are used, the larger vessels being out of season salmon fishing boats (Ichii 2000), which land their catch daily for processing which must occur within 24 hours.

On the east coast of Canada (Gulf of St. Lawrence) *Meganyctiphanes norvegica* is commercially harvested and there has been a proposed fishery for this species on the Scotian Shelf (Runge and Joly 1995). However, the krill population is subject to large climate-related fluctuations and there were (anecdotal) claims of substantial declines in *M. norvegica* abundance in 2004 (Noël 2004). These reports were used to oppose expansion of the fishery. In addition, the spatial limitation of the fishery and the emotive issue surrounding perceived threats to marine mammals mean that expansion of Canadian fisheries, of the magnitude necessary to make a contribution to global aquafeeds, seems unlikely.

3.3 OTHER FISHERIES

There are several other proposed or experimental scale krill fisheries which, whilst currently small, show continued interest in utilising krill and possibly may expand as market forces change and ecosystem management issues are resolved. The development of markets for these fisheries might be highly influenced by non-governmental organisations and pressure groups (§5.3), particularly where they are coastal and perceived to be deleterious to other fisheries or in relation to broader conservation issues (S. Nicol, personal communication, June 2007).

The Japanese have established fisheries for two other species, in addition to *E. superba* and *E. pacifica*. These species, both of which are coastal, are *T. inermis* and *E. nana* which have been commercially exploited for 30 and 20 years respectively (Nicol and Endo 1997). Fishing techniques for *E. nana* include the use of lights to attract swarms and the catch is predominantly used as a feed for red sea bream (Nicol and Endo 1997). The long-term development, and likely impact, of these fisheries on global fishmeal and fish-oil prices, remains unknown.

Nyctiphanes australis has also been proposed as a species with commercial potential (Virtue et al. 1995). This species is found off South East Australia and in the waters surrounding New Zealand. A detailed appraisal of its aquafeed potential is given in Virtue et al (1995) (see §6.1.1 and §6.3). However, the coastal nature of this small (20mm max), egg-brooding species means that an expansion of the fishery is likely to be opposed by local fishermen and conservation groups making it unlikely to develop (S. Nicol, personal communication, June 2007).

The *M. norvegica* standing stock, in the Norwegian Sea, has been estimated at 42 million tonnes and there is renewed interest in exploiting this stock (Melle et al, 2004 cited in Ringo et al. 2006). This led Ringo et al (2006) to undertake experiments to assess its suitability as an aquafeed (see §6.1.1 and §6.3). No further information about the development or potential of this fishery is currently available.

PRACTICAL 4 THE CAPTURE AND PROCESSING OF KRILL

Krill are a potentially massive resource and their swarming behaviour makes them amenable to fishing. However, in terms of fishery potential they suffer the disadvantages in being small necessitating a fine-mesh net to fish. This has considerable logistic and cost implications (Nicol 2000). They also spoil rapidly following capture. Overcoming these disadvantages is fundamentally a technological problem that, whilst having cost implications, is likely to be overcome as the pressure to harvest krill, and experience in so doing, develops.

4.1 FISHING FOR KRILL

The characteristics of the krill species being fished and the fishing grounds in which they occur determine the appropriate fishing techniques adopted by fishers. As a consequence fishing fleets differ considerably between different fisheries – the Antarctic fleet consisting of larger (3000 – 4000 tonne) stern trawlers, the Japanese of less than 20 tonne vessels using either bow-trawling or seining whilst the Canadian fishery is exploited using trawlers targeting krill in surface waters (Ichii 2000).

The fine mesh required to capture krill incurs several problems. The nets tend to clog easily and, even when clean, have considerable drag through the water column and induce a bow-wave which can deflect krill away from the net-opening. Although trawling is done at slow speeds considerable fuel is expended during fishing operations (Ichii 2000; Wikipedia 2007) meaning that fuel-oil price is likely to be disproportionately influential in determining the economic viability of krill fisheries.

One of the main problems of krill fishing is post capture handling. Krill are relatively fragile and spoil quickly particularly following rough treatment. Rough handling can occur as the krill are transferred from the sea to the boat, particularly when the haul is large, which squeezes and compacts the krill and can result in considerable losses of soluble proteins and some lipids. As a consequence, most operators use a maximum haul size of 7- 10 tonnes to reduce transfer damage (Ichii 2000). This issue has been further addressed, in the small-scale Japanese industry, by suction transfer, so maintaining their condition (Wikipedia 2007). The suction-transfer approach is planned for extension into the larger Antarctic fishery by Aker Biomarine (Bates 2007). To what extent this technology will improve profitability by reducing costs is unknown.

4.2 PRODUCT QUALITY

Following death krill deteriorate very rapidly. This spoilage occurs through the (i) rapid leaching of fluoride from the krill exoskeleton into the meat (see 6.1.5) and (ii) because of autolytic digestion by the powerful hydrolytic enzymes released from the digestive gland.

Spoilage through autolysis is a major problem in krill fisheries. In living individuals the activity of these enzymes, which include proteases, carbohydrases, nucleases and lipases, are restricted through cohabitation and inhibitor systems. These enzymes are particularly active in *E. superba* especially in those individuals actively feeding (Nicol 2000). Autolysis can result in substantial losses of hydrolysed proteins (although hydrolysed proteins can be a product in their own right, see §4.3) and lipids via the generation of undesirable free fatty acids. The solution to these problems is to minimise crushing through manageable haul size and the rapid processing of the catch (Nicol 2000).

4.3 KRILL PRODUCTS

Raw krill can be converted into a number of products sutiable for use in aquafeeds. These include hydrolysates (which are a speciality product) to krill-meal and frozen whole krill (Nicol 2000). Krill-meal is produced in a similar fashion to fishmeal (e.g.Olsen et al. 2006) and is the commodity usually incorporated into feeds as part of replacement research (see §6.3).

Research into the on-board processing of krill, to maximise efficacy and the hold value, is ongoing. For example Gullvika Ltd reported, from an experimental krill processing plant set up on the Fishery Patrol Vessel (FPV) “Dorada”, better results than expected in producing a low-fluoride krill protein using a combination of mechanical methods and enzymes (Anon 2005). One relevant patent has been filed in the US (Patent 6555155 “Method and apparatus for harvesting, digestion and dehydrating of krill hydrolysates and co-drying and processing of such hydrolysates” (April 2003) indicating continued interest in krill harvesting (PatentStorm 2007).

Further information is required to evaluate the extent to which catch processing technology currently limits the profitability of krill fishing.

4.4 MEAL PRODUCTION

In the review of the literature (see 6.3) several experimental diets, made using krill-meal to substitute fishmeal, were identified. In only one of these papers was there an issue with regard to the production of these feeds: Olsen et al.(2006) noted that the ability of the krill substituted pellet to absorb lipid during vacuum coating was inferior to that of the fish-based control. This was identified as a potential obstacle to the commercial production of krill-based aquafeeds and attributed to high levels of water soluble proteins, higher ash contents and lower protein contents compared with fishmeal. However, the lack of comment from other research groups indicates that, whilst this might be an issue in the short-term, it is not insurmountable.

4.5 EXPANDING THE KRILL FISHERY

Catching krill is a technologically demanding operation particularly in the extreme environment that characterises the Antarctic fishery. Fishing operations have, in the past, been beset by breakdowns limiting the tonnage of krill landed (P. Guzman, personal communication, June 2007).

Information regarding the drive to harvest krill is very difficult to assess and there is no evidence, at least in the western trade press, of substantial interest in krill fisheries from anywhere except Norway where the planned refit of one of their existing trawler fleet specifically to target krill, by the Norwegian company Aker BioMarine, suggests at least some confidence in the krill market. The Norwegians are the only country currently making such investments with the government there having recently issued four licences allowing krill fishing in the Antarctic with 10 companies having applied (S. Nicol, personal communication, June 2007). However, the issue of transfer of the catch to the vessel has, at least in part, been addressed by technological innovation in the form of suction transfer, which could reduce krill damage, increase product quality and reduce unit fishing costs. Japan, a nation often at the forefront of marine harvesting innovation, is not predicting an expansion of its harvesting operation in either Japanese or Antarctic waters (J. Morishita, personal communication, July 2007).

PRACTICAL 5 KRILL FISHERIES – THREATS AND CONSEQUENCES

Current krill fisheries (*E. superba* and *E. pacifica*) are relatively closely regulated (see §Practical 3) and it seems unlikely, in the current economic and technological environment, that they will be threatened by over-fishing, at least in the near future. However, global warming may have grave implications for krill populations reducing the size of the potential fishery and thereby limiting the scope of krill to make a significant contribution to aquafeeds.

5.1 EFFECTS OF CLIMATE CHANGE

The issue of climate change continues to receive an enormous amount of attention from many sectors of society. The impacts of climate change are particularly relevant to polar regions as even small changes in seawater temperature can cause considerable changes in the extent and thickness of sea-ice which has important ecosystem implications (Smetacek and Nicol 2005). The Antarctic is one of the fastest warming locations with a mean winter warming of 6 C since 1950 (Ducklow et al. 2007). In Antarctica this warming is closely associated with a reduction in the northward extent of winter ice and, consequently, a reduction in the habitat for over-wintering *E. superba* (see §Practical 2 and 3.1).

The extent of Antarctic sea ice is an important factor determining *E. superba* productivity and class strength in the following year (Nicol et al. 2000; Atkinson et al. 2004); following seasons characterised by reduced sea-ice the krill population declines. This decline is often associated with an increase in the population of the salp *Salpa thompsoni* (Tunicata) (Pakhomov et al. 2002; Atkinson et al. 2004), that tends to replace krill following poor krill recruitment, as the primary grazer in the Antarctic marine ecosystem. The implication of global warming for the Antarctic ecosystem (Pakhomov et al. 2002) and the interaction between sea-ice and the Antarctic Circumpolar Current (Nicol et al. 2000) is difficult to predict and is the subject of considerable ongoing debate (Hill et al. 2006).

Shorter-term natural fluctuation in seawater temperature also has implications for krill fisheries. For example, Tanasichuk (1999) has shown that *E. pacifica* production is negatively associated with El Nino Southern Oscillation (ENSO) events around Vancouver Island (Canada) presumably mediated through a decrease in overall productivity that typifies such water-warming events. Warming in relationship to other krill species is much less well researched, for example, there was nothing on the subject in the proceedings from 'The 4th International Zooplankton Production Symposium - Human and climate forcing of zooplankton populations' Hiroshima, Japan, May/June 2007.

5.2 BY-CATCH

Krill are caught in relatively fine-mesh nets that are towed slowly (approximately 2 knots) (Ichii 2000). In terms of the Antarctic fishery the main by-catch issue relates to larval fishes (Nicol and Endo 1997) particularly in the light of concerns regarding the sustainability of some Antarctic fish-stocks. There are several factors indicating that by-catch should not be an issue in krill fisheries: fishers avoid areas where there is likely to be a fish by-catch, large (targeted) krill swarms tend to be monospecific and the tow speed is sufficiently low to enable most larger organisms to escape. The issue of by-catch of fish larvae may be complicated by regional variations and it has been suggested, at least for *E. superba*, that moving krill fisheries further offshore may alleviate some potential problems (Watters 1996). Whilst the issue of by-catch remains a priority for CCAMLR and the Antarctic fishery, its relevance to the development of krill-based aquafeeds remains uncertain. Much less appears to be known with regard to by-catch issues relating to other krill species. Squid were reported as a minor by-catch by Ringo *et al* (2006) targeting *M. norvegica* and there is growing concern, particularly with regard to coastal krill fisheries (S. Nicol, personal communication, July 2007), partly a consequence of the by-catch issue.

5.3 RESPONSE OF NON-GOVERNMENTAL ORGANISATIONS

Conservation charities and pressure groups influence public perceptions with regard to the sustainability of fisheries and, consequently, the marketing of related products.

In order to assess the NGO viewpoint a number of pressure groups were contacted on the basis of their relevance to marine issues. These were the The Marine Conservation Society, The Antarctic Krill Conservation Project (http://www.krillcount.org/about.html) and WWF.

The responses of the NGOs were very similar; all expressed concerns with regard to the incipient expansion of krill fisheries, particularly in the Antarctic. The NGOs expressed the opinion that the ecosystem effects of krill fisheries were inadequately understood. Concerns were raised with regard to:

- Climate change induced reductions in krill being exacerbated by krill fishing
- Predator requirements and local depletion of krill stocks in the vicinity of land-associated predators such as seals and penguins.

The NGOs agreed that CCAMLR had predominantly adopted the correct approach in the management of the Antarctic environment. However, following the scientific community (eg Hill et al. 2006), the NGOs have concerns regarding the lack of data necessary to properly predict the effects of large-scale krill fishing. These data gaps relate to uncertainties regarding recruitment dynamics, advective processes, population size structure, predation rates and natural cycles, all of which may be further complicated by climate change. These concerns are also reflected by Greenpeace on their website (www.greenpeace.org.uk).

Other krill fisheries also raise concerns within the conservation movement. These apply particularly to Canadian and US fisheries for *E. pacifica*. Opposition to such fisheries is widespread - “last summer [2005], unusual weather resulted in low krill populations in the Pacific, and the most visible result was thousands of starved, dead sea birds washed up on Oregon, Washington, and California beaches. This tragic event underscores the delicate balance between krill and the health of our oceans” (Oceana 2005). This is likely to be exacerbated where there are concerns regarding wild fisheries, for example, Pacific salmon and northern stocks of whales which feed extensively on krill in the Gulf of St. Lawrence, Canada (Cotte and Simard 2005; Sourisseau et al. 2006) and where there is potential for extensive eco-tourism revenue.

PRACTICAL 6 KRILL COMPOSITION AND THEIR POTENTIAL FOR USE IN AQUAFEEDS

The composition of krill, including the proportions of protein, oil, minerals, chitin and fluoride, together with the degree of any contamination are pivotal factors in determining the potential value of krill as a source of aquafeeds.

There are a number of factors which influence the nutritive value of krill including species, age and gender, and the harvesting season and location. An understanding of these factors in determining the spatial and temporal quality of krill will enable fishermen to target those krill populations that have the most desirable properties.

6.1 KRILL COMPOSITION

Crustaceans, including krill, form an important natural part of the diet of many carnivorous and omnivorous fish including salmon (Storebakken 1988) and cod. It is, therefore, not surprising that such food sources offer considerable potential as sources of aquafeed to these, and similar species. Krill are a variable commodity but, as a generalisation, consist mainly of water (70 – 85%), protein (60 – 65% dry weight) and lipids (10 – 20% dry weight). In addition, there are smaller amounts of carbohydrates, chitin and salts (minerals) (Table 6). However, there are two natural components of krill, chitin and fluoride, that pose potential obstacles to their use as aquafeeds.

Table 6 – Crude compositions of various krill species

Source	Water (%)	Lipid (%)	Protein (%)	Chitin (%)	Source
E. superba	73 – 85	1.1 – 7.0 (ww)	9.9 – 17.7 (ww)	0.23 – 2.45 (ww)	Mauchline (1980)
		4.7 – 30.4 (dw)	43.0 – 76.8 (dw)	1.0 – 10.6 (dw)	Nicol et al. (1992)
		3- 36 (dw)			Falk-Petersen et al.(1981)
		up to 16 (ww)			Phleger et al. (2002)
E. pacifica	83 ± 4	0.4 – 2.4 (ww)	10.5 – 16.7 (ww)	0.22 – 0.28 (ww)	Mauchline (1980)
		1.7 – 10.4 (dw)	45.6 – 72.5 (dw)	1.0 – 1.2 (dw)	Nicol et al.(1992)
M. norvegica	81.5 ± 5	3.8 – 4.9 (ww)	6.0 – 12.5 (ww)	0.9 (ww)	Mauchline (1980)
		16.5 – 21.2 (dw)	26.0 – 54.3 (dw)	4.0 (dw)	Nicol (1992)
		40 (dw)			Mayzaud et al.(1999)
		4 – 20 (dw)			
N. australis		5.0 – 9.5 (dw)	52 (dw)	ns	Virtue et al. (1995)
Fishmeal		12	65 – 67		FAO

Values are proportion (%) of wet weights (ww) or dry weights (dw). ns – not specified

The relative proportions of these constituents vary both between species and, more significantly, between seasons particularly in high latitude species. Lipids show the highest intra- and interspecific variability in quantity and type and are particularly relevant to the potential value of krill as an aquafeed.

6.1.1 LIPIDS

Krill contain several classes of lipids. Their primary roles are in energy storage and for maintaining cellular structure (Lee et al. 2006). There has been considerable research into lipid content and metabolism in krill which is summarized in 13.1.1.2 and discussed below.

The actual lipid content of krill is dependent on a number of factors including diet and reproductive status. The roles of these factors, both of which normally relate to season, differ considerably between species allowing only a few generalisations to be made. Latitude is both positively correlated with average lipid content (Virtue et al. 1995) and variability in lipid content (Saether and Mohr 1987). This is primarily as a consequence of the greater degree of seasonality occurring with increased latitude and the krill's need for over-wintering strategies, which includes energy storage, to provide metabolic energy during periods of starvation (Falk-Petersen et al. 2000).

The different classes of lipids have different functions in different krill species. In general herbivorous species facing long periods of starvation (over long winters in high latitudes) tend to use wax-esters for energy storage (Clarke 1984) whilst omnivores species, which are generally not faced with long periods of starvation, utilise triacylglycerols for intermediate-term storage (Falk-Petersen et al. 2000) and generally do not accumulate large, long-term (wax-ester) lipid stores. Some species, such as *T. inermis,* utilize lipids stored from the previous season to fuel their reproductive effort the following season (Falk-Petersen et al. 2000). Reproductive status can have considerable consequences for lipid composition, for example female *E. superba* and *M. norvegica* can lose up to 54% of the total lipid content following spawning (Clarke 1984; Albessard and Mayzaud 2003).

Structural lipids such as cholesterol and phospholipids (which serve a dual storage and structural role in some polar krill) and essential fatty acids such as eicosapentaenoic (EPA) and docosahexaenoic acid (DHA) (Lee et al. 2006) are also found in variable, but generally high, concentrations (Table 7) making krill-oil an ideal aquafeed component.

The Antarctic krill (*E. superba)* switches feeding strategy depending on season. During the spring and summer they are exclusively herbivorous but shift to an omnivorous diet (detritus, zooplankton and sea-ice-based phytoplankton) whilst over-wintering under pack-ice (Nicol et al. 2000; Fraser and Hofmann 2003). In terms of krill fisheries, the target for *E. superba* depends on the expected market; for human consumption 'transparent' (white) krill are targeted. These krill are firm and easier to handle than their red or green coloured counterparts (Ichii 2000) and can contain 40% lipid (DW), a 10 – 20% increase on those caught earlier in the year (Hagen et al. 2001). Green *E. superba*, caught earlier in the season, are still suitable for use in the production of krill-meal (i.e. for aquafeeds) but are likely to contain less lipid potentially reducing their profitability.

N. australis, a relatively low latitude species, does not need to store energy as it is opportunistically omnivorous making use of prey and detritus other than algae during the winter (Mauchline 1980). As a consequence its lipid profile is stable (shows little seasonal variability) and is characterised by high concentrations of omega 3 fatty acids including EPA and DHA (Table 7).

Table 7 - Lipid characterisation in different krill species.

Source	Wax esters	Triacylglycerols	EPA	DHA	Notes and reference
Function	Long-term storage	medium and short term storage	Cell membrane integrity		General introduction Lee et al. (2006)
M. norvegica	low	ca. 20	21 – 38	9 - 21	Mayzaud et al.(1999) Falk-Petersen et al.(2000).
E. superba	<1% (Clarke 1984)	Moderate levels	19% (combined)		Falk-Petersen et al.(2000) (winter caught krill, Kolakowska et al. 1994)
			15-21	9-14	Phleger et al.(2002)
E. pacifica	Similar to *E. superba*	Similar to *E. superba*	23	14	Generally similar to *E. superba* but higher EPA and DHA (Yamada (1964) cited in Nicol 2000)
T. inermis	High, use for reproductive purposes.	no data	no data	no data	Falk-Petersen et al (2000)
*N. australis*1	68 – 86	5 – 21	17 – 37	11 - 25	Virtue et al. (1995)

Note: figures represent % of total lipid except EPA and DHA which are % of total fatty acids

.

Post-capture lipid stability is an important consideration in converting krill into aquafeeds. Post-mortality lipid profiles change rapidly with, *inter alia*, the rapid liberalization of undesirable free fatty-acids. However, as Nicol (2000) comments, krill lipids are more stable compared to their fish counterparts and deterioration can be effectively controlled by rapid post-capture freezing to sufficiently low temperatures.

6.1.2 PROTEINS

Protein makes up approximately 10 to 20% wet weight of krill (Table 6). Whilst there is considerable variation in protein content, in general krill-meal contains approximately 10% less protein (and higher concentrations of ash and salt) compared with fishmeal (Olsen et al. 2006).

Krill and fishmeal are both excellent sources of protein for farmed fish and contain all the essential amino acids (Table 8). It seems unlikely, and there is no literature to the effect, that significant changes in the amino acid composition will occur through the seasons or, broadly speaking, as a function of species.

Table 8 - Essential amino acid content) in *E. superba* meal compared with fishmeal.

Amino acid	Fishmeal	Krill-meal
Arginine	7.0	6.8
Histidine	2.7	2.2
Isoleucine	5.0	5.2
Leucine	8.7	7.9
Lysine	5.7	5.8
Methionine	3.3	3.0
Phenylalanine	39*	3.8
Threonine	4.9	4.9
Valine	5.7	5.4

(Source: Olsen et al. 2006). * - this is assumed to be a typographical error and should be 3.9. Values represent percentage of total protein.

The proportion of body mass comprising protein will change over seasons, both proportionately as krill store and utilize lipids, and in absolute terms through the catabolism of proteins to provide metabolic energy (e.g. in *E. superba* McGaffin et al. 2002). Whilst this might reduce the average size of *E. superba* early in the season it is likely to be less relevant than lipid content and colour in determining the value/marketability of krill products. This is because catching sufficient krill is not often a factor limiting fishery profitability, at least when targeting *E. superba* (Ichii 2000).

6.1.3 PIGMENTS

Many marine crustacea, including krill, naturally contain high levels of carotenoid pigments which, when transferred up the food chain, impart a red or pink colour to their predators which include salmon (Arai et al. 1987). Farmed salmon are fed diets that are supplemented with carotenoid pigments (generally astaxanthin) in order to impart a 'natural' colouring to the product. The utilisation of krill (*E. pacifica*) as a source of aquafeeds in Japan is based, at least in part, on the beneficial colouration they impart to cultured species that include red sea bream (*Pagrus major*), coho salmon (*Oncorhynchus kisutch*), rainbow trout (*Salmo gairdnerii*) and yellowtail (*Seriola quinqueradiata*) (Nicol and Endo 1997).

Pigments are an expensive component of fish-feeds, typically comprising 15 – 20% of the overall feed price (Forsberg and Guttormsen 2006). The presence of high concentrations of naturally occurring pigments in both krill-meal and krill-oil confers economic advantages to its inclusion in aquafeeds. Salmonid grow-out diets contain astaxanthin at concentrations of between 20 – 70 mg kg^{-1} (Forsberg and Guttormsen 2006). Krill-meal contains pigment concentrations at at least this level (

Table 9).

Table 9 - Pigment concentrations in various krill species.

Source	Astaxanthin (mg kg^{-1}) dw	Reference and notes
Fishmeal	Nil	Olsen et al. (2006)
Aquafeeds	20 – 70	Forsberg and Guttormsen (2006)
E. superba	95 (as esters) 5 (free)	Krill-meal (Olsen et al. 2006)
	150 -200	Nicol et al. (2000)
E. pacifica	Higher than *E. superba*	Nicol et al. (2000)
N. australis	171 (44 as canthaxanthin)	Virtue (1995)

Given the high cost of pigments targeting krill containing high astaxanthin levels is of obvious commercial relevance. Further understanding of the factors determining pigment concentrations in krill is required in order to focus fishing effort appropriately.

6.1.4 CHITIN

Chitin, a tough, structural polysaccharide derived from N-acetylglucosamine, is located in the krill's exoskeleton. It is relatively non-labile and resists digestion by salmon Olsen et al (2006) reports chitin making up 4.3% of krill-meal produced using a pilot meal-production plant. Chitin is not toxic to salmon, nor does it (or any derivatives) bioaccumulate in salmon flesh, but it does reduce the digestibility of the feed, possibly by increasing the rate of passage of food through the digestive tract or because it ionically binds to lipids reducing their availability to lipases (Olsen et al. 2006). Chitin is, therefore, associated with decreased food conversion rates in salmon.

Chitin, however, does confer some advantages to dietary formulations, at least for salmon. Olsen et al (2006) quoting Ringo (paper in preparation) notes that chitin may beneficially affect the balance of gut microbiota and act as a pre-biotic by selecting for autochthonous bacteria that help prevent the growth of pathogenic bacteria. It may also act as an immunostimulant (Sakai 1999).

Chitin, and its monomer chitosan, are useful products in their own right and there is considerable interest in sourcing chitin from krill for use in the manufacture of products as diverse as food thickeners and medical thread (Wilkipaedia, accessed June 2007). Whilst not directly related to aquafeeds chitin may, in the future, be sourced from krill increasing fishery profitability and the likelihood of other krill products entering the aquafeed industry.

6.1.5 FLUORIDE

Fluorine is present at relatively low concentrations in seawater (around 1.2 – 1.5 mg l^{-1}) mostly in the form of the fluoride ion (F^-) and magnesium fluoride (MgF^+) (Chester 1990). The euphausiids, as a group, naturally accumulate high concentrations of fluoride (Nicol and Stolp 1991) (Table 10), a discovery that led to the rapid decline in the fishery during the early 1980s (Nicol and Endo 1997). The concentration of fluoride in krill is highly variable, particularly between different body parts (Table

10). The reason why krill bioaccumulate fluoride and its chemical form remain unknown (Nicol 2000).

In living krill the fluoride is concentrated in the exoskeleton but, once harvested (dead), particularly following rough treatment, the fluoride rapidly leaches into the flesh. Fluoride contamination is currently minimised through rapid and efficient shelling following capture or freezing to temperatures below -30 C (Nicol 2000).

When fed to vertebrates fluoride, whether present in excess or at background concentrations, tends to accumulate in bone tissue where it can reach toxic levels. Animals that normally consume large quantities of krill have adaptations to the high fluoride content, for example fin whales accumulate it to concentrations of around 18,500 ppm in their bones (Landy et al. 1991) with seemingly no ill effect while some krill-predating penguins shed their stomach linings possibly as a consequence of the ingestion of high concentrations of fluoride (Beintema 1991). The inclusion of calcium in feeds containing high levels of fluoride reduces adsorption (and therefore toxicity) in mammals (Tenuta and Alvarenga 1999) but this should not be necessary, at least for salmon, as fish are very tolerant of fluoride, sequestering it to high levels in skeletal material where it is effectively isolated with no ill effect (Julshamn et al. 2004).

The current EU limit for fluoride in stock material destined for inclusion into animal feeds (including aquafeeds) is 3000 mg kg^{-1} (based on 88% dry matter) (Moren et al. 2006) whilst the maximum level allowed in diets has been set at 150 mg kg^{-1} (Moren et al. 2006). If krill-meal contains 3000 mg kg^{-1} fluoride then the maximum percentage that could be included in fish diets, under current EU regulations, is 5%.

Table 10 – Fluoride content of various krill species/ body parts

Source	Fluoride (mg kg^{-1} dw)	Notes and reference
E. superba	13,000	Mouthparts(Sands et al. 1998)
	2,232	Exoskeleton (Sands et al. 1998)
	96	Muscle (Sands et al. 1998)
	1160	Whole body (Moren et al. In press)
E. pacifica	no data	no data
E. crystallorophias	5,477	Exoskeleton (Sands et al. 1998)
M. norvegica	3,300	(Adelung et al. 1987)
N. australis	1,556	Highly variable (Virtue et al. 1995)
T. inermis	780	Whole body (Moren et al. In press)
T. macrura	5,100	Exoskeleton (Sands et al. 1998)
	257	Muscle (Sands et al. 1998)

6.2 CONTAMINANTS

Krill, like many marine plankters, have the capacity to bioaccumulate chemicals to a level far exceeding that found in their environment. There are two chemical groups of particular relevance to the current review. These are trace metals (which occur naturally in their environment) and anthropogenically derived persistent organic pollutants (POPs). The accumulation of these compounds, and the resultant high concentrations in krill derived products, may limit the potential for krill as a source of aquafeed.

6.2.1 TRACE METALS

The issue of fluoride contamination, derived from krill, somewhat obscured other issues pertaining to potential krill contaminants (Moren et al. 2006). Zooplankton have been shown to accumulate various heavy metals including copper, zinc, arsenic, cadmium, mercury and lead (Petri and Zauke 1993). These trace metals are thought to be derived from naturally enriched upwelling water that typifies many highly productive parts of the oceans where krill are fished (Petri and Zauke 1993).

Krill are considered to be particularly prone to contamination with cadmium and copper; *E. superba* being considered to be the main vector for cadmium into certain Antarctic food chains (Nygard et al. 2001). The concentrations of copper, zinc, arsenic, cadmium, mercury and lead found in two krill species and an amphipod (also considered to have some potential as an aquafeed source) and are shown in
Table 11, alongside values for a fishmeal and current (2006) EU limits on heavy metal contamination in both feedstocks and actual feeds.

Table 11 – Trace metal concentrations (mg kg^{-1}) in krill and krill based feeds

Source	Cu	Zn	As	Cd	Hg	Pb
Fish-feed[1]	4	80	14	0.19	0.08	0.09
E. superba[1]	46	51	4	0.61	0.008	0.09
E. superba [2]	29 – 54	41- 68		0.7 – 1.9		0.2 – 1.5
E. pacifica[2]		96 - 195		0.2 -2.2		
M. norvegica[2]	66 -72	97 - 104		0.3 – 1.3		
T. inermis[1]	22	81	9.4	1.4	0.009	0.22
EU's upper limit (feedstocks)[1]	25	200	15	2	0.5	10
EU's upper limit (complete feed)[1]	25	200	6	1	0.1	5

(Source: 1 - Moren et al. 2006, based on 100% krill substituted feeds (840 g kg-1 krill-meal); 2 - Petri and Zauke (1993), results from homogenised whole krill)

The data shown in
Table 11 indicate that meal derived from Antarctic krill may exceed EU feedstock copper limits (Moren et al. 2006). However, in salmon diets there is a nutritional requirement for copper and fishmeal-based diets are supplemented with bioavailable copper in many formulations (D. Lowe, personal communication, April 2007). Whilst a change in the EU regulatory framework may be required before krill could be used in high proportions in aquafeeds, there should be no need to reduce it from a fish husbandry /welfare perspective.

6.2.2 PERSISTENT ORGANIC POLLUTANTS

Persistent organic pollutants consist of a wide range of non-labile anthropogenic chemicals including polyaromatic hydrocarbons, flame retardants and polychlorinated biphenyls.

These lipid soluble compounds are transferred up the food chain and accumulate, to levels that cause concern, in predators including salmon (Jacobs et al. 2002).

Like a majority of plankton, the concentration of POPs present in krill reflects those in the body of water in which they have grown. The Antarctic ocean is one of the most pristine areas in the globe (Cripps 1992), and the pollutant load in Antarctic krill is much lower compared with fish-oil and aquafeeds in general (Corsolini et al. 2002) (

Table 12). The lack of contamination, particularly in the face of growing concerns regarding the contamination of oily fish, is another advantage to using krill in the production of aquafeeds.

Table 12 – Level of POPs present in fish-oil, salmon feeds and krill

Source	PCB	HCB	HCH	Reference
E. superba[1]	1.9	0.2	0.37	Corsolini et al (2002)
Fish oil[2]	8.8 – 225.5	2.5 +/-1.5	10+/-7	Jacobs et al. (2002)
Aquafeeds[2]	75.6 – 1153.2	9.2 +/-2.9	23.7+/-14.9	Jacobs et al. (2002)

1 – ng g^{-1} wet weight. 2 - ng g^{-1} present in lipid
PCB – polychlorinated biphenyl; HCB hexachlorbenzene; HCH – hexachlorohexane. 1 – includes HCB and DDE

It is likely that krill harvested from other oceans, particularly the northern hemisphere (e.g. *E. pacifica* and *T. norvegica*) are likely to exhibit higher levels of contamination, compared to *E. superba*, particularly where harvested close to sources of pollution. However, given the lack of relevant literature this remains speculative.

6.3 THE POTENTIAL FOR KRILL AS AN AQUAFEED

The development of krill fisheries, particularly in the Antarctic, during the 1970s and 80s, led to a considerable volume of research looking at the possibility of using krill products as an aquafeed (Storebakken 1988). However, the high-quality, suitability and then cost-effectiveness of fishmeal and oil available to the burgeoning aquaculture sector, and the discovery of fluoride in krill products, effectively blocked further research into the potential for krill (Ringo et al. 2006). It is only relatively recently that, with demand for fishmeal and oil outgrowing supply, further research has been initiated (Ringo et al. 2006).

There are two main issues relating to the substitution of fishmeal and/or fish-oil with krill products. These are animal health (including growth rates and immune system) and product quality (colour, taste, texture, smell, etc). Both these aspects have been addressed during recent research, are summarised in 13.1.1.2 and 13.1.1.3, and discussed below.

Research into the use of krill in aquafeeds has concentrated on the use of krill-meal as an alternative source of protein and there is less information with regard to the replacement of fish-oil with krill-oil. However, research has indicated that salmon utilise the wax-esters oil from other crustaceans, e.g. *Calanus finmarchicus*, effectively (Olsen et al. 2004) and there is no evidence that krill-oil is anything but an excellent source of lipids for aquafeeds.

Krill-meal is an excellent substitute for fishmeal for salmon. Research predominantly reports either no difference between krill and fishmeal or krillmeal as being superior. For example, whilst Ringo et al. (2006) found no difference in the growth rate between fish-based and 50% krill substituted diets, Olsen et al. (2006) observed that moderate (20 – 60%) amounts of fishmeal substitution using krill-meal resulted in an increase in the initial growth rate of salmon. This increase in growth rate was attributed to the attractant properties of krill-meal but other research has indicated that it may be as a consequence of the presence of growth promoting factors (steroids) originating in the krill’s cephalothorax (Nicol and Endo 1997).

Yoshitomi et al (2006) found that krill substitution, above 15%, resulted in a decrease in growth rates of trout, which was attributed to the correlation between krill substitution and bone fluoride concentration. In further work, using low-fluoride krill-meal, similar growth was shown between 100% substituted diets and control diets (Yoshitomi et al. 2007). However, other research, on salmon, has indicated that chitin, derived from the krill's exoskeleton and, therefore correlated with fluoride, may be responsible for decreased growth rates at high inclusion levels, through aiding the passage of food through the gut or by reducing lipid adsorbtion (Olsen et al. 2006). Changes in gut-flora have been recorded following the utilisation of krillmeal substituted feeds but with no effect on growth rates (Ringo et al. 2006).

The use of krill (*E. pacifica*) as a food source has also contributed to increased disease resistance in hatchery reared salmon smolts (Haig-Brown 1994 cited in Nicol and Endo 1997). This has been attributed to the improved early development of the immune system when using krill as a food source.

Product quality is critical to maintaining the consumer base and several recent studies have examined the effects on product quality following a change to krill-substituted diets.

Olsen et al. (2006) reported negligible differences in flesh quality (% dry weight and lipid quality) between salmon fed krill substituted diets and controls. Following on from this, and in an intensive study examining several aspects of the quality of salmon fed krill substituted diets, Suontama et al (2007) reported that in terms of taste, odour, colour and texture there were only minor, and unimportant, differences between fish fed krill substituted diets (40% *E. superba* and 60% *T. inermis*) and fish based controls.

The similarity in sensory attributes between fish fed fish-based and krill-substituted diets was also found by Karlsen (2006) working with cod. Here, the objective was to ascertain whether krill-based diets could be used to make farmed cod taste and look more like wild cod. It was found that, again, a majority of the sensory attributes were similar between both groups with the exception of an increased yellow and white hue in the flesh of krill-fed fish. Karlsen (2006) also observed an increase in the red skin hues of krill-fed fish, compared with controls, a factor attributed to the high levels of astaxanthins in krill-meal.

In summary, whilst there are slight differences in krill and fishmeal the literature indicates there are no fish-husbandry reasons why significant substitution of fishmeal by krill-meal in salmonid and cod diets should not occur.

PRACTICAL 7 KRILL FISHERY ECONOMICS

The economic viability of salmon farming (and krill as source of aquafeeds) depends on what the market is prepared to pay for the product. The following summarises the sequence (supply chain) through which prices are determined:

1. Consumers determine the upper price level for aquaculture products.
2. Fish-farmers determine the upper price level they are willing pay for aquafeeds (and other supplies and services).

3. Aquafeed manufacturers determine (normally using least cost formulae) the maximum price they are willing to pay for aquafeed ingredients, including protein and oil sources.
4. Protein and oil manufacturers determine the price levels they are willing to pay for the various fish species and fish offals available as raw material.
5. Fishermen determine the price levels for raw fish at which they are willing to harvest 'fishmeal' species.
(New and Wijkstrom 2002).

Krill must be acceptable to consumers and profitable at each stage in the supply chain before it can make a substantive contribution to aquafeed supplies.

There are no technical or fish-husbandry reasons why krill cannot be used extensively to replace a large proportion of fishmeal and fish-oil in aquafeeds. The lack of penetration by krill into this sector is because it is not currently profitable. In order for krill to become more competitive the price differential, between krill and fishmeal/oil, has to drop. The Antarctic fishery has by far the greatest potential to deliver the volume of krill required to make a substantial contribution to aquafeed supplies. Other fisheries, particularly those in coastal regions, are unlikely to expand markedly primarily because of conservation fears and because the standing stock could not sustain a high-volume fishery (S. Nicol, personal communication, June 2007).

The price differential between krill and fishmeal is decreasing, primarily because the fishmeal price is increasing (Figure 2).

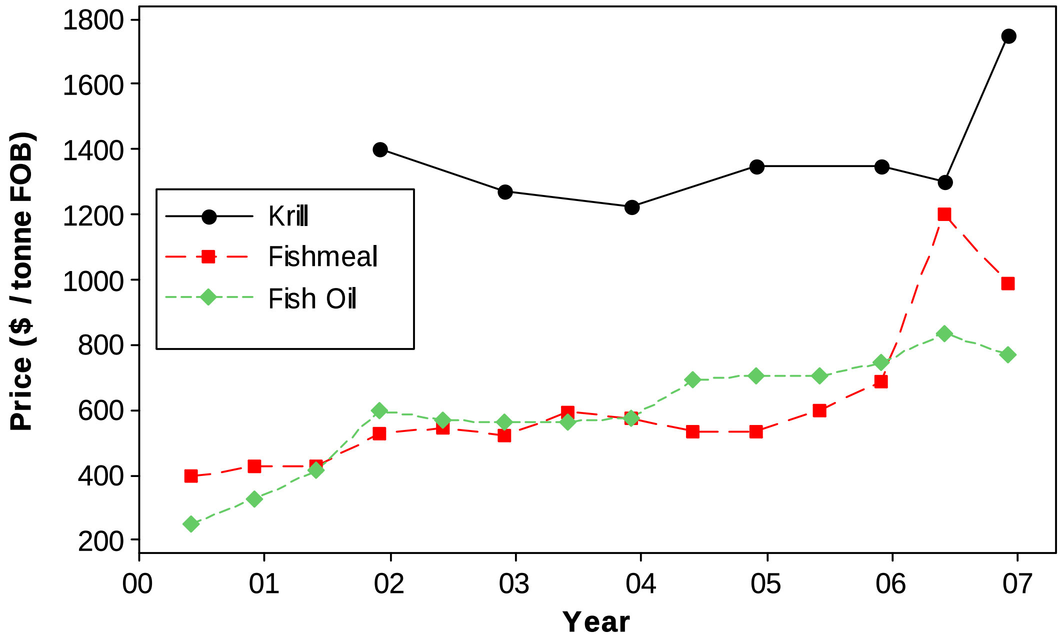

Figure 2 – Price trends (June 2000 to December 2006) in fishmeal and fish-oil.

(Source: for fishmeal and fish-oil (FOB Peru), A. Jackson, personal communication, June 2007. Estimates of krill prices from P. Guzman, personal communication, June 2007).

According to New (2002) krill-meal was, in 2001, approximately twice as expensive as fishmeal (Japanese market). This is less than the difference in price shown in Figure 2 (US market) for that period and more closely reflects the price differential at mid 2007 prices.

It is unlikely that the supply of fishmeal and oil can increase significantly as existing forage fisheries are fully exploited. The price of these commodities is, therefore, likely to increase unless suitable replacements are found which reduce demand. In the case of aquafeeds, there is already extensive vegetable substitution into existing formulations. This has already stabilised the price of fishmeal and fish-oil (P. Morris, personal communication, June 2007). The extent to which vegetable substitution will modify demand, in the face of an overall growing demand from the aquaculture sector, will determine the price of fishmeal and oil and the likely profitability of alternative (including krill) fisheries. New and Wijkstrom (2002) maintain that krill-catching-technology will improve and that increased demand will, at some point, make krill fisheries profitable. They test the scenario where fishmeal prices reach \$1100 $tonne^{-1}$ by 2015 (double the 2000 prices) and conclude that this should not (by 2015) necessarily increase the farm-gate salmon-product price through improvements in food conversion rate and increased substitution. New and Wijkstrom (2002) suggest that at a price of \$1100 $tonne^{-1}$ the inclusion of krill may become economically viable. However, from discussions with feed producers, krill remains uneconomic for inclusion in bulk feeds (D. Rowe, EWOS, personal communication, May 2007) even though fish-meal prices reached \$1100 per tonne (Figure 2) well before the projected 2015 used by New and Wijkstrom (2002). It is difficult to predict the price at which fishmeal prices will stabilise (i.e. where increased price reduces demand) though the Commercial Director of the IFFO said that a price of US\$1000 tonne FOB (Peruvian) fishmeal, is a “reasonable” level (IFFO 2007). If fishmeal prices do stabilse at this level then krill may become of borderline economic viability through technological developments reducing krill fishery costs.

PRACTICAL 8 DATA GAPS

There are several unknowns related to the potential for krill to make a substantial contribution to global aquafeed supplies. These often related questions are separated into four groups here: environmental, economic, consumer and regulatory.

ENVIRONMENTAL

1. What are the long-term consequences for krill populations under scenarios of continued global warming?
2. Is our understanding of the ecosystem consequences of an expansion of krill fisheries sufficient to protect the environment?
3. What is the temporal and spatial variation in POP content in any krill species considered for use in the production of aquafeeds?

ECONOMIC

The economic issues likely to influence the viability of krill fisheries are numerous and complex. The following questions should be considered prior to forecasting any expansion in krill fisheries.
1. Will the Chinese economy, particularly their aquaculture industry, continue to grow at current rates, increasing demand (and price), for aquafeeds?
2. Is the development of non-aquafeed products from krill fisheries (i.e. pharmaceutical and industrial) likely to increase fishery viability? This includes an evaluation of the potential profitability of chitin.
3. How will the biofuel industry influence vegetable oil prices?
4. What are the additional fuel costs associated with krill fishing and how susceptible is the fishery to increases in fuel-oil costs?
5. To what extent will krill fishing costs be reduced by technological innovation?
6. What economic advantages does the high natural pigment level in krill meal and oil confer?

CONSUMER

Consumer (or supermarket) acceptability will, ultimately, determine whether krill can be used as a source of aquafeeds. There are several issues relating to the consumer that require further study.
1. To what extent will NGO opposition to krill fisheries, be reflected in reduced demand?
2. Will substantial replacement of fishmeal by krill by non-UK farmers (e.g. Chile, China) have consumer implications for Scottish salmon?

REGULATORY

There are several regulations, particularly under the EU, that influence the likely profitability of krill fisheries. Some of these regulations apply directly to krill, others apply to broader feed issues.
1. Will changes in discard regulations in the EU fishery make a substantial increase to the supply (and decrease the cost) of fishmeal and oil?
2. Will relaxation of EU restrictions on the inclusion of animal by-products (meat render products) occur and will this reduce demand for fishmeal and oil?
3. Will feedstock/feed upper limits on fluoride and copper be lifted (assuming a sufficiently robust scientific case can be made)?

PRACTICAL 9 REALISTIC POSSIBILITIES

The prediction of the development of krill fisheries has exercised experts in krill population biology and fishery economics for decades – whether the long awaited ‘explosion’ in the fishery occurs is under the control of basic market forces and recent forecasts as to likely developments are not currently available.

Given the recent interest from Norwegian companies (notably Aker BioMarine) it is reasonable to speculate that fishing for Antarctic krill is considered potentially profitable enough to offset the considerable risk in operating in Antarctic waters.

Initially, the main profit is likely to be derived from krill-oil sold into the nutraceutical market. However, krill-meal, containing a proportion of oil, may not only be a 'by-product' from krill-oil fisheries available to the aquafeed industry but may also lead to technological innovation reducing fishing costs and allowing further fishery expansion.

A bulk of the UK's salmon is sold in supermarkets and a majority of these have ethical buying policies. Whether krill substitution is perceived as ethical will, to some extent, depend on the NGOs and other pressure groups. Currently these groups are rallied against the development of krill fisheries.

If krill fisheries developed, increased supply would reduce the price of fishmeal and have beneficial consequences for UK fish-farmers. The strategy may, therefore, be to substitute fishmeal for krill-meal in those areas, such as Chile, where there is likely to be less resistance from the consumer. The wide-scale adoption of krill substituted diets in such countries may have profound implications for UK aquaculture by affecting commodity prices.

PRACTICAL 10 CONCLUSIONS

The following aspects of krill make them a potentially significant contributor to global aquafeed supplies:

- Krill are a massive resource and consist of high quality protein and oil
- Krill can be used directly, or processed into products, that are ideal for use in a broad range of aquafeeds
- Salmon and cod grow at least as well on krill diets compared with traditional fish-based diets
- Krill can be used as an feed attractant, making highly vegetable substituted diets more acceptable to fish
- Krill based diets more confer immunological advantages to fish
- Krill contain high concentration of astaxanthins making them particularly useful in finishing (grow-out) diets
- There are no substantive product quality (taste/texture) issues in salmon or cod that have been reared using krill based diets
- Neither the fluoride or copper content of krill meals are issues from a fish husbandry or product quality perspective

There are a number of issues that need to be addressed before krill fisheries can develop. These include:

- The scope for technological innovation to reduce the unit price of krill
- The potential ecological implications of an expanding fishery, particularly in combination with other threats such as climate change
- The extent to which future market price for fishmeal and oil, and vegetable and fuel oil will determine krill fishery viability
- Consumer acceptability of fish fed krill substituted diets
- The potential for change in EU legislation with regard to animal feedstocks so that krill fluoride or copper content will not limit krill inclusion in fish-feeds.

PRACTICAL 11 RECOMMENDATIONS FOR FUTURE RESARCH

There is currently a pressing need to evaluate the economic potential for a large-scale development of krill fisheries. This economic appraisal should take into consideration the issues raised in §Practical 8and make projections concerning the following:

- Price/demand for fishmeal and oil
- Price/demand for krill-meal and oil
- Price/demand for fuel oil and (probably related), vegetable oil
- Influence of technological innovation on the likely price of krill
- Consumer acceptability of krill based aquaculture

Such an economic model would assist the fish-farming industry by predicting likely changes in both fishmeal and fish oil prices and the likelihood of the extent, if any, of a switch to krill.

PRACTICAL 12 REFERENCED LITERATURE AND ELECTRONIC SOURCES

AAD (2007) A time to krill. http://www.aad.gov.au/default.asp?casid=1143 Accessed: July 2007

Adelung D, Buchholz F, Culik B, Keck A (1987) Fluoride in tissues of krill Ephausia superba (Dana) and Meganyctiphanes norvegica (m Sars) in relation to the moult cycle. Polar Biology 7: 43-50.

Albessard E, Mayzaud P (2003) Influence of tropho-climatic environment and reproduction on lipid composition of the euphausiid Meganyctiphanes norvegica in the Ligurian Sea, the Clyde Sea and the Kattegat. Marine Ecology-Progress Series 253: 217-232.

Anon (2005) South Georgia Newsletter. http://www.sgisland.org/pages/main/news25.htm Accessed: June 2007

Arai S, Mori T, Miki W, Yamaguchi K, Konosu S, Satake M, Fujita T (1987) Pigmentation of juvenile coho salmon with carotenoid oil extracted from antarctic krill. Aquaculture 66: 255-264.

Atkinson A, Siegel V, Pakhomov E, Rothery P (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432: 100-103.

Bargu S, Powell CL, Coale SL, Busman M, Doucette GJ, Silver MW (2002) Krill: a potential vector for domoic acid in marine food webs. Marine Ecology-Progress Series 237: 209-216.

Bates Q (2007) Krill ship switch Vol 46, No. 5. May 2007 p 1 - 2

Beck H, Koops H, Tiews K, Gropp J (1977) Further possibilities to replace fish-meal in rainbow-trout feeds - replacement of fish-meal by alkane yeast and krillmeal. Archiv Fur Fischereiwissenschaft 28: 1-17.

Beintema AJ (1991) Penguins shed stomach linings. Nature 352: 480-481.

Buchholz F, Pradofiedler R (1987) Studies on the seasonal biochemistry of the northern krill *Meganyctiphanes norvegica* in the kattegat. Helgolander Meeresuntersuchungen 41: 443-452.

Chester R (1990) Marine Geochemistry. 1. Oceans. Chemical composition & chemical properties. Unwin Hyman Ltd., London

Clarke A (1984) Lipid-content and composition of Antarctic krill, *Euphausia superba* (Dana). Journal of Crustacean Biology 4: 285-294.

Clarke A, Murphy EJ, Meredith MP, King JC, Peck LS, Barnes DKA, Smith RC (2007) Climate change and the marine ecosystem of the western Antarctic Peninsula. Philosophical Transactions of the Royal Society B-Biological Sciences 362: 149-166.

Constable AJ, Nicol S (2002) Defining smaller-scale management units to further develop the ecosystem approach in managing large-scale pelagic krill fisheries in Antarctica. Ccamlr Science 9: 117-131.

Corsolini S, Romeo T, Ademolla N, Greco S, Focardi S (2002) POPs in key species of marine Antarctic ecosystem. Microchemical Journal 73: 187-193.

Cotte C, Simard Y (2005) Formation of dense krill patches under tidal forcing at whale feeding hot spots in the St. Lawrence Estuary. Marine Ecology-Progress Series 288: 199-210.

Cripps GC (1992) Natural and anthropogenic hydrocarbons in the Antarctic marine-environment. Marine Pollution Bulletin 25: 266-273.

Cripps GC, Atkinson A (2000) Fatty acid composition as an indicator of carnivory in Antarctic krill, Euphausia superba. Canadian Journal of Fisheries and Aquatic Sciences 57: 31-37.
Croxall JP, Nicol S (2004) Management of Southern Ocean fisheries: global forces and future sustainability. Antarctic Science 16: 569-584.
Demer DA (2004) An estimate of error for the CCAMLR 2000 survey estimate of krill biomass. Deep-Sea Research Part Ii-Topical Studies in Oceanography 51: 1237-1251.
Ducklow HW, Baker K, Martinson DG, Quetin LB, Ross RM, Smith RC, Stammerjohn SE, Vernet M, Fraser W (2007) Marine pelagic ecosystems: The West Antarctic Peninsula. Philosophical Transactions of the Royal Society B-Biological Sciences 362: 67-94.
Everson I (2000) Chapter 1. Introducing Krill. In: Everson I (ed) Krill: biology, ecology and fisheries. Blackwell Science Ltd, pp
Falk-Petersen S, Gatten RR, Sargent JR, Hopkins CCE (1981) Ecological investigations on the zooplankton community in Balsfjorden, northern Norway - seasonal-changes in the lipid class composition of Meganyctiphanes norvegica (m-Sars), Thysanoessa raschii (m-Sars), and Thysanoessa inermis (Kroyer). Journal of Experimental Marine Biology and Ecology 54: 209-224.
Falk-Petersen S, Hagen W, Kattner G, Clarke A, Sargent J (2000) Lipids, trophic relationships, and biodiversity in Arctic and Antarctic krill. Canadian Journal of Fisheries and Aquatic Sciences 57: 178-191.
FAO (2007) Species fact sheet -Euphausia superba Dana, 1852. http://www.fao.org/fi/website/FIRetrieveAction.do?dom=species&fid=3393 Accessed: June 2007
Forsberg OI, Guttormsen AG (2006) Modeling optimal dietary pigmentation strategies in farmed Atlantic salmon: Application of mixed-integer non-linear mathematical programming techniques. Aquaculture 261: 118-124.
Fraser WR, Hofmann EE (2003) A predator's perspective on causal links between climate change, physical forcing and ecosystem response. Marine Ecology-Progress Series 265: 1-15.
Fricke H, Gercken G, Schreiber W, Oehlenschlager J (1984) Lipid, sterol and fatty-acid composition of Antarctic krill (Euphausia-superba dana). Lipids 19: 821-827.
Hagen W, Kattner G, Terbruggen A, Van Vleet ES (2001) Lipid metabolism of the Antarctic krill Euphausia superba and its ecological implications. Marine Biology 139: 95-104.
Hill SL, Murphy EJ, Reid K, Trathan PN, Constable AJ (2006) Modelling Southern Ocean ecosystems: krill, the food-web, and the impacts of harvesting. Biological Reviews 81: 581-608.
Hofmann EE, Murphy EJ (2004) Advection, krill, and Antarctic marine ecosystems. Antarctic Science 16: 487-499.
Ichii T (2000) Chapter 9. Krill harvesting. In: Everson I (ed) Krill: biology, ecology and fisheries. Blackwell Science Ltd, pp
IFFO (2007) A future price does not exist. http://www.iffo.net/default.asp?fname=3&url=74&sWebIdiomas=1 Accessed:
Jacobs MN, Covaci A, Schepens P (2002) Investigation of selected persistent organic pollutants in farmed Atlantic salmon (Salmo salar), salmon aquaculture feed, and fish oil components of the feed. Environmental Science & Technology 36: 2797-2805.

Julshamn K, Malde MK, Bjorvatn K, Krogedal P (2004) Fluoride retention of Atlantic salmon (Salmo salar) fed krill meal. Aquaculture Nutrition 10: 9-13.

Karlsen O, Suontama J, Olsen RE (2006) Effect of Antarctic krillmeal on quality of farmed Atlantic cod (Gadus morhua L.). Aquaculture Research 37: 1676-1684.

Kolakowska A, Kolakowski E, Szczygielski M (1994) Winter season krill (*Euphausia superba* d) as a source of n-3 polyunsaturated fatty-acids. Nahrung-Food 38: 128-134.

Landy RB, Lambertsen RH, Palsson PA, Krook L, Nevius A, Eckerlin R (1991) Fluoride in the bone and diet of fin whales, Balaenoptera physalus. Marine Environmental Research 31: 241-247.

Lascara CM, Hofmann EE, Ross RM, Quetin LB (1999) Seasonal variability in the distribution of Antarctic krill, Euphausia superba, west of the Antarctic Peninsula. Deep-Sea Research Part I-Oceanographic Research Papers 46: 951-984.

Lee RF, Hagen W, Kattner G (2006) Lipid storage in marine zooplankton. Marine Ecology-Progress Series 307: 273-306.

Lindsay GJH, Gooday GW (1985) Chitinolytic enzymes and the bacterial microflora in the digestive-tract of cod, Gadus morhua. Journal of Fish Biology 26: 255-265.

Mauchline J (1980) The biology of mysids and euphausiids. Advances in Marine Biology 18: 1 - 681.

Mayzaud P, Albessard E, Cuzin-Roudy J (1998) Changes in lipid composition of the Antarctic krill Euphausia superba in the Indian sector of the Antarctic Ocean: influence of geographical location, sexual maturity stage and distribution among organs. Marine Ecology-Progress Series 173: 149-162.

Mayzaud P, Virtue P, Albessard E (1999) Seasonal variations in the lipid and fatty acid composition of the euphausiid Meganyctiphanes norvegica from the Ligurian Sea. Marine Ecology-Progress Series 186: 199-210.

McGaffin AF, Nicol S, Ritz DA (2002) Changes in muscle tissue of shrinking Antarctic krill. Polar Biology 25: 180-186.

Moren M, Malde MK, Olsen RE, Hemre GI, Dahl L, Karlsen O, Julshamn K (In press) Fluorine accumulation in Atlantic salmon (Salmo salar), Atlantic cod (Gadus morhua), rainbow trout (Onchorhyncus mykiss) and Atlantic halibut (Hippoglossus hippoglossus) fed diets with krill or amphipod meals and fish meal based diets with sodium fluoride (NaF) inclusion. Aquaculture

Moren M, Suontama J, Hemre GI, Karlsen O, Olsen RE, Mundheim H, Julshamn K (2006) Element concentrations in meals from krill and amphipods, - Possible alternative protein sources in complete diets for farmed fish. Aquaculture 261: 174-181.

Murphy EJ, Watkins JL, Trathan PN, Reid K, Meredith MP, Thorpe SE, Johnston NM, Clarke A, Tarling GA, Collins MA, Forcada J, Shreeve RS, Atkinson A, Korb R, Whitehouse MJ, Ward P, Rodhouse PG, Enderlein P, Hirst AG, Martin AR, Hill SL, Staniland IJ, Pond DW, Briggs DR, Cunningham NJ, Fleming AH (2007) Spatial and temporal operation of the Scotia Sea ecosystem: a review of large-scale links in a krill centred food web. Philosophical Transactions of the Royal Society B-Biological Sciences 362: 113-148.

Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MCM, Clay J, Folke C, Lubchenco J, Mooney H, Troell M (2000) Effect of aquaculture on world fish supplies. Nature 405: 1017-1024.

New MB, Wijkstrom UN (2002) Use of fishmeal and fish oil in aquafeeds: Further thoughts on the fishmeal trap. FAO Fisheries Circular No. 975 FIPP/C975 ISSN 0429-9329: 1 - 71.

Nicol S (2000) Chapter 10. Products dervied from Krill. In: Everson I (ed) Krill: biology, ecology and fisheries. Blackwell Science Ltd, pp

Nicol S (2003) Living krill, zooplankton and experimental investigations: A discourse on the role of krill and their experimental study in marine ecology. Marine and Freshwater Behaviour and Physiology 36: 191-205.

Nicol S (2006) Krill, currents, and sea ice: Euphausia superba and its changing environment. Bioscience 56: 111-120.

Nicol S, Endo Y (1997) Krill fisheries of the world. FAO Fisheries Technical Paper 367: 1 - 100.

Nicol S, Endo Y (1999) Krill fisheries: Development, management and ecosystem implications. Aquatic Living Resources 12: 105-120.

Nicol S, Pauly T, Bindoff NL, Wright S, Thiele D, Hosie GW, Strutton PG, Woehler E (2000) Ocean circulation off east Antarctica affects ecosystem structure and sea-ice extent. Nature 406: 504-507.

Nicol S, Stolp M (1991) Molting, feeding, and fluoride concentration of the Antarctic krill Euphausia superba (Dana). Journal of Crustacean Biology 11: 10-16.

Nicol S, Stolp M, Nordstrom O (1992) Change in the gross biochemistry and mineral-content accompanying the molt cycle in the Antarctic krill *Euphausia superba*. Marine Biology 113: 201-209.

Noël A (2004) Gulf of St. Lawrence Krill Decline 70 Percent in 10 Years. Environment News Service http://findarticles.com/p/articles/mi_kmens/is_200406/ai_kepm484664

Nygard T, Lie E, Rov N, Steinnes E (2001) Metal dynamics in an Antarctic food chain. Marine Pollution Bulletin 42: 598-602.

Oceana (2005) Krill - tiny creatures. http://www.oceana.org/fileadmin/oceana/uploads/Krill/brochure.pdf Accessed: July 2007

Olsen RE, Henderson RJ, Sountama J, Hemre G, Ringo E, Melle W, Tocher DR (2004) Atlantic salmon, Salmo salar, utilizes wax ester-rich oil from Calanus finmarchicus effectively. Aquaculture 240: 433-449.

Olsen RE, Suontama J, Langmyhr E, Mundheim H, Ringo E, Melle W, Malde MK, Hemre GI (2006) The replacement of fish meal with Antarctic krill, Euphausia superba in diets for Atlantic salmon, Salmo salar. Aquaculture Nutrition 12: 280-290.

Pakhomov EA, Froneman PW, Perissinotto R (2002) Salp/krill interactions in the Southern Ocean: spatial segregation and implications for the carbon flux. Deep-Sea Research Part Ii-Topical Studies in Oceanography 49: 1881-1907.

PatentStorm (2007) Method and apparatus for harvesting, digestion and dehydrating of krill hydrolysates and co-drying and processing of such hydrolysates. http://www.patentstorm.us/patents/6555155-fulltext.html Accessed: July 2007

Petri G, Zauke GP (1993) Trace metals in crustaceans in the Antarctic ocean. Ambio 22: 529-536.

Phleger CF, Nelson MM, Mooney BD, Nichols PD (2002) Interannual and between species comparison of the lipids, fatty acids and sterols of Antarctic krill from the US AMLR Elephant Island survey area. Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology 131: 733-747.

Rehbein H (1981) Amino-acid-composition and pepsin digestibilty of krill meal. Journal of Agricultural and Food Chemistry 29: 682-684.
Ringo E, Sperstad S, Myklebust R, Mayhew TM, Mjelde A, Melle W, Olsen RE (2006) The effect of dietary krill supplementation on epithelium-associated bacteria in the hindgut of Atlantic salmon (Salmo salar L.): a microbial and electron microscopical study. Aquaculture Research 37: 1644-1653.
Ritz DA (1994) Social aggregation in pelagic invertebrates Advances in Marine Biology, Vol 30, pp
Ritz DA (2000) Is social aggregation in aquatic crustaceans a strategy to conserve energy? Canadian Journal of Fisheries and Aquatic Sciences 57: 59-67.
Ross R, Quetin L (2000) Chapter 6. Reproduction in Euphausiacea. In: Everson I (ed) Krill: biology, ecology and fisheries. Blackwell Science Ltd, pp
Saether O, Mohr V (1987) Chemical composition of north Atlantic krill. Comparative Biochemistry and Physiology B-Biochemistry & Molecular Biology 88: 157-164.
Sakai M (1999) Current research status of fish immunostimulants. Aquaculture 172: 63-92.
Sands M, Nicol S, McMinn A (1998) Fluoride in Antarctic marine crustaceans. Marine Biology 132: 591-598.
Siegel V (2005) Distribution and population dynamics of Euphausia superba: summary of recent findings. Polar Biology 29: 1-22.
Smetacek V, Nicol S (2005) Polar ocean ecosystems in a changing world. Nature 437: 362-368.
Sourisseau M, Simard Y, Saucier FJ (2006) Krill aggregation in the St. Lawrence system, and supply of krill to the whale feeding grounds in the estuary from the gulf. Marine Ecology-Progress Series 314: 257-270.
Storebakken T (1988) Krill as a potential feed source for salmonids. Aquaculture 70: 193-205.
Suh HL, Toda T, Terazaki M (1991) Diet of calyptopes of the euphausiid *Euphausia pacifica* in the yellow sea. Marine Biology 111: 45-48.
Suontama J, Kiessling A, Melle W, Waagbo R, Olsen RE (2007) Protein from Northern krill (Thysanoessa inermis), Antarctic krill (Euphausia superba) and the Arctic amphipod (Themisto libellula) can partially replace fish meal in diets to Atlantic salmon (Salmo salar) without affecting product quality. Aquaculture Nutrition 13: 50-58.
Tanasichuk RW (1999) Interannual variation in the availability and utilization of euphausiids as prey for Pacific hake (Merluccius productus) along the south-west coast of Vancouver Island. Fisheries Oceanography 8: 150-156.
Tarling G, Burrows M, Matthews J, Saborowski R, Buchholz F, Bedo A, Mayzaud P (2000) An optimisation model of the diel vertical migration of northern krill (Meganyctiphanes norvegica) in the Clyde Sea and the Kattegat. Canadian Journal of Fisheries and Aquatic Sciences 57: 38-50.
Tenuta A, Alvarenga RCC (1999) Reduction of the bioavailability of fluoride from Antarctic krill by calcium. International Journal of Food Sciences and Nutrition 50: 297-302.
Tibbetts SM, Milley JE, Lall SP (2006) Apparent protein and energy digestibility of common and alternative feed ingredients by Atlantic cod, Gadus morhua (Linnaeus, 1758). Aquaculture 261: 1314-1327.

Virtue P, Johannes RE, Nichols PD, Young JW (1995) Biochemical composition of Nyctiphanes australisi and its possible use as an aquaculture feed source - lipids, pigments and fluoride content. Marine Biology 122: 121-128.

Virtue P, Nichols PD, Nicol S, Hosie G (1996) Reproductive trade off in male Antarctic krill, Euphausia superba. Marine Biology 126: 521-527.

Watkins J (2000) Chapter 4. Aggregation and verticle migrations. In: Everson I (ed) Krill: biology, ecology and fisheries. Blackwell Science Ltd, pp

Watters G (1996) By-catch of fishes captured by the krill fishing vessel Chiyo Maru No. 2 in Statistical Area 58 (January to March 1995). . CCAMLR Science 3: 111-123.

Wikipedia (2007) Krill fishery. http://en.wikipedia.org/wiki/Krill_fishery#_note-FAO05 Accessed: July 2007

Wilding TA, Kelly MS, Black KD (2006) Alternative marine sources of protein and oil for aquaculture feeds: State of the art and recommendation for further research. ISBN 978-0-9553427-4-5, The Crown Estate, 60 pages.

Yoshitomi B, Aoki M, Oshima S-i (2007) Effect of total replacement of dietary fish meal by low fluoride krill (Euphausia superba) meal on growth performance of rainbow trout (Oncorhynchus mykiss) in fresh water. Aquaculture 266: 219-225.

Yoshitomi B, Aoki M, Oshima S, Hata K (2006) Evaluation of krill (Euphausia superba) meal as a partial replacement for fish meal in rainbow trout (Oncorhynchus mykiss) diets. Aquaculture 261: 440-446.

PRACTICAL 13 APPENDICES

13.1.1.1 Organisations providing information for this report

Contact	Position and organisation
Dr N. Auchterlonie	European and Technical Manager, Scottish Salmon Producers' Organisation, Durn, Isla Road, Perth. UK
Dr D. Basset	Executive Officer, British Trout Association, West Mains, Ingliston, EH28 8NZ. UK
Dr K. Davidson	Marine microbiologist, Scottish Association for Marine Science, Oban, Scotland, UK.
Mr B. Eccles	Licencing Officer, Falkland Islands Government, Stanley, Falkland Islands, FIQQ 1ZZ.
Dr B. Gara	Aquaculture Development Manager, FIDC, Stanley, Falkland Islands
Dr V. Gascón González	Policy Advisor- Antarctic Krill Conservation Project Los Arrayanes 244, Bariloche, Argentina
Mr P. Guzman	H. J. Baker and Brothers Inc., Westport, US.
Dr S. Hill	Ecological modeller, British Antarctic Survey, Cambridge. UK
Dr A. Jackson	Technical Director International Fishmeal and Oil Organisation, IFFO, St. Albans, Herts. UK
Mr D. Lowe	Managing Director, EWOS Limited, UK & Ireland EWOS Ltd, West Lothian, Scotland. UK
Dr J. Morishita	Director for International Negotiations, International Affairs Division, 1-2-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8907, Japan.
Mr P. Morris	Skretting, UK and Ireland Research Manager, Northwich Cheshire, CW9 6DF. UK
Dr S. Nicol	Australian Antarctic Division, Kingston, Tasmania, Australia.
Ms D. Purchase	Mariculture Officer, Marine Conservation Society Edinburgh. UK
Dr S. Walmsley	Head of Marine Program, WWF. Godalming, Surrey

13.1.1.2 Summary of nutritive analyses (lipids, amino acids, carotenoids and seasonal variabilty)

Species/group	Area of interest	Reference
Zooplankton in general	Good introduction to storage lipids in krill	Lee et al (2006)
Euphausia sp.	Seasonal, species and diet related changes in lipids content	Phleger et al (2002)
E. superba	Spatial and sexual maturity related differences in lipid composition	Mayzaud et al (1998)
	Lipid stability, crude breakdown	Kolakowska et al (1994)
	Nutritive value (water, ash, protein, chitin, lipid and trace metals) as a function of moult cycle	Nicol et al (1992)
	Lipid, sterol and fatty-acid composition	Fricke et al (1984)
	Lipid composition	Clarke (1984)
	Amino-acid-composition and pepsin digestibility of krill-meal.	Rehbein (1981)
M. norvegica	Chemical-composition	Saether and Mohr (1987)
	Seasonal biochemistry	Buchholz and Pradofiedler (1987)
	Sex and seasonal variation in lipid (only)	Mayzaud et al (1999)
N. australis	Lipid, protein carotenoid and fluoride analysis	Virtue et al (1995)

13.1.1.3 Summary of the use of krill in aquafeeds - feed trials

Krill species	Farmed species	Major conclusions	Reference
(i) Feed trials			
E. superba and T. inermis	salmon	*E. superba* and T. *inermis* can replace 40 – 60% fish-meal with negligible effect on product quality.	Suontama et al (2007)

E. superba	salmon	During preparation krill feeds less able to absorb lipids compared to fishmeal. Krill inclusion increased growth rate initially. Wellfare parameters unaffected by krill inclusion.	Olsen et al (2006)
M. norvegica	salmon	Krill can replace 50% of fish-meal with no adverse effects on growth. Gut flora (proportion anaerobic/aerobic bacteria) changed as a function of diet.	Ringo et al (2006)
E. superba	trout	Low fluoride krill-meal demonstrated to have a nutritional value equivalent to fishmeal.	Yoshitomi et al (2007)
		No effect on growth at up to 15% replacement but at 30% significantly lower – attributed to the accumulation of fluoride in bones	Yoshitomi et al (2006)
Krill (unspecified) and a range of other comparable species	cod	Digestibility and independence of digestibility	Tibbetts et al (2006)
E. superba	cod	Product quality	Karlsen et al (2006)
Chitin derived from crab shells	cod	The digestibility of chitin and the action of chitinolytic enzymes	Lindsay and Gooday (1985)