MEASURING AND CHARACTERIZING THE ECOLOGICAL FOOTPRINT AND LIFE CYCLE ENVIRONMENTAL COSTS OF ANTARCTIC KRILL (*EUPHAUSIA SUPERBA*) PRODUCTS

by

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Abstract

The fishery for Antarctic krill (*Euphausia superba*) has received considerable attention in recent years, owing largely to the possibility of its significant expansion and the ecological implications of increased extraction of a keystone species. This thesis employed Ecological Footprint (EF) analysis and life cycle assessment (LCA) to measure the resource use, energy use, and emissions associated with three krill-derived products: meal and oil for aquaculture feeds, and omega-3 krill oil capsules for the nutraceutical market. The product supply chains of one krill fishing and processing company, Aker BioMarine, were used as a case study to examine Antarctic krill-derived products. Antarctic krill products were compared to products from similar fisheries targeting other species for reduction into meal and oil, including Peruvian anchovy (*Engraulis ringens*), Atlantic herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*) and Gulf menhaden (*Brevoortia patronus*), on the basis of marine footprint, carbon footprint, and fuel use intensity.

List of Abbreviations and Symbols Used

AB	Aker BioMarine ASA
AP	Acidification potential
BRU	Biotic resource use
C	Carbon
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CED	Cumulative energy demand
CF	Carbon footprint
CFC-11	Trichlorofluoromethane
CFC-11-e	Trichlorofluoromethane equivalent
CML	Institute of Environmental Sciences, Leiden University
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CZCS	Coastal Zone Colour Scanner
DHA	Docosahexaenoic acid
EF	Ecological Footprint
EP	Eutrophication potential
EPA	Eicosapentaenoic acid
FAO	Food and Agriculture Organization of the United Nations
FUI	Fuel use intensity
g	Gram(s)
GHG	Greenhouse gas
GJ	Gigajoule(s)
GWP	Global warming potential
ha	Hectare(s)
IFO	Intermediate fuel oil
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	Kilogram(s)
km	Kilometre(s)
kWh	Kilowatt hour(s)
L	Litre(s)
LCA	Life cycle assessment
m^2	Square metre(s)

MDO	Marine diesel oil
MF	Marine footprint
MJ	Megajoule(s)
MSC	Marine Stewardship Council
NASA	National Aeronautics and Space Administration
NO_x	Nitrogen oxides
NPP	Net primary productivity
ODP	Ozone depletion potential
Pg	Petagram(s)
PO_4	Phosphate
PO_4-e	Phosphate equivalent
SETAC	Society for Environmental Toxicology and Chemistry
SO_2	Sulfur dioxide
SO_2-e	Sulfur dioxide equivalent
SO_x	Sulfur oxides
t	Tonne(s)
TAC	Total allowable catch
tkm	Tonne-kilometre(s)
WMO	World Meteorological Organization
WWF	World Wildlife Fund

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Chapter 1. Introduction

It has been clear for some time that global food production is pushing the sustainable limits of natural systems to provide resources and assimilate wastes without significant long-term environmental consequences (Pimental *et al.*, 1973; Borgstrom, 1974; Millennium Ecosystem Assessment, 2005; Beaumert *et al.*, 2005; Pelletier & Tyedmers, 2010a). With a growing global population, food production will need to increase substantially, and the environmental burden of the global food supply will also grow if current trends continue (Pimental *et al.*, 1997; FAO, 2009a; Pelletier & Tyedmers, 2010a; Pollard *et al.*, 2010). A report published by the Food and Agriculture Organization of the United Nations (FAO) in 2010 estimated that the world's population will reach 9.1 billion by 2050, requiring a 70 per cent increase in food production (Pollard *et al.*, 2010). It has been demonstrated that the environmental burden of food production and consumption can be greatly influenced by dietary choices as well as by technological improvements in production practices (Tilman *et al.*, 2002; Reijnders & Soret, 2003; Carlsson-Kanyama *et al.*, 2003; Robertson & Swinton, 2005; Gerbens-Leenes & Nonhebel, 2005; Pelletier *et al.*, 2008; Nilsson & Sonesson, 2010). The need for information regarding the environmental performance of different food production systems, and the positive or negative influence of changes in both production and consumption patterns, has never been greater. The measurement and communication of resource demands, energy consumption, and emissions associated with production systems is a necessary complement to government-, industry- and consumer-led initiatives to improve the environmental sustainability of the global food production system.

Demand for seafood products is growing globally. In 2006, fisheries and aquaculture together produced 110 million tonnes of fish for human consumption, or 16.7 kg per capita, one of the highest rates of production on record (FAO, 2009b). As demand for high-quality protein increases in developing economies, seafood production will need to increase as well if demand is to be met. However, production from wild fisheries has peaked and we have already surpassed the sustainable capacity of the oceans to provide us with food: 52 per cent of world fish stocks today are fully exploited, and a further 28 per cent are considered overexploited, depleted, or in recovery (FAO, 2009b). As a result, a growing portion of seafood today is produced by aquaculture. Aquaculture has grown from the annual production of approximately one million tonnes in the 1950s to over 50 million tonnes in 2006 (FAO, 2009b). In western countries, much of this production is focused on high-value species like Atlantic salmon (*Salmo salar*), Rainbow trout (*Oncorhynchus mykiss*), European sea bass (*Dicentrarchus labrax*) and red sea bream (*Pagrus major*). Salmonids alone now account for 11 per cent of world trade of seafood commodities, and demand for these high-value fishes increases each year (FAO, 2009b). However, farming of high trophic level species requires large inputs of energy, protein and amino acids. As a result, aquaculture of these species has traditionally been heavily dependent on capture fisheries to provide meal and oil inputs to aquafeeds (Naylor *et al.*, 2000; Tacon, 2008; Tacon & Metian, 2008). A number of small pelagic fish species have been targeted for reduction into meal and oil for use as inputs to aquafeeds and other livestock feeds. In 2002, 46 per cent of produced fish meal and 81 per cent of fish oil was destined for the aquaculture market (Tacon, 2008). The top harvested species for these products include Peruvian anchovy (*Engraulis ringens*, average 7.4 million tonnes caught per annum in 2006-2008), Atlantic herring (*Clupea harengus*, 2.4 million tonnes per annum), and blue whiting (*Micromesistius poutassou*, 1.7 million tonnes per annum) (Tacon, 2008; FAO, 2010a). One relatively new and to-date minor source for meal and oil is the fishery for Antarctic krill (*Euphausia superba*).

1.1 Antarctic Krill

Krill is the collective name given to species in the order *Euphausiacea*, being small shrimp-like crustaceans ranging in size from a few millimeters up to 15 cm. The word krill comes from the Norwegian word literally meaning “small fry of fish” (Baker *et al.*, 1990). There are 85 known species of euphausiids in the world, although the most abundant, longest lived, and most commercially significant is Antarctic krill (Baker *et al.*, 1990; Hewitt & Linen Low, 2000).

Antarctic krill inhabit the wide circumpolar belt of seasonal pack-ice in the Southern Ocean, ranging from the Antarctic continent in the south to the Antarctic Convergence in the north (Figure 1). In the ice-free zone north of the Antarctic Convergence, primary productivity is lower and krill are mostly absent (Hempel, 1985). Closer to the continent, where pack-ice remains year round, Antarctic krill are again absent, although other euphausiid species are present but scarce (Hempel, 1985). Although Antarctic krill can be found throughout this belt of seasonal pack-ice, they are not evenly distributed. Areas of greatest abundance tend to be located in the Atlantic sector of the Southern Ocean, including the Scotia Sea, the Weddell Sea, and off the Antarctic Peninsula, although high abundances have also been reported in other regions such as the Kerguelen-Gaussberg Ridge in the Indian Ocean sector and the Ross Sea in the Pacific sector (Figures 1 and 2) (Marr, 1962; Nemoto, 1968; Mackintosh, 1973; Ichii, 1990; FAO, 2010b).

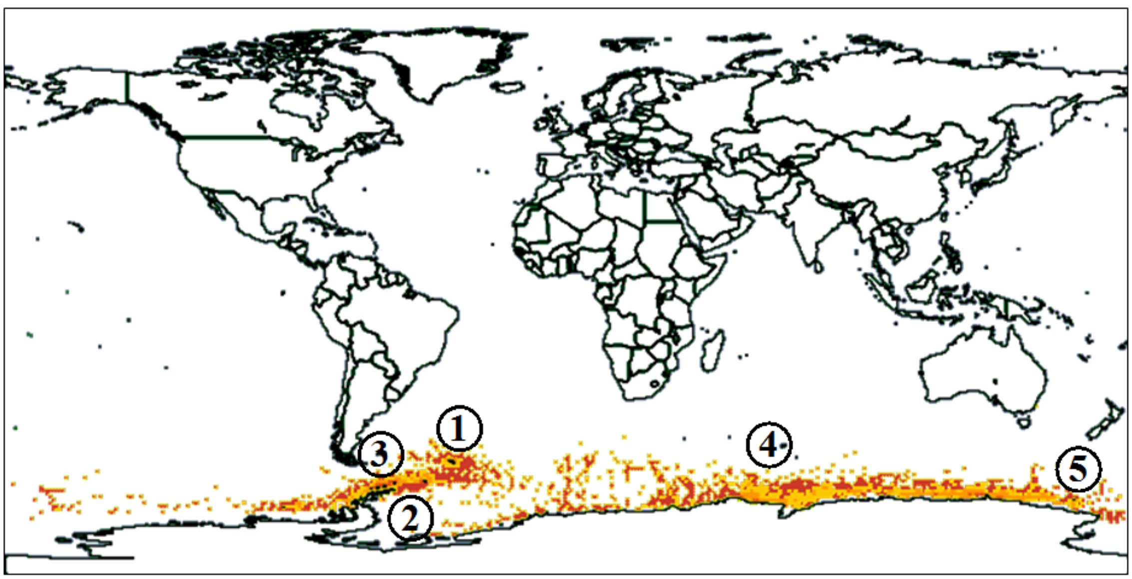

Figure 1. Global distribution of Antarctic krill, highlighting locations of measured biomass abundances: (1) Scotia Sea, (2) Weddell Sea, (3) Antarctic Peninsula, (4) Kerguelen-Gaussberg Ridge, and (5) Ross Sea. Biodiversity occurrence data provided by OZCAM (2011).

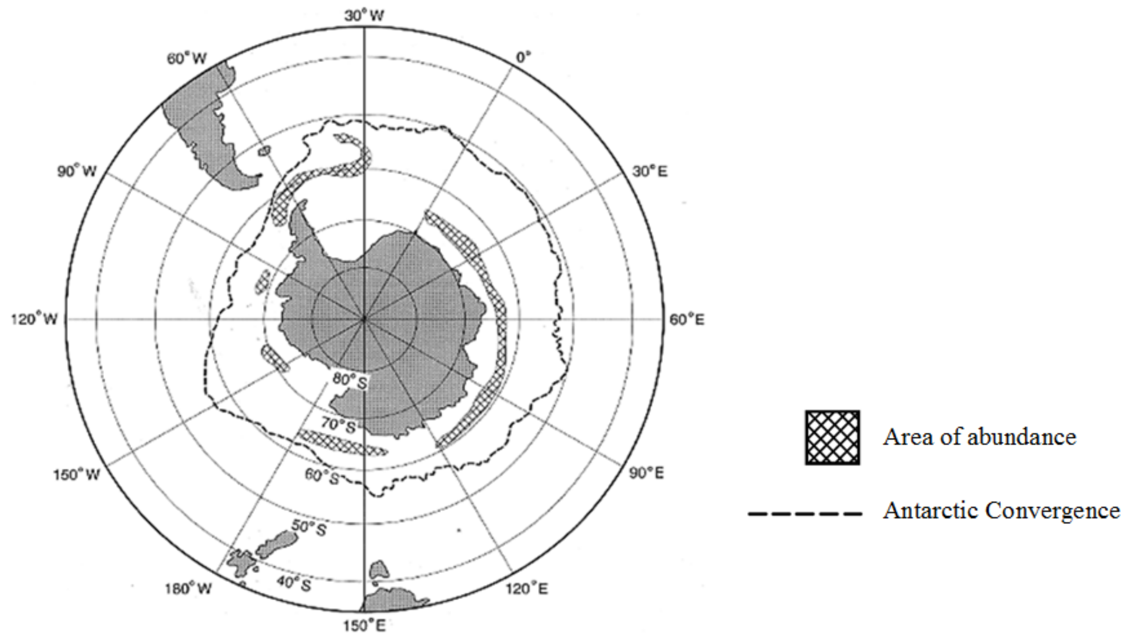

Figure 2. Range of Antarctic krill showing the Antarctic Convergence and areas of measured abundance (Everson, 2000).

Estimates of Antarctic krill biomass vary greatly due to natural changes in distribution over space and time as well as differences in biomass estimation methods (Budziński *et al.*, 1985; FAO, 2010b). Historic estimates of Antarctic krill biomass range from as low as 40 million tonnes to as high as 5 billion tonnes (Table 1). More recent estimates continue to show significant variance, ranging from 37 million tonnes (Demer *et al.*, 2007) to 208 million tonnes (Heywood *et al.*, 2006), although it is now generally agreed that the total biomass is likely under 500 million tonnes (Nicol & Endo, 1997).

Antarctic krill often form large concentrated swarms which can range in size from a few metres in diameter to an area of several hundred square kilometers (Macauley *et al.*, 1984). These large swarms, where Antarctic krill is typically the only small animal species present, are typically associated with islands, continental shelves, and zones of water mixing (FAO, 2010b). Swarmings can last for less than a day or for the entire lifetime of some individuals – up to seven years (Hempel, 1987; FAO, 2010b).

Table 1. Summary of estimates of Antarctic krill biomass

Study	Estimate (million tonnes)
Marr (1962)[a]	44.5
Gulland (1970)[a]	750
Lyubimova *et al.* (1973)	800-5,000
Doi and Kawamaki (1979)	1,200
Voronina (1983)	60-100
Kalinowski and Witek (1983)	100-400
Trathan *et al.* (1992)[b]	40[c]
CCAMLR (2000a)	44.3
Heywood *et al.* (2006)	208
Demer *et al.* (2007)	37

a. As cited in Everson (1977).
b. As cited in Everson (2000).
c. Includes only areas 41, 48.1, 48.2, 48.3, 48.6, and 58.4.2.

Because of their substantial collective biomass, the presence of large concentrations where other small animal species are not present, and the reliance of many higher trophic level species on these concentrations for a food source, Antarctic krill have been recognized as a keystone species in the ecosystem of the Southern Ocean (Hempel 1985; Hempel, 1987; Nicol & Endo, 1997; Hewitt & Linen Low, 2000). Krill feed primarily on diatoms and other phytoplankton, although they can also feed on their own eggs and larvae and break down their own body mass into amino acids in periods of low food availability (FAO, 2010b). They often provide the only link between the bottom of the food web and large marine animals, including seals (e.g. *Arctocephalus gazelle*, *Lobodon carcinophagus*, *Hydrurga leptonyx*), whales (e.g. *Balaenoptera musculus*, *Eubalaena australis*, *Megaptera novaeangliae*), penguins (e.g. *Pygoscelis adeliae*, *Pygoscelis antarcticus*, *Pygoscelis papua*) and other seabirds (e.g. *Sterna paradise*, *Catharacta maccormicki*) (Hempel, 1985, Hempel, 1987; Hewitt & Linen Low, 2000). Annual consumption of krill by these predators can be considerable (Table 2).

Table 2. Estimated annual consumption of Antarctic krill by major predators

Predator	Annual consumption (millions of tonnes)[a]
Whales	34-43
Seals	63-130
Birds	15-20
Squid	30-100
Fish	10-20
Total	152-313

a. From Miller and Hampton (1989), as cited in Nicol and Endo (1997).

1.2 The Fishery for Antarctic Krill

Records of fishing for krill species (although not specifically for Antarctic krill) date back to the 19th century (Fisher *et al.*, 1953; Mauchline & Fisher, 1969). However, modern industrialized fishing for krill did not begin until the mid-20th century. Early proponents for a fishery targeting Antarctic krill believed that the massive biomass could sustain a harvest equal to that of all marine fishes, and argued that Antarctic krill could play an important role in feeding the world (Hewitt & Linen Low, 2000). Today, aside from the fishery for Antarctic krill, there are also smaller fisheries targeting several other krill species: North Pacific krill (*Euphausia pacifica*) and *Euphausia nana* in the north Pacific Ocean, and *Thysanoessa inermis*, Arctic krill (*Thysanoessa raschii*), and Atlantic krill (*Meganyctiphanes norvegica*) in the north Atlantic Ocean (Nicol & Endo, 1997). Fishing for Antarctic krill has been focused in the Atlantic sector of the Southern Ocean, due to the greater abundances of krill found there, as well as the relatively favourable fishing conditions (Nicol & Endo, 1997).

Early exploratory fishing for Antarctic krill was undertaken by two Soviet research vessels in 1961 and 1962, and Soviet vessels continued to catch small quantities throughout the 1960s (<200 tonnes per annum) until the permanent fishery began in the early 1970s (Everson, 1977; Nicol & Endo, 1997). Throughout the 1970s and 1980s, the fishery continued to be dominated by the Soviet Union, and catches gradually climbed to a reported maximum of 528 thousand tonnes in 1982 (Figure 3) (CCAMLR, 1990; FAO, 2010b). Low krill catches from 1983 to 1985 coincided with low krill availability and poor krill predator reproductive success at South Georgia (Hewitt & Linen Low, 2000), although the decline in those years may also be explained by the discovery of high fluoride levels in krill exoskeletons or by processing and marketing difficulties (Soevik & Breakkan, 1979; Budziński *et al.*, 1985; Nicol & Endo, 1997). After 1985, catches remained high until the collapse of the Soviet Union in 1991 (Figure 3).

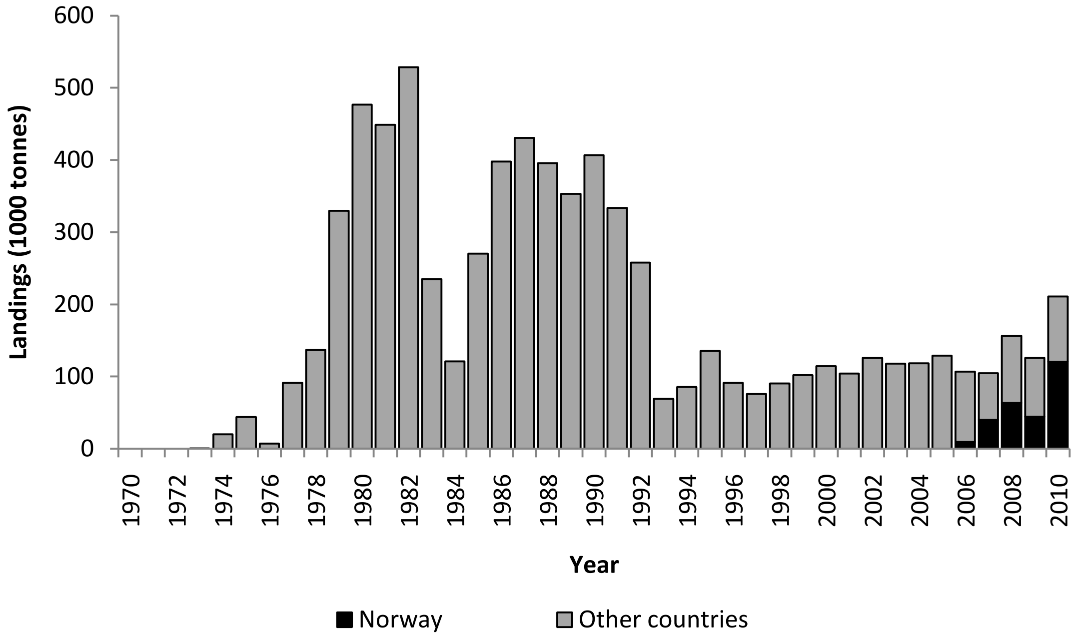

Figure 3. Annual reported catch of Antarctic krill, 1970-2010, highlighting catches by Norway (FAO, 2010b; CCAMLR, 2010a&b).

While historic catches of Antarctic krill were dominated by the Soviet Union, a number of other countries have been active at different times in the fishery as well. In the early 1970s, Japan began exploratory fishing and soon joined the permanent fishery in the mid-1970s (CCAMLR, 1990). Since the beginning of the 1990s, numerous other countries have participated, including Poland, South Korea, Ukraine, the United States, Vanuatu, and Norway. However, no country has reached the levels of fishing actively achieved by the Soviet Union in the 1980s (CCAMLR, 1990, 2000b, 2010a).

With the fall of the Soviet Union in 1991, the Antarctic krill fishery quickly declined, and remained relatively stagnant throughout the 1990s and 2000s, with recent annual catches typically in the range of 100 to 150 thousand tonnes (Figure 3) (CCAMLR, 2010a). Numerous factors have contributed to this stagnation. Some of these barriers have been directly related to the ability of vessels to efficiently fish Antarctic krill: distance to fishing grounds, variations in distribution and abundance, early overestimates of abundance, and difficulties in separating krill from bycatch, which historically often accounted for over 20 per cent of catches (Budziński *et al.*, 1985; Hempel, 1987; Nicol, 1995; Hewitt & Linen Low, 2000). However, even more important than these fishing-related barriers have been difficulties in processing krill efficiently into valuable products and successfully marketing them (Budziński *et al.*, 1985). A notable contributor to processing difficulties has been the rapid post-mortem breakdown of krill as a result of the release of the same enzymes that allow them to break down proteins during periods of low food availability. This rapid physiological breakdown results in substantial loss of nutritional value if krill are not processed quickly after harvesting (Budziński *et al.*, 1985).

Modern advancements in fishing and processing technology have overcome some of the barriers facing the commercial viability of the Antarctic krill fishery (Tilseth & Hostmark, 2009; Rokke *et al.*, 2010). Since the mid-1990s, the fishery has experienced slow but gradual and apparently accelerating growth (Figure 3). The ability to process Antarctic krill more efficiently, together with growing markets for today's krill products, may result in significant growth in the fishery over the coming years. Much of the current growth in the fishery comes as a result of Norway's entrance into the industry, which now accounts for a significant portion of total reported catches (Figure 3).

1.3 Antarctic Krill Products

The greatest challenge historically facing the krill industry has been the lack of a krill-derived product which provides sufficient economic return on investment to justify fishing and processing (Nicol, 1995; Nicol *et al.*, 2000). Difficulties have stemmed from some inherent properties of krill, such as their small size, rapid breakdown rate, and high fluoride levels, as well as from the fact that human consumption of krill products has failed to become popular outside of Asian markets (Nicol *et al.*, 2000). Perhaps in response to this need for the industry to discover profitable krill-derived endeavours, the prospects of producing and marketing products derived from Antarctic krill have been the focus of many reviews since the 1970s (Grantham, 1977; Suzuki, 1981; Budziński *et al.*, 1985; Suzuki & Shibata, 1990; Nicol *et al.*, 2000; Tou *et al.*, 2007).

Budziński and colleagues (1985) reviewed a number of uses and potential uses for Antarctic krill products. These include direct human consumption of all or part of the animal, production of meal for animal feeds, extraction of chitin from the shell for industrial applications (e.g. waste water treatment, heavy metal removal), use of enzymes for multiple purposes (e.g. in animal feeds, pharmaceuticals), and use of krill oil either as an energy source or for cosmetic or pharmaceutical purposes. A more recent review by Nicol and colleagues (2000) showed the most common uses of krill to be bait for sport fishing (45 per cent of the Japanese krill market in 1999), feed for aquaculture and aquariums (43 per cent), and human consumption (12 per cent).

Although meal for animal feeds was originally thought to be the primary krill-derived product, the early market was driven more by human consumption (Budziński *et al.*, 1985; Nicol *et al.*, 2000). Krill for human consumption can take many forms, including whole frozen or dried krill, tail meat after removal of the shell, and processed krill products such as pastes, minces and sauces for cooking. Budziński and colleagues (1985) expected that human consumption of tail meat would ultimately be the most economically viable use for krill. Throughout the 1980s, development of krill products was focused primarily on human food products (Figure 4). However, this use remains confined to Asian markets and accounts for only a small portion of the global krill industry in recent years (Nicol *et al.*, 2000; Nicol & Foster, 2003).

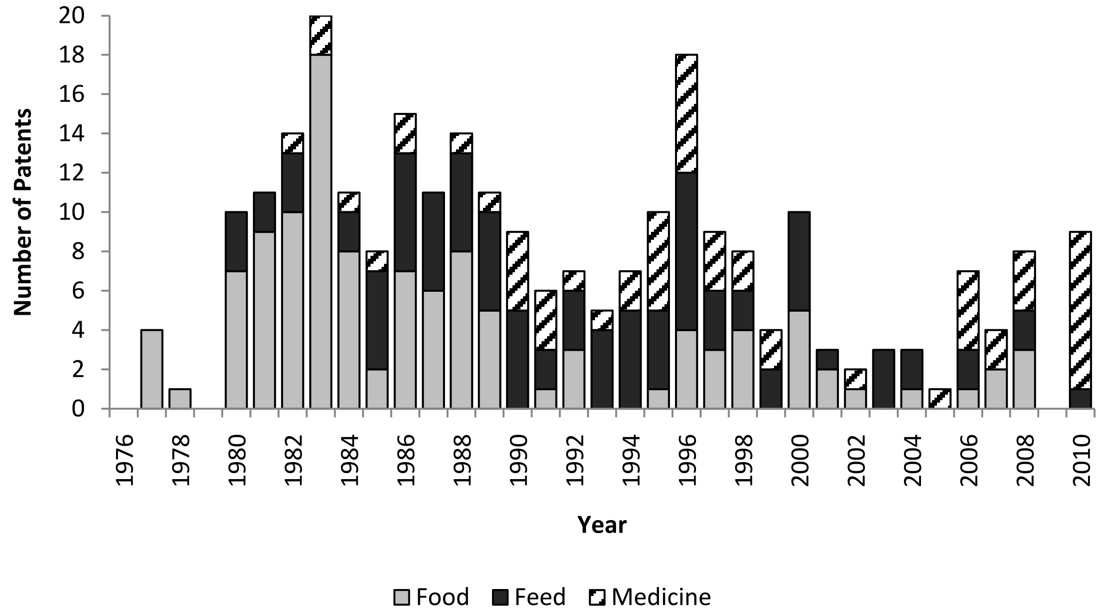

Figure 4. Krill patents per year for products targeted at human use for food, feed and fish bait, and human medical/nutritional use, 1976-2010. Data from 1976 to 2002 from Nicol and Foster (2003). Data from 2003-2010 based on number of patents with keyword 'krill' from the online database at http://ep.espacenet.com, as recommended by Nicol and colleagues (2011).

Starting in the mid-1980s and accelerating through the early 1990s, the emphasis of the krill industry's development shifted from products for human consumption to products for animal consumption (Figure 4). Krill-based inputs to aquafeeds can take the form of krill meal, frozen blocks of whole krill, krill oil or hydrolysates (Nicol *et al.*, 2000). As early as the 1970s, the Soviet Union was using krill meal and frozen krill for animal feeds, and Poland was selling krill products to Norway for use in salmonid feeds (Budziński *et al.*, 1985). By 2000, fish feed and bait were the primary drivers of the fishery (Nicol *et al.*, 2000). The use of krill meal in the aquaculture industry has grown in popularity in recent years as evidence has emerged that krill feed inputs may positively affect feeding behavior and promote growth in some fish (Allahpichay & Shimizu, 1985; Shimizu *et al.*, 1990; Oikawa & March, 1997; Olsen *et al.*, 2006; Kolkovski *et al.*, 2007). Nicol and colleagues (2000) predicted that, although the earlier history of Antarctic krill use was dominated by human consumption, the future of the industry is likely to be focused on the production of aquaculture feeds.

Another growing driver of the krill industry in recent years is the use of krill for medicinal and nutritional purposes. This is an interesting development in the industry, because in the 1980s products based on krill oil were considered too expensive and were expected to be, at best, by-products of krill processing for other uses (Budziński *et al.*, 1985). However, while human consumption dominated the industry in the 1980s and animal feed products dominated the industry in the 1990s, it appears that medical and pharmaceutical products derived from krill oil may become the leading drivers of the industry in the 21st century (Figure 4). The primary focus of these products is the provision of desired enzymes and nutrients such as omega-3 fatty acids. Promoted health benefits shown to be associated with the use of krill supplements range from relief of arthritic inflammation and soreness (Deutsch, 2007; Ierna *et al.*, 2010) to decreased symptoms of premenstrual syndrome and dysmenorrhea (Sampalis *et al.*, 2003) and reduction of blood glucose and cholesterol levels (Bunea *et al.*, 2004; Tandy *et al.*, 2009).

1.4 Management of the Antarctic krill fishery

Fisheries targeting Antarctic krill and other species in the Southern Ocean are regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR is responsible for assessing stocks of Antarctic krill and other species, monitoring changes in the Southern Ocean ecosystem, determining total allowable catch (TAC) and precautionary limits, and administering quotas to fishery participants (Nicol & Endo, 1997). CCAMLR's guiding Convention was originally negotiated between 1978 and 1980, was ratified in 1980, and came into effect in 1982 (Nicol & Endo, 1997; Miller & Agnew, 2000). Today, the Commission has 25 member countries, and an additional nine countries are party to the Convention but are not full members. The Convention Area covers 32.9 million square kilometers, spanning from the Antarctic continent to the Antarctic Convergence (Nicol & Endo, 1997).

The management approach taken by CCAMLR has been praised and considered more ecologically progressive than those taken by many other fisheries management organizations (Parkes, 2000; Miller & Agnew, 2000). CCAMLR was the first such organization to explicitly adopt both a precautionary approach to catch limits, and an ecosystem-based approach to fisheries management (Miller & Agnew, 2000). This approach is outlined in Article II of CCAMLR's guiding Convention, which states that:

> 3. Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provision of this Convention and with the following principles of conservation:
>   (a) prevention of decreases in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size should not be allowed to fall below a level close to that which ensures the greatest net annual increment;
>   (b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and
>   (c) prevention of changes or minimization of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of the introduction of alien species, the effects of associated activities on the marine ecosystem and of the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine living resources. (Article II, par. 3, from CCAMLR, 2010c)

CCAMLR establishes a number of limits on fishing for Antarctic krill. These include a TAC of 3.47 million tonnes, or 10 per cent of the total estimated biomass in Area 48; a precautionary catch limit of 620,000 tonnes since 1992, which marks the level of catch at which significant ecological impacts can be expected; and annual fishing quotas to vessels, which have ranged from 165,000 to 764,000 tonnes since 2004 (CCAMLR, 2000b; CCAMLR, 2010a&b). The actual level of fishing in recent years (excluding illegal, unregulated and unreported fishing) has been far below each of these levels (Figure 3). For the 2008-2009 year, licenses were granted to 55 vessels from 12 countries, with a total quota of 363,000 tonnes, although not all notified vessels actually fished and the actual harvest was less than 130,000 tonnes (CCAMLR, 2009a, 2010a).

Because of the important role that Antarctic krill play in the ecosystem of the Southern Ocean (Hempel, 1985; Hempel, 1987; Hewitt & Linen Low, 2000), much concern has been voiced recently over the potential increased exploitation of Antarctic krill as a resource (Leape *et al.*, 2009; Barnes, 2009; Schiermeier, 2010; Jacquet *et al.*, 2010). These concerns arise primarily out of uncertainty concerning potential impacts of large-scale krill extraction on populations of predating species. These are not new concerns: In 1987, Hempel wrote that "a major fishery super-imposed on natural fluctuations may have a substantial impact on local consumer populations, at least on a short term" (Hempel, 1987, p. 35). Further concerns arise out of uncertainty as to how Antarctic krill populations will respond to changing environmental conditions, regardless of fishing activities. Sea ice, for example, is a crucial component in krill habitat, providing an essential feeding ground for larvae and over-wintering adults, and possible effects on sea ice extent as a result of climate change could affect long-term populations (Nicol *et al.*, 2008). As well, potentially extreme ocean acidification associated with elevated levels of atmospheric carbon dioxide (CO_2) levels could have a substantial effect on krill gestation and hatch success (Kawaguchi *et al.*, 2010).

Renewed interest in the use of Antarctic krill for multiple products, the established importance of Antarctic krill in the Southern Ocean ecosystem, uncertainty in biomass estimates, and uncertainty in the response of Antarctic krill to environmental changes, combine to make this fishery an important and difficult one to manage in the long-term.

1.5 Thesis Objectives

The overall goal of the research undertaken in this thesis was to expand understanding of the environmental implications of products derived from the Antarctic krill fishery. While previous research has focused primarily on issues of stock status, catch limits, and ecological impacts of extraction, the focus here is on relatively unexplored contributions of Antarctic krill products to globally significant environmental concerns: appropriation of net primary productivity (NPP), energy use, and greenhouse gas (GHG) and other emissions. More specifically, the research undertaken here had four essential objectives:

1) To quantify the direct and indirect resource use and emissions associated with krill meal and krill oil for use as aquaculture feed inputs, and omega-3 krill oil capsules;

2) To determine the marine and terrestrial ecosystem support required to sustain krill product-related activities;
3) To identify hotspots of environmental burden in the krill-product supply chain; and
4) To model potential benefits resulting from possible changes made to the krill-product supply chain.

In addition to measuring the environmental performance of Antarctic krill-derived products and comparing krill products to those derived from other reduction fisheries, this thesis also seeks to address the methodology of the Ecological Footprint (EF) as applied to fisheries products and examine the role of uncertainty and natural variability in EF results.

Outcomes of this thesis will be of interest to a number of parties. Scientists and fisheries management authorities will be provided with a broader understanding of the holistic environmental implications of the Antarctic krill fishery. Krill-fishing companies will be provided with insight into the performance of their products relative to a range of similar products from other fisheries, as well as some guidance in improving the performance of their production systems. Consumers and clients in the aquaculture and nutraceutical industries will be provided with an understanding of the relative environmental performance of the products they purchase. Finally, fisheries and environmental scientists will be provided with further insight into the methodology of EF analysis as applied to marine products, as well as the addition of an Antarctic krill case study to the growing literature of EF and life cycle assessment (LCA) applications to fishery-derived products.

1.6 Methodology

To achieve the objectives stated above, two biophysical accounting frameworks were employed to assess the environmental performance of Antarctic krill products and compare Antarctic krill products to products from other reduction fisheries. These methods were EF analysis and LCA. The products of one company, Aker BioMarine ASA (AB) of Norway, were examined as a case study.

1.6.1 Case Study: Aker BioMarine

AB was established in 2006 as an independent enterprise under the Aker Group of companies in Norway, with the objective of harvesting Antarctic krill to be processed into high-value products (Aker BioMarine, 2010a). Prior to the establishment of AB, krill-fishing operations took place under Aker Seafoods ASA (Aker BioMarine, 2010a). Since 2006, AB's fishing activities have quickly grown: Norway now accounts for approximately one third of total reported Antarctic krill catches from 2007-2009 and over half of reported catches in 2010 (Figure 1).

AB produces krill meal and oil products for use as inputs to aquaculture feeds, as well as omega-3 krill oil capsules for the nutraceutical industry. All krill harvested for the production of AB's products is fished by a single vessel, Saga Sea, which has been retrofitted as a custom factory trawler, both fishing and processing krill simultaneously. Saga Sea is fitted with a patented trawl system (Rokke *et al.*, 2010), called Aker Eco Harvesting, that pumps krill directly from the cod end of the trawl to processing facilities onboard, allowing the trawl to stay underwater and making it possible to process the catch efficiently before it begins to break down and lose nutritional value (Figure 5). In the 2008-2009 fishing season, Saga Sea was granted a license to fish Antarctic krill in FAO areas 48.1., 48.2, and 48.3, including areas off the northern coast of the Antarctic Peninsula and fishing grounds around South Georgia and the South Orkney Islands, southeast of Argentina (CCAMLR, 2009b).

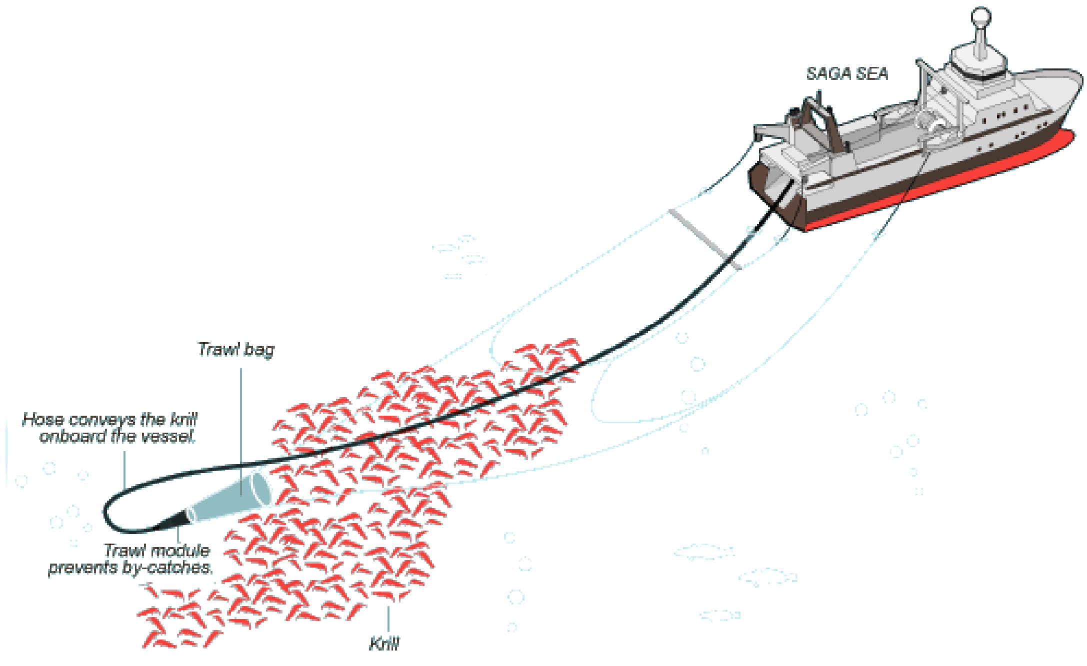

Figure 5. Diagram of Aker Eco Harvesting trawl technology (Aker BioMarine, 2010b)

In 2010, AB received sustainability certification from the Marine Stewardship Council (MSC). This was the first time MSC certified a reduction fishery for meal and oil, as well as the first time a single fishing company, rather than an industry-wide fishery, received certification. Originally established by the World Wildlife Fund (WWF) and Unilever in 1997, MSC is now a wholly independent, international, non-profit organization which has become the world's leading fisheries-ecolabeling body (Cummins, 2004). Certification assessment under MSC considers direct impacts of fishing on target and non-target species as well as a number of fishing-related ecological impacts, including costs to biodiversity, bycatch, destruction and alteration of marine habitat, and threats to the integrity of marine ecosystem structure and function (Cummins, 2004; MSC, 2010). The assessment of AB's krill fishery for MSC certification was carried out by Moody Marine Ltd. (Medley *et al.*, 2010). This assessment examined the performance of the krill fishery on the basis of three key principles, including the sustainability of krill populations in the face of increasing exploitation, the maintenance of the structure and function of the Southern Ocean ecosystem, and the effectiveness of the current fishery management system. The report concluded that the fishery was considered sustainable when judged against each of these categories, although this conclusion was accompanied by a number of conditions, including further research into appropriate precautionary catch limits, assessment of risks posed to fish larvae by trawling activities, and the creation of an adaptive management strategy to respond to potential occurrence of localized resource depletions (Medley *et al.*, 2010). A number of scientists and environmental groups have responded to MSC's certification of AB's fishing activities with criticism and concern, citing, among other things, uncertainty regarding predator-prey dynamics, uncertainty of impacts from climate change, and concerns regarding the certification of an industrial fishery (i.e. a fishery with the primary purpose of providing non-human consumption products) (Leape *et al.*, 2009; Barnes, 2009; Schiermeier, 2010; Jacquet *et al.*, 2010).

AB provides an appropriate case study for the examination of Antarctic krill-derived products for several reasons. First and foremost, although AB is a single company, fishing activities by Saga Sea now account for the majority of total reported catches of Antarctic krill. AB also produces products for both aquaculture and nutraceutical purposes, the two primary uses of krill today. Finally, if AB's products prove to be an economically viable venture for the krill industry, their processes may be indicative of the future direction of the industry.

1.6.2 Ecological Footprint

The EF is based on the well-established concept of carrying capacity, defined by ecologists as the population that a given area can support indefinitely without significantly hampering the ability of the environment to support future generations. Applied to the global human society, it is the total population that the earth can support sustainably at a given rate of resource consumption and waste assimilation. In 1974, Borgstrom warned that the rapidly increasing global population was already threatening the ability of the earth to provide food, water and other necessities of life – at a time when the earth's population was less than two thirds that of today. Borgstrom based his warning on the concept of "ghost acreage", being the area that a population does not inhabit but still requires to support resource consumption. He used the term to demonstrate, for example, that Europe required an area 50 per cent larger than the actual continent to support consumption, and Japan required an area some five times the size of that country (Borgstrom, 1974). Applied at a global scale, the human population's ghost acreage exceeds the actual bioproductive land and sea available on the planet, thereby exceeding the earth's carrying capacity, and additional earths would theoretically be required to support global consumption. Catton (1980) subsequently called these additional earths "phantom planets".

The spatial representation of mankind's dependence, and overdependence, on ecosystem support was popularized by Rees and Wackernagel in the form of the EF (Rees, 1992; Rees and Wackernagel, 1994; Wackernagel & Rees, 1996). They defined the EF as the inverse of carrying capacity: "the area of productive land… needed to sustain a defined population indefinitely, wherever on Earth that land is located" (Rees, 1996, p. 203). Building upon Borgstrom's concept of ghost acreage, Rees (1992) demonstrated that urban areas have an EF at least an order of magnitude greater than the actual space they occupy. If humans lived in a fashion that did not exceed the biocapacity of the earth, the average individual's EF would be about two hectares (Wackenagel *et al.*, 1999), taking into account the 12 per cent of bioproductive area that the Brundtland Commission suggested is needed to sustain the other 10 to 30 million species we share the planet with (WCED, 1987). The actual EF of individuals in the western world is likely in the range of four to seven hectares or more (Wackernagel & Rees, 1996; Rees, 1996; Wackernagel *et al.*, 1999; Ewing *et al.*, 2010; Pollard *et al.*, 2010).

These broad-scale measurements of EF based on aggregate population and resource consumption data are what Wackernagel and Monfreda (2004) call compound-based footprints. Throughout the 1990s, these regional or national aggregated measures were the typical form of communicating the EF, and they are still the emphasis of many EF-based analyses (Rees & Wackernagel, 1994; Rees, 1996; Wackernagel *et al.*, 1999; Wackernagel *et al.*, 2002; Ewing *et al.*, 2010). Component- or product-based measurements of individual products and services, however, are now also becoming common. Some early studies did examine the EF at a product scale: Wackernagel and

Rees (1996), for example, recognized the value of the EF for comparing the resource intensity of different products and technologies, and demonstrated its application to products using the example of a tomato. Huijbregts and colleagues (2008) applied the EF method to assessments of over 2600 products and services, making EF-based comparisons of, for example, sources of energy (fossil, nuclear, biomass, wind and solar), and determining the main drivers of the EF of each product and service (e.g. direct land occupation, energy land based on CO_2 emissions). Product-based EFs allow for finer scale analysis of what activities drive the results of compound EFs, and provide a platform for consumers and other stakeholders to compare products and services.

Ecosystem support has been measured at national and global scales for fisheries and at the farm and product scale for numerous aquaculture systems (Table 3). Generally, the EFs of fisheries as well as those of aquaculture systems farming carnivorous species are dominated by the marine ecosystem area required to sustain NPP appropriation (Folke, 1988; Berg *et al.*, 1996; Tyedmers, 2000). In the case of aquaculture systems, this NPP appropriation is to provide fish meal and oil for aquafeed inputs to higher trophic level species like salmon and trout (Folke, 1988; Tyedmers, 2000; Papatryphon *et al.*, 2004; Aubin *et al.*, 2006). Pauly and Christensen (1995) developed a standard method for calculating NPP appropriation by fisheries and estimated that global fisheries appropriate approximately 8 per cent of total aquatic NPP; regionally, appropriation ranges from 2 per cent in the open ocean to 25 per cent in upwelling zones and tropical shelves and 35 per cent in non-tropical shelves.

Table 3. Summary of ecosystem support studies of fisheries and aquaculture systems

Study	Fishery or culture system	Ecosystem support required
Vitousek *et al.* (1986)	Global annual harvest from fisheries	2 Pg C, or 2.2% of total marine NPP
Folke (1988)	Atlantic salmon culture in Sweden	100 ha per tonne[a]
Folke and Kautsky (1989)	Salmon and mussel culture in Scandinavia	100 ha per tonne salmon; 0.1 ha per tonne mussels
Larsson *et al.* (1994)	Shrimp farming in Colombia	5.4 ha per tonne[a]
Pauly and Christensen (1995)	Global annual harvest from fisheries	363.8 million km^2, or 8% of marine NPP
Berg *et al.* (1996)	Intensive net-pen culture and semi-intensive pond culture of Tilapia in Zimbabwe	17 ha per tonne net-pen culture; 0.3 ha per tonne pond culture[a]
Tyedmers (2000)	Farmed and commercially caught salmon in British Columbia	9.9-12.4 ha per tonne farmed salmon; 4.5-10.1 ha per tonne caught salmon
Papatryphon *et al.* (2004)	Rainbow trout fed feeds with varying portions of fish meal and oil	18.7-34.4 tonnes C NPP per tonne trout[b]
Aubin *et al.* (2006)	Turbot culture in France	60.1 tonnes C NPP per tonne turbot
Talberth *et al.* (2006)	Industry-wide estimates of fisheries at national and global scales	61 billion global hectares for the global fishing industry, an estimated biological overshoot of 157%

a. As re-calculated by Tyedmers (2000).

b. Ranged from 18.7 to 34.4 and 41.2 tonnes C NPP per tonne fish fed 30%, 72%, and 63% fish products, respectively. Trout grown on food with 0% fish meal and oil were associated with 0 kg C NPP appropriation.

1.6.3 Life Cycle Assessment

LCA is an International Organization for Standardization (ISO)-standardized biophysical accounting framework which traces material and energy flows throughout an entire production system, from “cradle to grave” (ISO, 2006a&b). LCA follows products from raw resource extraction through processing, packaging, transportation, distribution, and disposal, and quantifies contributions to a suite of environmental impact categories. These impact categories include both resource-based and emissions-based impacts which are of global significance, such as the depletion of limited energy resources, utilization of renewable biotic resources, emissions of GHGs, emissions of sulfur dioxide (SO_2) and other substances leading to acid precipitation, emissions of nitrogen and phosphorous into water bodies resulting in eutrophication, and emissions of ozone-depleting substances such as trichlorofluoromethane (CFC-11).

LCA-styled studies began exploring environmental impacts of packaging materials and other industrial products in the late 1960s and early 1970s. Interest in quantifying energy use and waste production with a life-cycle approach emerged largely out of the oil shocks and energy crises of the 1970s as well as growing concern over excess waste and packaging (Baumann & Tillman, 2004). These early studies were commissioned by businesses like the Coca-Cola Company, who wished to compare the environmental impacts of alternative bottling materials. In the 1990s, under the leadership of the Society for Environmental Toxicology and Chemistry (SETAC), the LCA methodology was refined and improved, and ISO developed a standard framework for its application, providing guidelines to practitioners on a number of methodological choices. Today, the rigour associated with the LCA process has achieved it a position as a preferred method for quantifying GHGs – the carbon footprint (CF) – of production systems (BSI, 2008; GFN, 2009). LCA can provide insight into which activity or product choice would be more environmentally responsible, identify hotspots in a product's supply chain which require attention and improvement, predict the environmental outcomes of a change in a process or product, and make recommendations as to how to decrease the impacts of specific phases of a product life cycle.

The formalized structure of LCA includes four stages. In the first stage, goal and scope definition, the objectives and parameters of the study are established. This includes the functional unit, or quantity of product against which environmental burden will be measured; system boundaries to define what processes and activities will or will not be included in analysis; and methods of analysis and impact assessment. In the second stage, data are collected and organized according to life cycle stage, producing an inventory of material and energy flows into and out of each unit process. The third stage translates these material and energy flows into quantified contributions to environmental impact categories using established characterization models. Finally, the fourth stage involves extraction of meaningful results, and analysis of results using sensitivity analysis and checks for completeness and consistency (ISO, 2006a&b, Guinée *et al.*, 2001).

1.7 Organization of the Thesis

This thesis is structured around the production of two manuscripts intended for publication in academic journals. Primary data collection, analysis, and writing of both papers was carried out by Robert Parker. Dr. Peter Tyedmers was involved in the original development of the research project, and provided guidance throughout the research process and editorial assistance during writing of the manuscripts.

The first of these papers, presented in Chapter 2, is an in-depth analysis of the variables influencing the marine portion of the ecological footprint, or the marine footprint (MF), as applied to fisheries products. Five reduction fisheries are examined using EF analysis, including Antarctic krill, Peruvian anchovy, Atlantic herring, Gulf menhaden (*Brevoortia patronus*), and blue whiting. Special attention is paid to the modeled uncertainty and natural variability associated with each variable, and the resulting variance in the final MF results. The discussion examines the usefulness of MF as a measure of fishery performance, and the role played by uncertainty and variability in the results of EF analysis and other indicators of ecological impact. This paper was presented at the Global Footprint Network's Footprint Forum 2010 in Siena, Italy, and is currently in review for the journal *Ecological Indicators*.

The second paper, presented in Chapter 3, contains the results of the LCA case study of AB's krill-derived products. Results of both the life cycle inventory analysis of material and energy inputs to the krill production system, and the life cycle impact assessment quantifying contributions to a suite of six environmental impact categories, are included. Interpretation of results includes both characterization of impacts associated with different stages of the production chain, and scenario analysis to model potential improvements from a number of possible changes made to the system. The discussion compares results to other LCAs of fishery-derived products, and compares the performance of the Antarctic krill fishery to other reduction fisheries on the basis of fuel use intensity (FUI), and also considers comparisons to non-fish inputs to aquafeeds. Results of this paper were presented at the 7th International Conference on LCA in the Agri-Food Sector in Bari, Italy, and at the Kinki-Ifremer Symposium on minimizing the footprint of aquaculture and fisheries, in Sète, France.

Chapter 4 discusses the results of the two papers in the context of the above stated thesis objectives. This discussion includes consideration of the significance of results to the Antarctic krill fishery, other reduction- and non-reduction fisheries and aquaculture systems, and the future of food production in the face of numerous environmental and other challenges. The aggregate EFs of products from Antarctic krill and other reduction species, including both the MF and the CF, are also presented in this chapter and briefly discussed, including comparisons of the marine and terrestrial (energy land) portions.

This discussion is followed by appendices which provide additional data and detailed results, intended to both support the results presented in the two papers and provide data for future research. Appendix A provides nutritional content information for krill and fish meals, used to calculate energy density of meal products in Chapter 2. Appendix B provides more detailed results from the sensitivity analysis appearing in Chapter 2. Appendix C reports the energy use and emissions used to populate background pork production processes in the LCA. Appendix D lists the background processes used to build the krill product life cycle inventory. Appendix E provides fuel-specific characteristics and data for marine diesel oil (MDO) and intermediate fuel oil (IFO) as well as Bunker C fuel for comparison. Appendix F provides further details on the calculation of biotic resource use (BRU) in the krill LCA. Appendix G reports catch by month, and production and fuel use by year, pertaining to AB's fishing and resupply vessels for. Appendix H provides distribution routes and distances for AB's meal and oil products. Appendix I provides a detailed breakdown, by production stage and sub-process, of the characterized life cycle environmental impacts of Aker BioMarine's three krill-derived products: krill meal, krill oil, and omega-3 krill oil capsules. Finally, Appendix J provides a detailed analysis of the CF of meal and oil derived from Antarctic krill and the four other reduction species for which the MF is measured in Chapter 2.

Chapter 2. Uncertainty and Natural Variability in the Ecological Footprint of Fisheries: A Case Study of Reduction Fisheries for Meal and Oil

2.1 Abstract

It is well understood that measurements of EF and many other ecological indicators are associated with varying degrees of uncertainty, yet imprecision in EF results is rarely assessed or communicated. We calculated the marine portion of the EF of products derived from five reduction fisheries: Peruvian anchovy, Atlantic herring, Gulf menhaden, blue whiting and Antarctic krill. Monte Carlo analysis was used to measure the imprecision in MF measurements resulting from uncertainty and natural variability in input parameters, and to determine the degree to which imprecision affects our ability to draw meaningful conclusions when comparing products sourced from different fisheries on the basis of EF. Gulf menhaden and Antarctic krill were found to have the smallest MFs, while blue whiting was found to have the largest. Results show that there is much uncertainty associated with MF calculations and that the most significant drivers of this imprecision are uncertainty and natural variability regarding measurements of trophic level and trophic transfer efficiency. MF is highly correlated with trophic level, and clear differences can be seen when comparing species of very different trophic levels. However, comparisons of products derived from species with similar trophic levels are less likely to provide conclusive results. The choice of mass, protein or energy content as the basis of comparison was also considered and was found to influence the results, particularly when comparing species' with similar trophic levels. While it is likely that imprecision of MF measurements of fishery-derived products will remain high, technological improvements and a better understanding of marine ecosystem dynamics may make future studies more precise.

2.2 Introduction

In the context of modern environmental concerns, there is growing interest in the ability to understand and successfully measure the degree to which human beings are placing demands upon the resources and services of the ecosphere (Millennium Ecosystem Assessment, 2005; Pollard *et al.*, 2010; Butchart *et al.*, 2010). Measuring environmental burden and improving the environmental performance of human activities and products requires close inspection of the tools with which we quantify and communicate environmental impact and guide decision makers. The EF (Rees, 1992; Rees & Wackernagel, 1994) is a representation of the land and sea area required to sustain human population and human activities and the degree to which demand on ecological resources and services fits within, or overshoots, the capacity of the earth to provide them. It has been widely applied to inform individuals, governments, businesses and others of the pressure their activities place on the capacity of natural systems to provide resources and assimilate wastes (Wackernagel & Rees, 1996; Wackernagel *et al.*, 1999; Talberth *et al.*, 2006; Huijbregts *et al.*, 2008; Ewing *et al.*, 2010; Pollard *et al.*, 2010).

Measurements of EF are typically communicated in absolute values of land and sea area, and are obtained using calculations which incorporate absolute values of input parameters (Wackernagel *et al.*, 1999; Talberth *et al.*, 2006; Huijbregts *et al.*, 2008; Ewing *et al.*, 2010). The importance of natural variability and uncertainty in influencing the actual value of input variables, as well as the accuracy with which they are translated into spatial reflections of environmental burden, is recognized (GFN, 2009), though not commonly assessed and communicated in EF studies. To date, the sources and influence of uncertainty and natural variability for many elements of the EF have not been formally addressed.

Uncertainty can be broadly defined as "any departure from the unachievable ideal of complete determinism" (Walker *et al.*, 2003, p. 8). This definition infers that sources of uncertainty include any forces which inhibit our ability to produce single, precise and accurate measurements of phenomena. While the exact definition of uncertainty and the categorization of its sources varies between researchers and fields of study, many authors have come to distinguish between two general types: epistemic uncertainty (reflecting a lack of knowledge as a result of limited data, measurement error, imperfect models, *etc.*) and ontological uncertainty (inherent variability of phenomena over space and time) (Baecher & Christian, 2000; Walker *et al.*, 2003; Brugnach *et al.*, 2008). Throughout the remainder of this paper, we will refer to epistemic uncertainty simply as 'uncertainty' and to ontological uncertainty as ‘natural variability’. Together, sources of uncertainty and natural variability contribute to the overall imprecision associated with measurements and models and, ultimately, confidence in the accuracy of single, static measurements.

The EF, applied to marine ecosystems and the extraction of marine resources, is a measurement of demand upon the productivity of the world’s oceans by humans. It is well understood that humans, like all species, rely on the life support systems of the natural environment to provide us with resources and assimilate our wastes (Odum, 1993), and it is clear that our demands on the natural environment often exceed the ability of the world’s ecosystems to provide resources and assimilate wastes, placing us in a state of “ecological overshoot” (Wackernagel *et al.*, 2002). Within this context, the MF provides an indication of our demands on aquatic life support systems and the degree to which those demands fit within – or overshoot – the biocapacity of the oceans. The MF does not, as critiques have clearly pointed out (Roth *et al.*, 2001), provide a measure of the direct and indirect impacts of fishing, such as habitat alteration, interference in aquatic food webs, or pollution of the oceans, nor does it provide a holistic measure of the full environmental, economic and social costs of fisheries, whether positive or negative. The MF typically measures appropriation of NPP – the extraction of photosynthesis-produced carbon from the ocean in the form of biomass – as a fraction of the total NPP of marine environments. It can be applied to the assessment of any product, service or activity which directly or indirectly relies on the extraction or otherwise use of marine-sourced biotic resources.

Previously, the EF has been used to evaluate several aquaculture systems, including production of salmon, tilapia, shrimp and mussels (Folke, 1988; Folke & Kautsky; 1989; Larsson *et al.*; 1994; Berg *et al.*, 1996; Tyedmers, 2000). While early applications varied slightly with regard to the inclusion or exclusion of different draws on ecological productivity, appropriation of NPP from marine and agricultural systems was a common consideration. Other elements considered in some studies included mangrove area required for production of juvenile stock, and marine ecosystem area required to assimilate wastes, provide oxygen and facilitate phosphorous assimilation. These early studies demonstrated the magnitude of ecological life support area demanded by aquaculture production, particularly for carnivorous species: Folke (1988), while not explicitly calling it an EF, suggested that salmon net pen culture in the Baltic relied on ecosystem areas 40,000-50,000 times the area occupied by the pens. These studies also highlighted the relative importance of the marine portion of the EF to provide fish meal and/or oil from pelagic fisheries, easily overshadowing the area of agricultural land required to provide crop-derived inputs. Interestingly, the role of marine ecosystem productivity represented a smaller portion of the footprint for non-carnivorous species, such as shrimp which rely more heavily on mangrove area for nursery production (Larsson *et al.*, 1994). This domination of NPP appropriation by marine inputs to feed production is echoed in Papatryphon and colleagues' (2004) assessment of salmonid feeds. Tyedmers (2000) analyzed the portion of the ecological footprint devoted to marine inputs in the context of wider ecosystem reliance of salmon production, taking into account ecosystem area needed to support energy use, labour and provision of raw materials, and found that marine ecosystem area still represented the largest share of the total EF. This body of research on the environmental demands of aquaculture and aquaculture feed inputs highlights the important role of capture fisheries as significant determinants of the ecosystem reliance of many farmed fish species.

Ecosystem support for fisheries has been measured at both national and global scales (Vitousek *et al.*, 1986; Pauly & Christensen, 1995). Pauly and Christensen (1995) advanced a method for calculating the NPP required to sustain extraction of fish species, and used this method to estimate that global fisheries appropriate approximately 8 per cent of total marine NPP; regionally, appropriation ranged from 2 per cent in the open ocean to 25 per cent in upwelling zones and tropical shelves and 35 per cent in non-tropical shelves. More recently, Talberth and colleagues (2006) measured the MF or "fishprint" of fishing industries by country, following the method established by Pauly and Christensen (1995). They compared the NPP required to sustain actual harvests of different fish species to the modeled biocapacity of the world's oceans and concluded that, on a national scale, 90 per cent of countries considered were appropriating NPP from the ocean at a rate greater than their exclusive economic zones were producing. On a global scale, Talberth and colleagues found that NPP appropriation overshot the biocapacity of the world's oceans by 150 per cent.

While these broad scale evaluations of national and global fisheries have provided an indication of human dependence on marine productivity, there has been relatively little evaluation of ecosystem dependence on individual products derived from fisheries. The non-trivial role played by fishery-derived products in the footprint of aquaculture systems suggests that these analyses, performed on reduction fisheries for meal and oil, may provide a useful tool for understanding and possibly decreasing the Ecological Footprint of seafood. Meal and oil from reduction fisheries have long been used as inputs to livestock feeds, consumed directly by humans, and as bait for sport and commercial fishing. In recent years the aquaculture industry has become a major destination for these products: by 2002 aquaculture feeds accounted for 46 per cent of total fish meal usage worldwide and 81 per cent of fish oil usage (Tacon, 2008; Tacon & Metian, 2008). The fisheries that provide these products constitute some of the largest in the world, with catches from six of the top ten currently harvested species being destined for reduction plants, including Peruvian anchovy, Atlantic herring, and blue whiting (FAO, 2009a). Péron and colleagues (2010) estimated that, on average, some 30 million tonnes of pelagic fish are extracted per annum to be reduced to meal and oil.

Here we examine the application of the MF to fisheries-derived products and critically assess the drivers of imprecision and the degree to which uncertainty and natural variability in input variables affect our ability to draw meaningful conclusions from EF results. We have chosen five reduction fisheries as case studies to illustrate this assessment, which we evaluate using the MF methodology advanced by Pauly and Christensen (1995). The five fisheries were chosen based on relative significance to the global meal and oil industry and the availability of data, and include those targeting Peruvian anchovy, Atlantic herring, blue whiting, Gulf menhaden and Antarctic krill. These species cover a wide range of biological and ecological characteristics, ranging from low trophic level zooplankton to high trophic level predatory fish. They also vary widely in source locale, spanning the Southern, Pacific and Atlantic oceans, and annual harvest rates (Table 4). Together, the five fisheries considered account for approximately half of the global harvest of marine species destined for reduction into meal and oil, and include several of the top harvested species globally; the fishery for Peruvian anchovy, for example, is the largest in the world by catch (Tacon, 2008; FAO, 2009b).

Table 4. Annual global harvest and primary fishing region of species included in EF analysis.

Species		Annual Harvest (t)[a]	Region[b]
Peruvian anchovy		7,350,000	Coastal Chile and Peru
Atlantic herring		2,360,000	Northeast Atlantic
Blue whiting		1,670,000	Northeast Atlantic
Gulf menhaden		430,000	Gulf of Mexico
Antarctic krill		120,000	Southern Ocean

a. Annual harvest rates are three-year average global catches for 2006-2008 from FAO (2010a).
b. Primary fishing region based on Kaschner and colleagues (2008).

2.3 Methods

We calculated the MF of five reduction fisheries, based solely on NPP appropriation, using the equation:

$$MF = \frac{\frac{B}{W} \cdot \left({}^{1}/_{E} \right)^{T-1}}{N}$$

where MF is the marine footprint in hectares, B is the biomass extracted in tonnes, W is the ratio by mass of wet weight biomass to carbon, E is the transfer efficiency of carbon between trophic levels, T is the species-specific trophic level, and N is the net primary productivity of the source ecosystem in tonnes per hectare (adapted from Pauly & Christensen, 1995). Because yields of meal and oil, and the nutritional value of meal products, vary between species, it was necessary to establish a common basis of comparison. Output of nutritional energy was chosen here as a basis for calculating the biomass input parameter, because provision of energy was considered to be the primary function of the products. Therefore, the MF of each species is here defined as the marine ecosystem area required to sustain the production of 100 GJ of combined meal and oil product, respecting the species-specific yields of meal and oil.

To examine the uncertainty and natural variability associated with results of the calculation, it was necessary to establish mean values, probability distributions, and maximum and minimum limits for a number of parameters (Table 5). For some parameters, established distributions, in the form of ranges, standard deviations or standard errors, could be found in the literature. For others, in the absence of previously established values and ranges, we had to rely on expert opinion and communications with industry representatives. We modeled probability distributions for each input parameter for each fishery, based on established mean values, ranges, standard deviations and/or standard errors when available.

Table 5. Sources of data used to inform MF calculations in this study.

Parameter		Source
Biomass	Meal yield	Robb, 2007, pers. comm.; Nordrum, 2009, pers. comm.
	Oil Yield	Robb, 2007, pers. comm.; Nordrum, 2009, pers. comm.
	Meal nutritional content	NRC, 1994
	Meal energy density	Sauvant *et al.*, 2004
	Oil energy density	Sauvant *et al.*, 2004
Wet weight to carbon ratio		Strathmann, 1967
Transfer efficiency	Standard value	Lindeman, 1942
	Distribution	Pauly & Christensen, 1995
Trophic level		Froese & Pauly, 2010
Net primary productivity	Primary fishing region	Kaschner *et al.*, 2008
	Productivity of region	Longhurst *et al.*, 1995

Meal and oil yields for all species were solicited from industry in the form of personal correspondence with one fish feed supplier (Robb, 2007, pers. comm.) as well as, in the case of Antarctic krill, a questionnaire to a Norwegian krill-fishing and processing company, Aker BioMarine (Nordrum, 2009, pers. comm.). Yields for fish species were given as typical values and were considered to be ‘best case’ scenarios and used as the upper range of expected yields, with probability distributions negatively skewed to account for occurrence of lower yields. Oil yields were expected to vary more heavily than meal yields as they tend to be more sensitive to changes in environmental conditions, and so wider ranges of variability were placed around oil yield rates gathered from industry. Energy densities of all meals were calculated following Sauvant and colleagues (2004) and applying nutritional content values for species-specific meals (NRC, 1994; see Appendix A). Oil was assumed to have a constant energy density of 39.3 MJ/kg (Sauvant *et al.*, 2004).

Species characteristics and ecological relationships can vary widely between ecosystems and under changing conditions (Pauly & Christensen, 1995). An established average value of 9:1 for the ratio of wet weight to carbon (Strathmann, 1967; Pauly & Christensen, 1995) was used, and a normal distribution was assumed with a standard deviation of 20 per cent of the mean, reflecting relatively high variation between estimates (Strathmann, 1967). Trophic transfer efficiency has been modeled for many marine ecosystems and was found to have an average value of 10 per cent (Pauly & Christensen, 1995), equal to the previously established typical value (Lindeman, 1942; Odum, 1993). The natural variability of transfer efficiency between ecosystems, however, is high, ranging from 2 per cent to 24 per cent (Pauly & Christensen, 1995). Trophic levels of fish along with associated standard errors were taken from Froese and Pauly (2010) based on diet composition data. The trophic level of krill was taken from Pauly and Christensen (1995) with an assumed standard deviation of ten per cent. It was assumed that the upper and lower limits of each species' trophic level would not be greater than one full level above or below values reported by Froese and Pauly (2010) and that no species included here would be likely to have a trophic level greater than 5 or less than 2.

We applied regional measurements of NPP based on satellite radiometer data (Longhurst *et al.*, 1995). These data are derived from the Coastal Zone Colour Scanner (CZCS) satellite launched by the National Aeronautics and Space Administration (NASA) in 1978, which measured upwelling radiance from the earth's oceans as an indicator of absorption of light by phytoplankton pigments (Joint & Groom, 2000). Translating these radiance measurements into estimates of primary standing stock of phytoplankton allowed for the first global-scale estimates of marine productivity, broken down regionally and expressed in grams carbon per unit area per year (g $C/m^2/yr$) (Longhurst *et* *al.*, 1995). There is high uncertainty associated with the actual measurements of upwelling radiance as well as with the algorithms used to translate them into estimates of productivity (Longhurst *et al.*, 1995; Joint & Groom, 2000), so we allowed for a wide range of variance in our NPP parameter (Table 6).

We employed Palisade Corporation's @Risk software application for Microsoft Excel to run Monte Carlo analysis using the modeled probability distributions for each parameter. Histogram results from a Monte Carlo simulation of 10,000 iterations provided a probability distribution of MF outcomes for each species, and sensitivity analysis was used to measure the degree to which changes in each of the input variables influenced the final MF outcome. We performed this analysis using several different methods of biomass determination (provision of 100 GJ of energy from meal and oil; provision of one tonne of protein from meal and oil; provision of one tonne wet weight biomass) to identify possible outcome sensitivity to our choice of basis of comparison.

2.4 Results

Absolute limits, mean values and standard deviations for the modeled probability distributions of each parameter for each species appear in Table 6. Meal yield and meal energy density varied little between species, with the exception of Antarctic krill, which has significantly lower yields of both meal and oil but higher meal energy density related to a high lipid concentration in krill meal. Oil yield varies greatly between species, ranging from less than 1 per cent for Antarctic krill and 2 per cent for blue whiting, to 16 per cent for Gulf menhaden. Using the mean values for yield and energy density, the biomass of each species required to provide 100 GJ of energy from combined meal and oil are: 9.5 tonnes of Gulf menhaden, 11.4 tonnes of Atlantic herring, 17.9 tonnes of Peruvian anchovy, 23.7 tonnes of blue whiting and 26.0 tonnes of Antarctic krill.

The median MF value, i.e. marine ecosystem area required to sustain the production of 100 GJ of combined meal and oil, varied widely between species, as did the relative range of potential values when all sources of uncertainty and natural variability were accounted for (Figure 6). Median MF values per 100 GJ were calculated to be 8.4 hectares (ha) for products derived from Gulf menhaden, 18.7 ha for Antarctic krill products, 26.9 ha for Atlantic herring products, 35.5 ha for Peruvian anchovy products, and 989 ha for blue whiting products. In general, greater variance of results is associated with higher trophic level species (Figure 6). These probability distributions are positively skewed, with skew also being correlated with trophic level. Probability distributions for low trophic level species' like Gulf menhaden and Antarctic krill are relatively narrow, with 90 per cent of values falling below 30 ha and 75 ha, respectively. Meanwhile, the upper range of values for blue whiting products extends into the tens and even hundreds of thousands of hectares per 100 GJ (Figure 6). Interestingly, the median value for Peruvian anchovy is greater than that for Atlantic herring, but the upper range of expected values for herring are much higher, with 90 per cent of results falling below 310 ha for herring and 240 ha for anchovy (Figure 6).

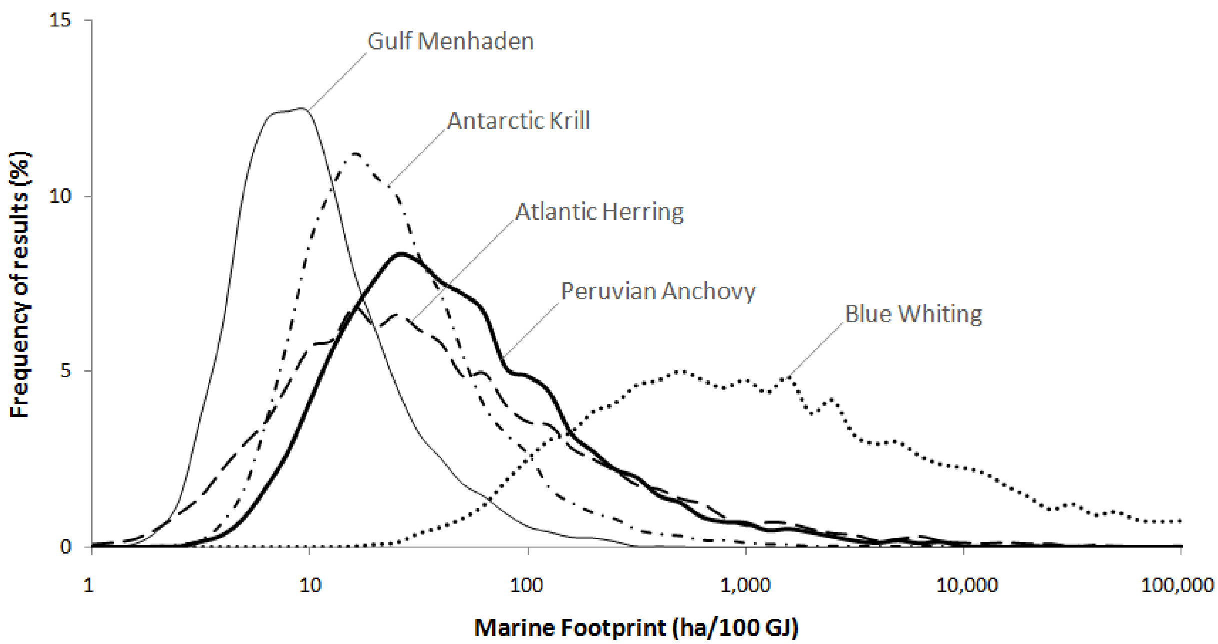

Figure 6. Distribution of marine footprint results showing the marine ecosystem areas required to sustain production of 100 GJ of combined meal and oil from five species. X-axis is logarithmic and shows the range of results. Y-axis shows the frequency with which any given result occurred in Monte Carlo analysis simulation.

Table 6. Maximum and minimum limits, mean values (μ) and standard deviations (σ) used to model probability distributions of input parameters for calculating MF.

Variable	Atlantic herring	Peruvian anchovy	Gulf menhaden	Blue whiting	Antarctic krill
Meal yield (kg/tonne)[a]	*180-218* $\mu = 200$ $\sigma = 9.0$	*180-225* $\mu = 205$ $\sigma = 10.2$	*189-230* $\mu = 220$ $\sigma = 7.5$	*180-211* $\mu = 195$ $\sigma = 7.6$	*140-180* $\mu = 160$ $\sigma = 7.6$
Oil yield (kg/tonne)[a]	*90-130* $\mu = 111$ $\sigma = 10.9$	*20-61* $\mu = 46$ $\sigma = 8.0$	*120-190* $\mu = 161$ $\sigma = 18.5$	*10-23* $\mu = 18$ $\sigma = 2.9$	*0.6-1.0* $\mu = 0.8$ $\sigma = 0.05$
Meal energy density (MJ/kg)[b]	*19.9-24.3* $\mu = 22.1$ $\sigma = 1.1$	*16.6-20.2* $\mu = 18.4$ $\sigma = 0.9$	*17.2-21.0* $\mu = 19.1$ $\sigma = 1.0$	*16.2-19.8* $\mu = 18.0$ $\sigma = 0.9$	*22.0-25.0* $\mu = 23.84$ $\sigma = 1.2$
Oil energy density[c] (MJ/kg)	$\mu = 39.3$	$\mu = 39.3$	$\mu = 39.3$	$\mu = 39.3$	$\mu = 39.3$
Protein content (%)[d]	$\mu = 72.3$	$\mu = 64.2$	$\mu = 60.1$	$\mu = 62.6$	$\mu = 56.0$
Wet weight to carbon ratio[e]	*6-20* $\mu = 9$ $\sigma = 1.8$	*6-20* $\mu = 9$ $\sigma = 1.8$	*6-20* $\mu = 9$ $\sigma = 1.8$	*6-20* $\mu = 9$ $\sigma = 1.8$	*6-20* $\mu = 9$ $\sigma = 1.8$
Transfer efficiency (%)[f]	*1-25* $\mu = 10.13$ $\sigma = 5.81$	*1-25* $\mu = 10.13$ $\sigma = 5.81$	*1-25* $\mu = 10.13$ $\sigma = 5.81$	*1-25* $\mu = 10.13$ $\sigma = 5.81$	*1-25* $\mu = 10.13$ $\sigma = 5.81$
Trophic level[g]	*2.23-4.23* $\mu = 3.23$ $\sigma = 0.37$	*2-3.7* $\mu = 2.7$ $\sigma = 0.31$	*2-3.19* $\mu = 2.19$ $\sigma = 0.07$	*3.01-5.0* $\mu = 4.01$ $\sigma = 0.50$	*2-3.2* $\mu = 2.2$ $\sigma = 0.17$
Net primary productivity[h] (gC/m^2/year)	*183-1278* $\mu = 730$ $\sigma = 180$	*68-471* $\mu = 269$ $\sigma = 66$	*48-333* $\mu = 190$ $\sigma = 47$	*60-420* $\mu = 240$ $\sigma = 59$	*71-494* $\mu = 282$ $\sigma = 70$

a. Fish meal and oil yields from industry (Robb, 2007, pers. comm.). Krill meal and oil yields based on data from Nordrum (2009, pers. comm.).
b. Calculated based on nutritional value (Sauvant *et al.*, 2004).
c. Oil energy density assumed to be constant across fish species (Sauvant *et al.*, 2004).
d. It was not required here to formulate a distribution range for protein content. Mean values for fish species are from NRC (1994). Value for Antarctic krill from Nordrum (2009, pers. comm.).
e. Mean value from Strathmann *et al.* (1967). 20% standard deviation assumed.
f. Range and standard deviation from Pauly and Christensen (1995).
g. Fish species trophic levels and standard errors from Froese and Pauly (2010).
h. Fishing region based on Kaschner *et al.* (1995). Regional NPP from Longhurst *et al.* (1995).

Contribution analysis shows that the magnitude of influence by variables on MF distribution is relatively consistent between fisheries (Figure 7; see Appendix B). Ecological variables play the most significant roles in contributing to the variance of MF results. Importantly, transfer efficiency of carbon between trophic levels contributes most to the distribution of values for all species, with an average correlation coefficient of -0.77. Results are also very sensitive to changes in trophic level, with an average correlation coefficient of 0.47. The much lower influence of this variable on results for Gulf menhaden is explained by the lower standard error associated with the trophic level input value (Table 6). Primary productivity of the source locale and the ratio of wet weight to carbon also influence the distribution of results, having correlation coefficients of -0.23 and 0.21, respectively. Source locale was found to be particularly influential in cases where fisheries from regions with markedly different productivity rates were compared; the high productivity of the North Atlantic, for example, explains why products derived from Atlantic herring were found to have a smaller MF than those from Peruvian anchovy. The greater influence of these variables on Gulf menhaden MF values is again explained by the lower relative variation in the trophic level input. Interestingly, oil yield, meal yield and meal energy density contribute very little to the overall variance for all species, having correlation coefficients of -0.04, -0.03, and -0.02, respectively.

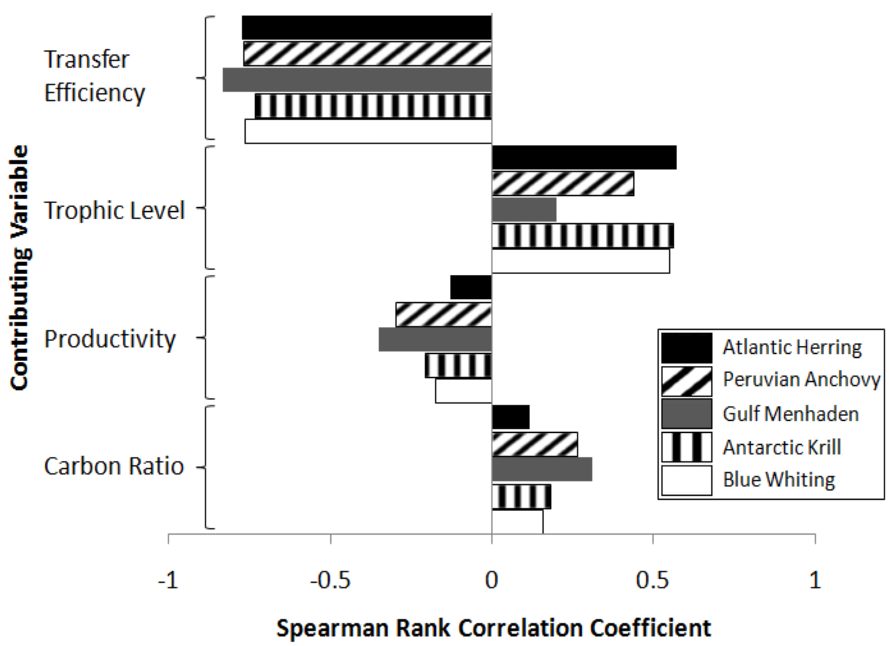

Figure 7. Correlation between changes in input variables and changes in marine footprint results, for each species. Oil yield, meal yield, and meal energy density variables are not included, as they have very little influence on final results.

The choice of basis of comparison is shown to have a strong influence on the outcome of MF results when multiple species are being compared (Figure 8). Generally, the pattern of lower trophic level species having lower MFs holds true regardless of the basis of comparison. However, closer inspection of results shows that, when two or more species are similar in trophic level, one basis of comparison may result in one species having the larger MF while another basis of comparison would result in the same species having the smaller MF. For example, results calculated using energy and protein as bases of comparisons show Antarctic krill to have a larger MF than Gulf menhaden, while mass-based results show krill products to have a smaller MF. This is explained by the lower overall energy and protein yields from krill when compared to oil-rich menhaden. Similarly, energy-based results show Peruvian anchovy to have a higher MF than Atlantic herring, as opposed to a lower MF when mass- and protein-based comparisons are used.

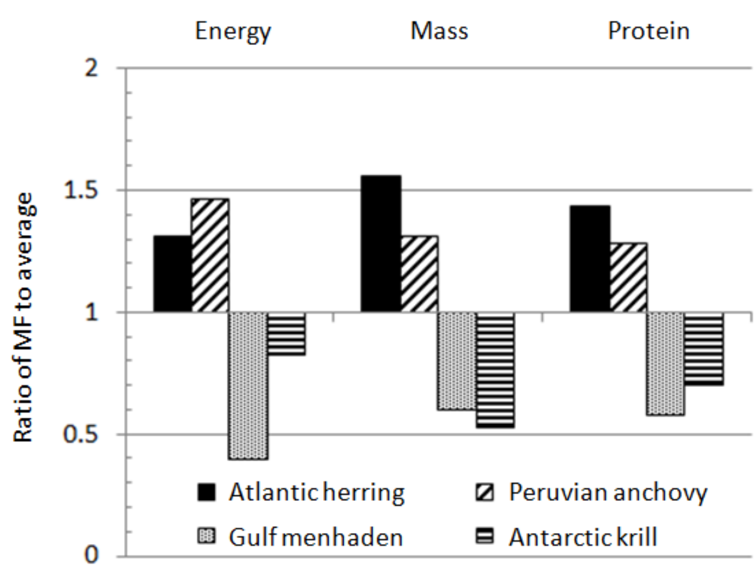

Figure 8. MF outcomes for four species relative to the average, showing results of comparisons based on gross energy content (100 GJ of combined meal and oil), mass (1 tonne wet weight mass) and protein content (1 tonne protein from combined meal and oil).

2.5 Discussion

The results of our analysis demonstrate the magnitude of imprecision apparent in MF results when input parameter uncertainty and natural variability are considered. The most significant drivers of the low precision of results are the ecological parameters of trophic level and trophic transfer efficiency. Our modeling, however, did not differentiate between potential sources of imprecision within each input parameter, whether they be epistemic (uncertainty regarding the accuracy of measurements) or ontological (natural variation over time or space) in nature.

Uncertainty arises in our ability to accurately measure inputs and our understanding of the ecological processes associated with modeling the MF. This includes uncertainty regarding satellite radiometer data and algorithms to translate reflectance into measures of productivity; the formula used to calculate energy density from nutritional content; the standard 9:1 wet-weight-to-carbon biomass conversion estimate; and the assumption of 10 per cent transfer efficiency between trophic levels. The magnitude of uncertainty in species-specific MF measurements of fisheries may be decreased through technological improvements, along with a better understanding of marine ecological systems and the use of more species-specific and ecosystem-specific values rather than relying on generalized estimates of, e.g., NPP and trophic transfer efficiency of carbon. Future research measuring the MF of marine products may benefit from the use of locale-specific ecosystem models such as those developed using EcoPath software (Pauly *et al.*, 2000).

Along with epistemic uncertainty in input parameters, natural variability also explains much of the distribution in expected MF outcomes. Natural variability can be seen in the expected meal and oil yields of any fish species, as well as meal energy content, which vary seasonally and as a result of significant environmental disturbances such as El Niño events (Barber & Chavez, 1983; Stenseth *et al.*, 2002). Trophic dynamics vary between ecosystems and life cycle stages within each species, and as a result of pressures by fishing and other disturbances (Cushing, 1975; Utne-Palm *et al.*, 2010). Productivity also varies seasonally and as a result of environmental disturbances (Barber & Chavez, 1983;

Sathyendranath *et al.*, 1995). Unlike the imprecision introduced into our model by uncertainty, little can be done to decrease the influence of natural variability on the results of the MF. In fact, changing global climatic conditions, as well as ecological shifts that result from marine disturbances such as fishing and pollution, may well result in even greater variability around many of these parameters in the future.

The question must be asked, does this demonstrated imprecision in results devalue the absolute estimates typically used to communicate the MF of fisheries? It is important to point out that most of the parameters included here are assumed to be normally distributed, excluding meal and oil yields which had little influence on the total variance in the results. Results therefore, unsurprisingly, show median values which closely resemble those outcomes achieved by using absolute estimates rather than probability distributions for input values. This suggests that, provided our assumptions of normal distribution are correct, the single-value estimates typically communicated in MF results are as robust as possible with our current understanding of ecological processes. However, the magnitude of variance and the degree to which distributions overlap are critical in determining the weight which can be placed on comparative analyses. In some cases, for example the comparison of products derived from fisheries targeting Gulf menhaden and blue whiting, vastly separated median values and distributions which overlap very little make a comparative judgment that blue whiting products are associated with a larger MF relatively easy to make. However, in other cases, such as the comparison of Atlantic herring and Peruvian anchovy products, close medians coupled with significant overlap make judgments less reliable and conclusive statements less justified.

While little work has been done to analyze the uncertainty and natural variability associated with EF results (exceptions include Simmons *et al.*, 2007, and Beynon & Munday, 2008), similar approaches to that taken here have been applied to measurements of greenhouse gases, or the CF (Lenzen *et al.*, 2010; Röös *et al.*, 2010.; de Koning *et al.*, 2010). Studies which have used Monte Carlo analysis to measure the uncertainty surrounding the CF of products have come to a similar conclusion: that significant uncertainty, particularly regarding the differences between footprints of competing products, affects the ability of companies to fairly and effectively label products as having a greater or lesser environmental cost (Röös *et al.*, 2010.; de Koning *et al.*, 2010).

From our comparative analysis of five reduction fisheries, it is apparent that there are clear and significant differences in required ecosystem support of products derived from different fisheries. These results have clear implications for the systems that require inputs of products derived from reduction fisheries, including aquaculture and livestock sectors as well as other industries (e.g. nutraceuticals). Because of the importance of these inputs in driving the total EF of many aquaculture-derived products, knowledge of the relative MF of inputs from different fisheries can help guide decision makers who wish to minimize the EF of aquaculture products and make EF-based product declarations. Companies seeking to reduce the EF of products which rely heavily on inputs from reduction fisheries may benefit from the use of products derived from Gulf menhaden or Antarctic krill fisheries rather than blue whiting fisheries, for example. Analyses of ecosystem support required to sustain culture of various organisms (Papatryphon *et al.*, 2004; Aubin *et al.*, 2006; Pelletier *et al.*, 2009; Welch *et al.*, 2010) would benefit from consideration of the differences between meal and oil products originating from different source fisheries.

A number of assumptions and limitations are inherent in our study. First and foremost, our analysis of the EF of fisheries is based on NPP assimilation alone. While the measurement of MF based on NPP as the most basic level of biotic resource production has merit (Venetoulis & Talberth, 2008), there are many elements that have been excluded which, if considered, could be decisive. Land area required to provide materials (boat, gear, packaging, etc.) is excluded, but it is likely that demands on land use would be similar across different fisheries. Perhaps more importantly, the CF of reduction fisheries was not included. FUI, while it does not take into account the energy use and emissions associated with non-fishing stages of the production life cycle, is generally a good indicator of total CF in fisheries systems (Ziegler *et al.*, 2003; Hospido & Tyedmers, 2005) and can vary significantly between those fisheries examined here (Table

7). These other elements of the EF would, of course, also be subject to numerous sources of uncertainty and natural variability; for example, Driscoll and Tyedmers (2010) report marked variation in fuel use intensity within a fishery targeting a single species as a result of the use of purse seine or pair trawl fishing gear (Table 7).

Table 7. Fuel use intensities of reduction fisheries in litres burned per tonne wet weight landings.

Fishery	Gear (if known)	Fishing Locale	Fuel Use Intensity (L/t)
Atlantic herring[a]	Purse Seine	Northwest Atlantic	21
Gulf menhaden[b]	Purse Seine	North Atlantic	32
Blue whiting[b]	Purse Seine	North Atlantic	85
Atlantic herring/sand eels[b]	Purse Seine	North Atlantic	100
Blue whiting[c]		Northeast Atlantic	106
Atlantic herring[c]		Northeast Atlantic	106
Atlantic herring/mackerel[b]	Trawl	North Atlantic	110
Atlantic herring[a]	Trawl	Northwest Atlantic	118
Atlantic herring[d]	Purse Seine	Northeast Atlantic	140
Antarctic krill[e]	Trawl	Atlantic Southern Ocean	191

a. Driscoll & Tyedmers (2010).
b. Tyedmers (2004).
c. Schau *et al.* (2009).
d. Thrane (2004).
e. See Chapter 3.

The use of ours and other MF results as measures of sustainability assumes that, first, MF is an appropriate measure of environmental sustainability, and second, decreasing MF would translate into greater fisheries sustainability. We recognize that a number of important elements of sustainability, including damage to marine habitats and actual harvest rates in relation to stock status, are not reflected in these results. It is also important to recognize that socio-economic indicators of sustainability are disregarded.

Our analysis of the sensitivity of MF results to the choice of a basis of comparison demonstrates the importance of this methodological choice to the outcome of MF studies. Mass is typically used as a basis of comparison for fishery-derived products. However, we have opted to use energy-based analysis as energy density is a more accurate reflection of the function of the products, that is to provide nutritional inputs to feeds. This choice can clearly change the outcome of comparative analyses, with products from one fishery having a larger MF when the basis of comparison is mass and a smaller MF when the basis of comparison is energy. It is critical, then, for MF studies to be consistent and transparent in their methodological choices, as bias can easily be introduced. Although our analysis was restricted to the marine portion of the EF, these methodological issues should be considered in the broader discussion of EF and other ecological indicators and the basis upon which we evaluate and compare products.

2.6 Conclusions

We measured the MF of five reduction fisheries and critically assessed the influence of uncertainty and natural variability on our ability to draw conclusions when comparing different fisheries. The trophic level of the target species was found to be a good indicator of MF, as products from low trophic level species such as Gulf menhaden and Antarctic krill were calculated to have the smallest MFs while products from high trophic level blue whiting were found to have the largest MF. However, probability distributions for each species' MF overlapped, with the greatest overlap being between species with similar trophic levels. This imprecision was driven largely by uncertainty and natural variability regarding ecological processes: trophic level of the targeted species, and transfer efficiency of carbon through aquatic food webs. While some fisheries have MFs too similar to draw meaningful conclusions, significant differences between species of vastly different trophic levels would allow for MF-based declarations.

Future work should be directed to quantify and better understand the sources of uncertainty and natural variability on other elements of the EF. The growing popularity of the EF and similar metrics as measures of environmental sustainability, and growing interest in the use of the EF and similar tools as bases for product declarations, make understanding the dynamics that drive the results of these assessments critical. While absolute values do provide rough estimates of human dependence on ecological systems, recognizing, and where possible improving, the degree of precision associated with the implementation of these tools is necessary as we continue to attempt to measure, precisely and accurately, the impact of human activities on the natural world.

Chapter 3. Life Cycle Environmental Impacts of Products Derived from the Antarctic Krill Fishery

3.1 Abstract

Much concern has been voiced in recent years regarding the environmental implications of the Antarctic krill fishery. Attention has been focused on ecological concerns, while other environmental impacts, including emissions and material and energy demands, have not been examined in detail. Here we apply LCA to measure the environmental burden of products derived from the operations of one krill fishing and processing company, Aker BioMarine ASA of Norway. We calculated energy use, BRU, and emissions of GHGs and other substances along the krill product supply chain, including contributions from fishing, processing, packaging, intermediate transportation and distribution. Impacts were quantified for three Antarctic krill-derived products: meal and oil for aquafeed inputs, and omega-3 krill oil capsules for the nutraceutical market. Impacts of all three products, meal and oil in particular, were found to be driven primarily by fuel use onboard the fishing/processing vessel and the secondary resupply vessel which also transports products from the fishing vessel to port. Packaging and distribution contribute very little to life cycle impacts of krill meal and oil, although packaging is a significant driver of energy use and emissions associated with omega-3 krill oil capsules. Approximately 190 L of fuel were burned per tonne of krill landed from 2007 to 2009 during fishing and transport to port, a fuel use intensity which is significantly higher than that of reduction fisheries targeting other species. In contrast, BRU, measured on the basis of NPP appropriation, associated with extracting krill is relatively low when compared to extraction of many other species targeted for reduction into meal and oil. The most significant improvements to the life cycle environmental performance of krill-derived products would be achieved by decreasing FUI or transitioning to use of cleaner energy carriers. Results of this study provide insight into the broader environmental implications of the krill fishery, provide actors in the krill product industry with guidelines for improvement and a baseline against which to measure future performance, and provide a basic comparative analysis of krill and other reduction fisheries in the context of emissions, energy use, and BRU.

3.2 Introduction

Global food production systems contribute significantly to environmental change at all scales though resource consumption, habitat alteration, material and energy demands, and resulting emissions to air and water (Millennium Ecosystem Assessment, 2005; Beaumert *et al.*, 2005; Steinfeld *et al.*, 2006; Garnett, 2008; Pelletier & Tyedmers, 2010a). The provision of seafood from wild and cultured sources is associated with a wide range of environmental alterations (Alverson *et al.*, 1994; Naylor *et al.*, 2000; Chuenpagdee *et al.*, 2003; Worm & Myers, 2004; Naylor & Burke, 2005; Pelletier & Tyedmers, 2008). Energy use and related emissions can be highly heterogeneous across fisheries and culture systems (Tyedmers, 2004; Troell *et al.*, 2004; Schau *et al.*, 2009; Pelletier *et al.*, *in review*), and have been found to vary with target species, technologies and gears, and the locale of fishing or culture operations (Tyedmers, 2001; Troell *et al.*, 2004; Thrane, 2006; Ayer & Tyedmers, 2009; Schau *et al.*, 2009; see Chapter 2).

In recent years, wild fisheries have been characterized by wide-scale depletion of many stocks, with most wild stocks being exploited to capacity or overexploited (Pauly *et al.*, 2002; Worm & Myers, 2004; FAO, 2009b). Opportunities for fisheries expansion are scarce, and a rapidly increasing portion of global demand for seafood is being met by aquaculture production (Naylor *et al.*, 2000; FAO, 2009; Bostock *et al.*, 2010). Fisheries targeting small pelagic species for industrial purposes, most notably inputs to livestock and aquaculture feeds (Tacon & Metian, 2008; Tacon & Metian, 2009; Bostock *et al.*, 2010), currently make up some of the largest fisheries in the world (FAO, 2009). Antarctic krill is a relatively unexploited fishery resource which has attracted attention in recent years as a potential source of meal and oil inputs to aquaculture supply chains as well as numerous other products. This fishery may provide a unique opportunity for growth in coming years, and improved understanding of the environmental implications of expansion in this fishery is needed.

3.2.1 The Antarctic Krill Fishery

Antarctic krill are small shrimp-like crustaceans belonging to the order *Euphausiacea*. Of the 85 known species of euphausiids, Antarctic krill are the most abundant, the longest lived, and the most commercially significant (Baker *et al.*, 1990; Hewitt & Linen Low, 2000). They are found in the seasonal pack-ice zone between the Antarctic continent and the polar front, with greatest abundances occurring in the Atlantic sector of the Southern Ocean (Hempel, 1985; Nicol & Endo, 1997; FAO, 2010b). Estimates of total Antarctic krill biomass vary, with recent estimates between 37 and 208 million tonnes, making them one of the most abundant animal species on the planet (Trathan *et al.*, 1992; CCAMLR, 2000a; Heywood *et al.*, 2006; Demer *et al.*, 2007).

The modern industrial fishery for Antarctic krill began in the early 1970s and catches were dominated by the Soviet Union until 1992 (Nicol & Endo, 1997; CCAMLR, 1990; CCAMLR, 2000b). Since the collapse of the Soviet Union, a number of countries have remained active in the fishery, although fishing levels have been far below those of the 1980s (Figure 9). In recent years, Norway has been the most prominent country in the fishery, accounting for one third of total reported catches from 2007 to 2009, and over half of 2010 landings (Figure 9) (CCAMLR, 2010a&b).

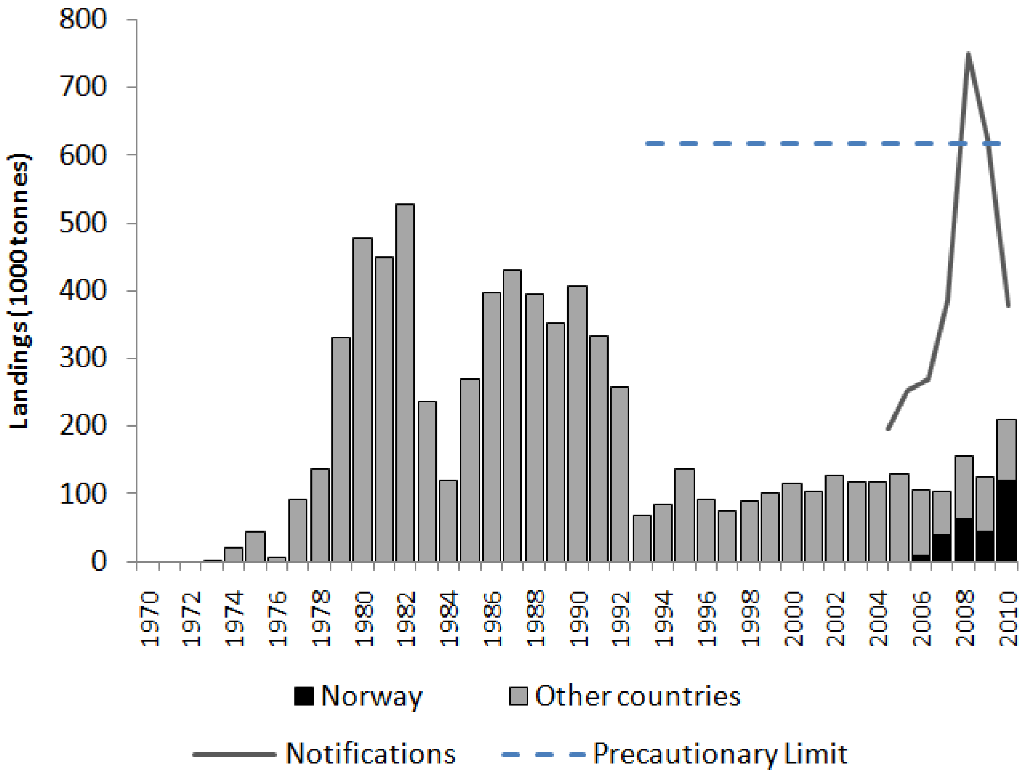

Figure 9. Annual reported landings of Antarctic krill, 1970-2010, highlighting catches by Norway, precautionary catch limit and total quota allowances issued by CCAMLR (CCAMLR, 2010a&b; FAO, 2010b).

Uses for Antarctic krill products have included direct human consumption of whole krill, tail meat, or processed sauces and pastes; feed products for aquaculture and aquarium fish; fish bait for sport and commercial fishing; extraction of chitin from shells for industrial purposes; and use of enzymes and krill oil for medical and nutritional purposes (Budziński *et al.*, 1985; Nicol *et al.*, 2000). Recent demand for Antarctic krill products has been driven by the aquaculture industry, arising from evidence that krill inputs to aquafeeds may enhance fish growth and eating behavior (Oikawa & March, 1997; Kolkovski *et al.*, 2000; Olsen *et al.*, 2006), and by the nutraceutical industry for products containing omega-3 fatty acids and other nutrients (Bunea *et al.*, 2004; Tandy *et al.*, 2000; Ierna *et al.*, 2010).

Historically, a number of challenges have faced the economic viability of the Antarctic krill fishery, including highly variable distributions, rapid post-mortem decomposition and associated loss of nutritional value, and the lack of a krill-derived product which provides sufficient economic return on investment to justify fishing and processing (Nicol, 1995; Nicol & Foster, 2003). New fishing and processing technologies (Tilseth & Hostmark, 2009; Rokke *et al.*, 2010) and the increasing popularity of krill inputs to aquafeeds and highly valued pharmaceutical and nutraceutical products may provide the economic impetus to expand the fishery moving forward.

Recent indications of the potential for expansion of the Antarctic krill fishery have raised alarm over the possible ecological consequences of significantly increased extraction (Leape *et al.*, 2009; Barnes, 2009; Schiermeier, 2010; Jacquet *et al.*, 2010). Concern has focused primarily on the ecological consequences of extracting a keystone species from a relatively underexploited ecosystem, as well as uncertainty surrounding krill biomass estimates, predator-prey interactions, and effects on Antarctic krill populations by changes in sea ice and ocean acidification associated with increasing atmospheric CO_2 levels (Nicol *et al.*, 2008; Kawaguchi *et al.*, 2010). While population status and ecological impacts of Antarctic krill extraction have received much attention in the literature, many other aspects of environmental sustainability have been largely overlooked. Specifically, contributions to broad environmental concerns such as global warming and depletion of energy resources have been excluded from analyses of the fishery.

3.2.2 Life Cycle Assessment

Prior analyses of fishing systems have examined various aspects of fisheries product supply chains using LCA to quantify contributions to a suite of environmental impact categories, including biotic and abiotic resource use, energy demands, and GHG and other emissions (Ziegler *et al.*, 2003; Hospido & Tyedmers, 2005; Ellingsen & Aanondsen, 2006; Thrane, 2006; Ziegler & Valentinsson, 2008; Vásquez-Rowe *et al.*, 2010; Driscoll *et al.*, *in review*). Fossil fuel consumption has emerged in these studies as a consistent and major contributor to the overall environmental impacts of fisheries supply chains, although other processes, such as bait use, refrigerant losses, product air transport, and consumer use, can contribute substantially in some instances as well (Ziegler & Valentinsson, 2008; Ziegler *et al.*, 2009; Driscoll *et al.*, *in review*).

Here we use ISO-compliant LCA to examine the operations and products of one krill fishing and processing company, Aker BioMarine ASA of Norway, and quantify and characterize the environmental burdens associated with three Antarctic krill-derived product supply chains. Results should be of interest to krill-fishing companies, consumers and customers of krill-derived products in the aquaculture and nutraceutical industries, fisheries management authorities, and LCA practitioners as well as any other organizations and individuals interested in better understanding the environmental costs of the Antarctic krill fishery and its associated products.

3.3 Methods

Life cycle environmental burdens were quantified for three product units: 1 kg krill meal, 1 L krill oil, and 1 consumer-ready bottle of 60 omega-3 krill oil capsules. Krill meal and oil provide nutritional content to aquaculture feeds in the form of energy, protein and other nutrients. Krill meal provides an estimated 23.8 MJ of energy and at least 560 g of protein per kg (Aker BioMarine, 2008), while oil provides 39.3 MJ of energy per kg (see Appendix A for detailed nutritional content of krill meal). Omega-3 krill oil capsules supply omega-3 fatty acids and other nutrients to supplement human diets. AB's omega-3 krill oil capsules contain approximately 90 mg of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) omega-3 fatty acids per 500 mg capsule (Aker BioMarine, 2010c).

Products were evaluated on the basis of global warming potential (GWP, measured in carbon dioxide equivalent emissions [CO_2-e]), cumulative energy demand (CED, in megajoules [MJ]), ozone depletion potential (ODP, in trichlorofluoromethane equivalent emissions [CFC-11-e]), acidification potential (AP, in sulfur dioxide equivalent emissions [SO_2-e]), eutrophication potential (EP, in phosphate equivalent emissions [PO_4-e]), and BRU expressed as NPP appropriation. While the intention here is to be broadly informative on the environmental costs of Antarctic krill products and production systems, analysis was limited to operations and processes specific to AB's product supply chain.

3.3.1 Production System Boundaries

Scope of analysis included all activities up to the point of delivery to aquaculture clients and nutraceutical retailers, including fishing, processing, packaging, intermediate transport, and distribution (Figure 10). Processing of Antarctic krill into meal and oil takes place directly onboard AB's fishing vessel, while omega-3 krill oil capsules are processed at a secondary facility in France. Intermediate transportation includes both transport of processed meal and oil from the fishing vessel to port in Montevideo, Uruguay, via a resupply vessel, and transport of a small portion of meal to France for secondary processing into omega-3 krill oil capsules. Background processes considered in the analysis included coarse inputs to vessel construction and maintenance, manufacturing of gear, production of fuel, production of all packaging materials, and production of electricity for processing. Activities excluded from the analysis included use of products by consumers, storage, disposal and recycling associated with final waste flows, and all administrative and corporate activities. Inputs excluded from analysis included provision of food and other supplies to vessel crews, and infrastructure at land-based processing and packaging facilities.

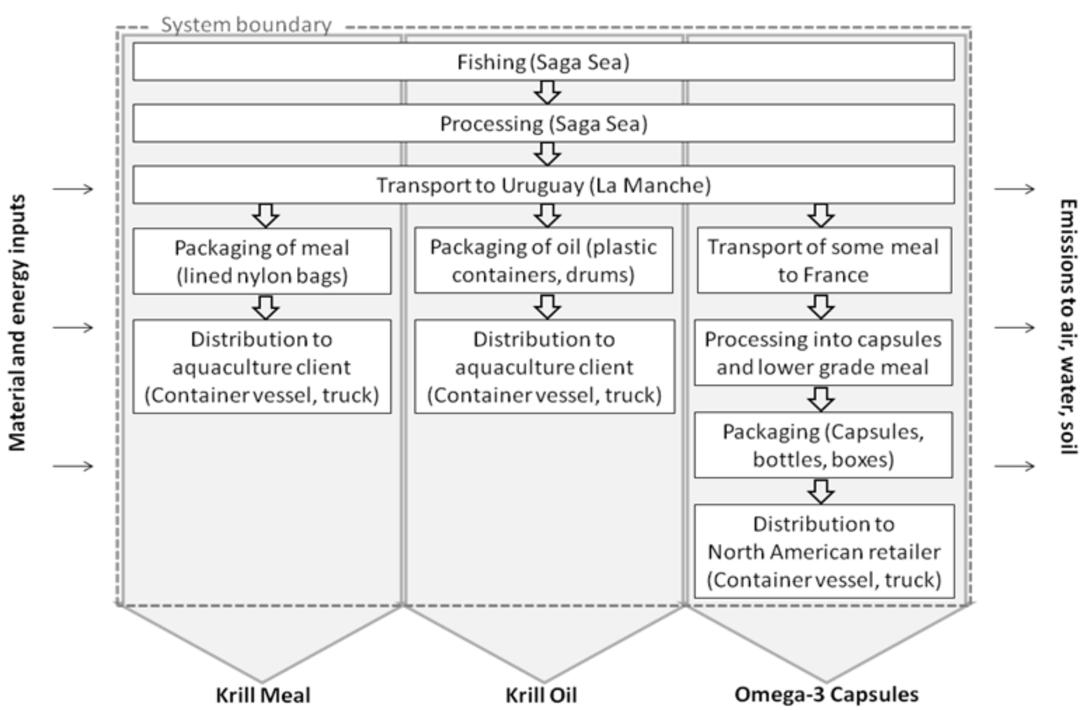

Figure 10. Product supply chains of krill meal, krill oil, and omega-3 krill oil capsules.

3.3.2 Sources of Data

Data relating to krill capture and processing, including vessel characteristics, fuel use, energy and material inputs to processing, packaging materials, and transportation routes and modes were solicited from AB via surveys and personal communications. Additional data relating to secondary processing of omega-3 krill oil capsules were solicited from a France-based processor, and data pertaining to construction of fishing gear were solicited from a trawl gear manufacturer which supplies AB.

Material and energy inputs to the production of gelatin for omega-3 krill oil capsules were solicited from a Canadian gelatin manufacturer. Gelatin supply chain processes were characterized as either processing-related or base material-related, where the base material was assumed to be pig skin. Direct emissions from gelatin production were not available; however, eutrophying emissions to water were estimated based on the difference between the stoichiometric composition of dry, unprocessed pig skin and that of the extracted collagen, assuming that remaining nitrogen and phosphorous is entirely emitted to water (Nguyen *et al.*, 1986). Energy use and emissions associated with pig production were taken from Pelletier and colleagues (2010; see Appendix C). Slaughtering and transport activities associated with pig skins were excluded, as was transportation of finished gelatin.

Background data for upstream processes relating to construction, packaging and processing materials, energy production, and transportation were compiled from the EcoInvent 2.0 database of European life cycle inventory data (see Appendix D). Fuel-specific properties and emissions related to burning MDO and IFO marine fuels were used to supplement heavy fuel oil processes in EcoInvent 2.0 to allow for comparison of energy carriers (see Appendix E).

3.3.3 Co-Product Allocation

Environmental burden associated with processes which contribute to multiple products needed to be allocated logically. This is a common methodological challenge in LCAs of seafood products (Ayer *et al.*, 2007). Economic allocation based on relative contributions to revenue streams is common practice in many seafood LCAs (Ayer *et al.*, 2007). However, allocation based on prices and revenue streams is associated with some fundamental limitations (Pelletier & Tyedmers, *in press*). Product prices vary over space and time, invalidating results based on out-of-date prices, and prices and revenues are not necessarily relevant to biophysical relationships between processes and products, a recommended criterion for allocation in standardized LCAs (ISO, 2006b; Pelletier & Tyedmers, *in press*). Here we instead applied allocation based on biophysical criteria (mass and energy density) to avoid the effects of market conditions and reflect relationships between process inputs, process outputs, and product functions.

Allocation was required for fishing, primary processing of krill into meal and oil, secondary processing of omega-3 krill oil capsules from meal, and intermediate transportation. Environmental burdens of product transport from the fishing vessel to port were allocated based on product mass. In all other cases, energy density of co-products was used as the basis for allocation, assuming that the primary function of krill-derived products is the provision of nutritional energy.

3.3.4 Impact Assessment

Inventory data were compiled on spreadsheets and SimaPro 7.0 software from PRé Consultants was employed to assist in translating inventory data into quantified contributions to energy use and emissions. Established characterization models were applied to quantify contributions to each impact category (Table 8).

Table 8. Characterization models and methods employed in life cycle impact assessment.

Impact category	Characterization Model	SimaPro LCIA Method
Global warming potential	IPCC, 2007	CML 2000
Ozone depletion potential	WMO	CML 2000
Acidification potential	RAINS10 (IIASA)	CML 2000
Eutrophication potential	Stoichiometric procedure	CML 2000
Cumulative energy demand	MJ	Cumulative energy demand
Biotic resource use	Manual calculation (NPP)	

Quantification of BRU associated with krill extraction followed the NPP appropriation formula developed by Pauly and Christensen (1995), which has been previously applied in other seafood product-related LCAs (Papatryphon *et al.*, 2004; Aubin *et al.*, 2006; for description of NPP method and application to Antarctic krill, see Chapter 2 and Appendix

F). BRU associated with the use of pig skin for gelatin production was calculated by estimating the carbon content of U.S. pig fodder and reported feed use rates (Pelletier *et al.*,2010; see Appendix F).

3.3.5 Scenario Modeling and Sensitivity Analysis

In order to explore the potential environmental performance benefits of possible changes to Antarctic krill product supply chains, six scenarios were independently modeled and resulting changes to life cycle impacts of both krill meal and omega-3 krill oil capsules were measured. Four of these scenarios tested the sensitivity of results to uniform changes in a single unit process, for the purpose of identifying those stages of the product life cycle where changes would provide the most effective improvements. These include (1) a 10% reduction in fuel use by the fishing and resupply vessels; (2) a 10% reduction in final product distribution distances; (3) a 10% reduction in packaging inputs; and (4) a 10% increase in meal yield per tonne of krill harvested. Two additional scenarios involved replacing a process or input with an alternative option: (5) switching to a 100% MDO fuel mix on both vessels; and (6) using air freight rather than container vessel as the primary mode of distribution.

3.4 Results

3.4.1 Inventory

Operational inputs to fishing, processing and transport of primary products to port in Uruguay were secured for each of three seasons of operation, spanning from 2007 to 2009 (Table 9; see Appendices G and H). Over these years, AB harvested an average of 45,700 metric tonnes of krill per annum and produced approximately 144 kg of krill meal and 0.7 kg of krill oil onboard the fishing vessel per tonne of krill harvested, as well as 7.2 g of krill paste product for unspecified development purposes. Material and energy inputs to the fishing and processing of krill onboard the fishing vessel, and the subsequent transport of processed products to port in Uruguay, are largely dominated by the input of fuel to both vessels (Table 9). Together, these activities demand 256 litres of fuel per tonne of Antarctic krill harvested, processed and transported to port, with a combined fuel mix of 24 per cent MDO and 76 per cent IFO. On a mass basis, inputs to vessel construction and maintenance and gear manufacturing, per tonne of krill landed, are relatively insignificant (Table 9).

Table 9. Inputs to AB's fishing and resupply vessels, average values for 2007-2009.

Input	Unit	Fishing vessel / Resupply vessel	
Vessel Construction[a]		*per vessel*[a]	*per tonne krill*[b]
Steel	kg	4204000 / 11685000	3.065 / 2.840
Copper	kg	110500 / 307500	0.081 / 0.075
Other Materials	kg	110500 / 307500	0.081 / 0.075
Vessel Maintenance[c]		*per vessel*[c]	*per tonne krill*[b]
Steel	kg	1051000 / 2921000	0.766 / 0.710
Gear[d]		*per trawl net*[d]	*per tonne krill*[d]
Polyethylene	kg	4000 / -	0.025 / -
Synthetic Rubber	kg	3000 / -	0.019 / -
Fuel consumption		*per year*	*per tonne krill*
(propulsion/fishing)[e]			
Marine Diesel Oil	L	911083 / 1192500	19.929 / 25.393
Intermediate Fuel Oil	L	3089667 / 3681000	67.583 / 78.383
(processing)[e]			
Marine Diesel Oil	L	490583 / -	10.731 / -
Intermediate Fuel Oil	L	1663667 / -	36.391 / -

a. Vessel characteristics obtained through personal communications with AB (Nordrum, 2009, pers. comm.). Steel hull and superstructure was assumed to represent 95% of vessel mass following Tyedmers (2004), the remaining 5% were divided equally among copper and other materials, including aluminum, glass, fiberglass, *etc.*

b. Per tonne values calculated based on 2007-2009 catches and assuming a 30-year vessel lifespan following Tyedmers (2004).

c. Steel inputs to vessel maintenance were assumed to be equal to one quarter of the total steel hull and superstructure, following Tyedmers (2004).

d. Inputs to gear construction from Eikrem (2010, pers. comm.). Per tonne values calculated using 2007-2008 catches and assuming an average gear lifespan of 3.5 years (Eikrem, 2010, pers. comm.).

e. Fishing vessel fuel allocated 65% to fishing and propulsion, and 35% to processing. 10% of operations by resupply vessel are dedicated to other vessels; the other 90% is included here (Nordrum, 2009, pers. comm.).

Inputs to packaging of krill meal and oil destined for the aquafeed market are relatively small (Table 10). Meal is packaged in three sizes of plastic-lined nylon bags, while oil is packaged in large plastic-lined cardboard drums as well as smaller plastic bottles. Using average values for three packaging sizes, 1 kg of meal requires an average of 19 g packaging, while 1 litre (0.92 kg) of oil requires 67 g of packaging material. Products derived from 1 tonne of krill, if processed solely into aquafeed inputs, would therefore require just over 3 kg of packaging material, 90 per cent of which would be nylon to package meal.

Table 10. Inputs to packaging of krill meal and oil.

		Meal[a]			Oil[b]		
		25 kg	*200 kg*	*500 kg*	*1L*	*5L*	*198L*
Nylon	kg	0.27	4.50	9.00	-	-	-
Polyethylene	kg	0.03	0.50	1.00	0.08	0.25	1.40
Steel	kg	-	-	-	-	-	6.30
Cardboard	kg	-	-	-	-	-	6.30

a. Average packaging inputs to meal calculated assuming one third of product is packaged in each of 25 kg, 200 kg, and 500 kg bags. Packaging inputs obtained through personal communication with AB (Nordrum, 2009, pers. comm.).
b. Average packaging inputs to oil calculated assuming one third of product is packaged in each of 1 L and 5 L plastic containers and 198 L cardboard drums. Packaging inputs to cardboard drums assumed to be 50% steel and 50% cardboard. Packaging inputs to plastic containers based on measurements of HDPE containers from a UK packaging company (Nexus Packaging Ltd., 2008).

Ethanol extraction is used to strip omega-3-rich oil from krill meal. The extracted oil is packaged in gelatin capsules, at an approximate ratio of 500 mg oil to 225 mg gelatin. Transport of finished capsules to nutraceutical distributors takes place in bulk cardboard boxes, and capsules are ultimately packaged in plastic bottles for final distribution to retailers. Interestingly, the largest input to the packaging of capsules, by mass, is the input of pig skin to the manufacturing of gelatin (Table 11). The production of one kg of gelatin requires 1.85 kg of pig skin. Material inputs to packaging of capsules in cardboard boxes for transport are relatively low, compared to inputs to gelatin manufacturing and subsequent packaging in bottles for distribution (Table 11). The krill meal that remains after oil extraction is ultimately used as a lower grade meal product for input to aquafeeds, though this supply chain was not modeled further.

Table 11. Inputs to processing omega-3 krill oil capsules at France-based processor and packaging in gel caps, lined boxes for transport, and plastic bottles for retail.

Input	Unit	Amount	
Processing[a]		*per kg meal*	*per 60 capsules*
Krill Meal	g	1000.0	49.30
Ethanol	g	294.0	14.50
Electricity[b]	kWh	6.5	0.32
Fuel Oil[b]	g	568.0	28.00
Packaging: Gel Capsules[c]		*per kg gelatin*	*per 60 capsules*[d]
Pork skin	g	1850.0	25.00
Sulphuric acid	g	230.0	3.11
Sodium hydroxide	g	390.0	5.27
Electricity	kWh	2.7	0.04
Packaging: Lined Boxes[d]		*per box*[e]	*per 60 capsules*
Cardboard	g	1.8	0.011
Polyethylene	g	0.1	0.001
Packaging: Bottles[d]			*per 60 capsules*
Polyethylene	g		0.70
Polypropylene	g		3.13
PE terephthalate	g		16.53

a. Inputs to processing obtained through personal communications with AB (Nordrum, 2010, pers. comm.; Holm, 2010, pers. comm.).
b. Assuming half of energy use to be coming from electricity and half from fuel oil (Holm, 2010, pers. comm.).
c. Data from one North American gelatin manufacturer using pig skin as the primary input, the typical base product for the majority of global gelatin production (Anon., 2010, pers. comm.).
d. Ratio of gelatin to oil, and inputs to plastic bottles, estimated using measurements of a packaged bottle of 60 krill oil capsules.
e. Inputs to packaging for transport measured for a box containing 10,000 capsules for transport.

3.4.2 Co-Product Allocation

Krill meal makes up the majority of product, on both a mass- and energy-basis, derived from primary processing onboard the fishing vessel, while oil and paste together account for approximately 5 per cent of production (Table 12; see Appendix G). However, the higher energy density of krill oil results in more burden being allocated to oil when energy-based allocation is used than when allocation is based on mass. Interestingly, energy-based allocation results in only one third of the environmental burden of secondary processing being allocated to omega-3 krill oil capsules, while the rest is allocated to the lower grade meal by-product (Table 12).

Table 12. Co-product allocation of environmental burden in krill product supply chains, showing differences in mass- and energy-based allocation factors.

Product	Mass	Energy Density	Mass Allocation Factor	Energy Allocation Factor
From one tonne krill				
Meal	144.0 kg	23.8 MJ/kg	94.80%	96.12%
Oil	0.7 kg	39.3 MJ/kg	0.46%	0.75%
Paste	7.2 kg	15.5 MJ/kg	4.74%	3.13%
From one kg meal, further processed				
Omega-3 Oil	180 g	39.3 MJ/kg	18.00%	32.40%
Meal (grade B)	820 g	20.5 MJ/kg	82.00%	67.60%

3.4.3 Impact Assessment

The pattern of sub-system contributions was found to be similar for both krill meal and oil products for the aquafeed market (Table 13; see Appendix I). The use of energy-based allocation for fishing and primary processing and mass-based allocation for transport to port accounts for slight differences in the relative contribution of those processes to the overall burdens of meal and oil. The fishing, processing, and transport-to-port stages of production account for an average of 96 and 97 per cent of total impacts across energy and emissions-based impact categories for meal and oil, respectively (Figures 10 and 11). Impacts up to the point of delivery in Uruguay are driven almost entirely by the combustion of fossil fuels, which represents an average of 95 and 96 per cent of total life cycle environmental impacts for meal and oil, respectively. Meanwhile, contributions from vessel construction and maintenance, gear provision, and upstream processing of fuel are relatively negligible, together accounting for less than 2 per cent of the burden of both products. Packaging and distribution also contribute very little to the overall environmental burdens of krill meal and oil, accounting for 1 and 2 per cent respectively across energy use and emissions-based impact categories for both products (Figure 10).

Table 13. Life cycle environmental impact assessment results for krill meal, krill oil, and omega-3 krill oil capsules (for a detailed breakdown of results, see Appendix I).

Impact Category	Unit	Krill meal	Krill oil		Krill oil capsules	
		(per kg)	*(per L)*	*(per kg)*[a]	*(per bottle)*	*(per kg)*[a]
GWP	kg CO_2-e	5.4	7.1	7.7	0.55	18.3
ODP	mg CFC-11-e	0.64	0.85	0.92	0.05	1.7
AP	g SO_2-e	134	176	191	9.48	316
EP	g PO_4-e	15.6	20.4	22.2	1.77	59.0
CED	MJ	80.2	106	115.2	13.1	436.7
BRU	kg C	11.6	19.1	20.8	0.66	22.0

a. One kg corresponds to 1.09 L of krill oil and 2,000 krill oil capsules, or 33.3 60-capsule bottles.

The life cycle environmental impacts of omega-3 krill oil capsules are, perhaps not surprisingly, relatively higher, on a mass-to-mass basis, than those of krill oil destined for aquafeeds (Table 13). This is explained by substantial additional processing and packaging which takes place after intermediate meal product is landed in Uruguay. Fishing, onboard processing and transport to port together account for an average of 50 per cent of burdens across energy use and emissions-based impact categories for capsules, and these impacts are again dominated by the combustion of fossil fuels. Secondary processing of krill meal to extract and encapsulate oil accounts for an average of 18 per cent across all emissions-based impact categories considered and 50 per cent of energy use (Figure 12). The use of nuclear energy in France results in lower GWP than would be expected with similar energy use in regions relying more heavily on fossil fuels for electricity.

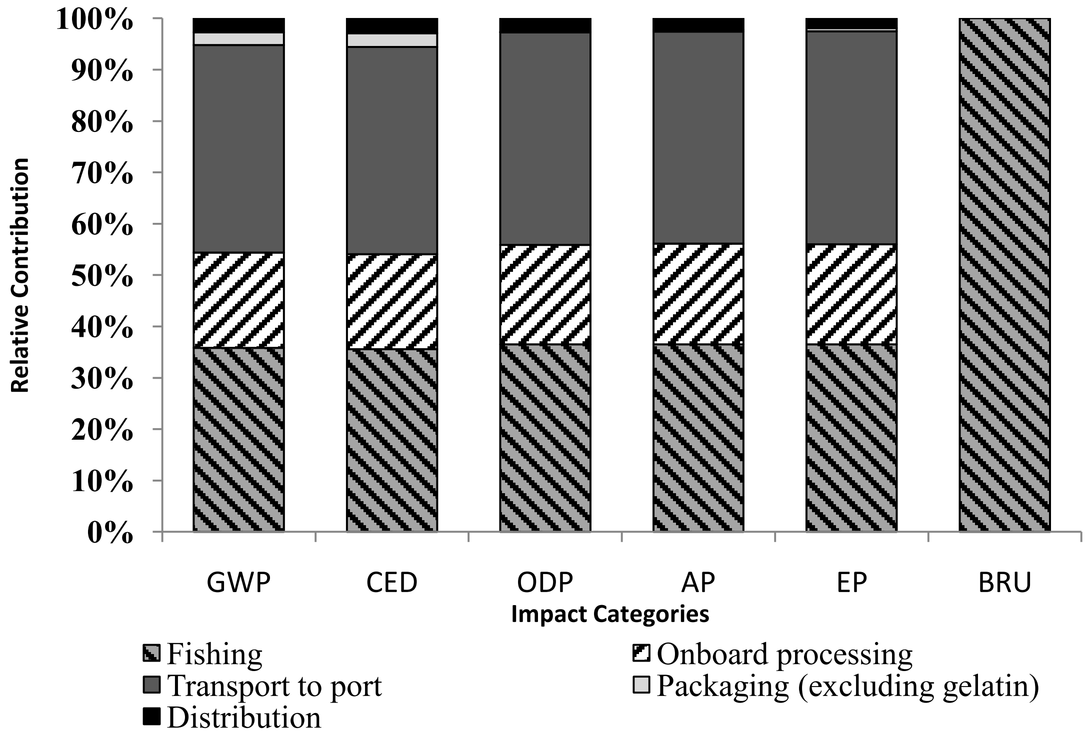

Figure 11. Life cycle impact assessment contribution analysis – 1 kg Antarctic krill meal.

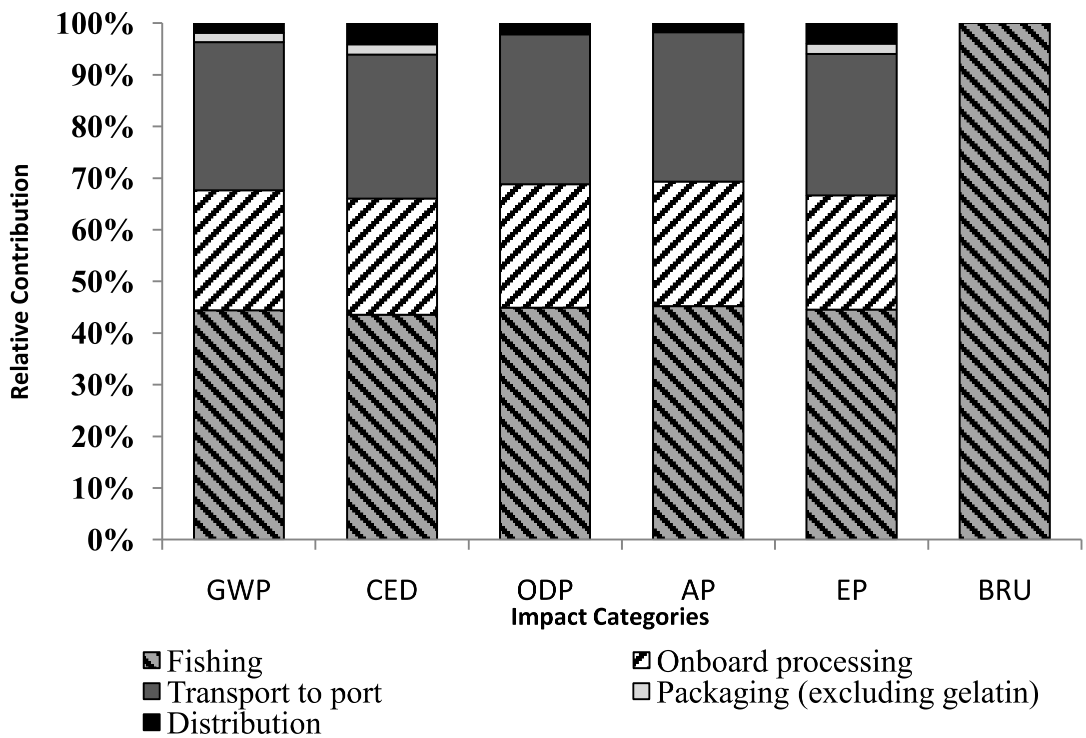

Figure 12. Life cycle impact assessment contribution analysis – 1 L Antarctic krill oil.

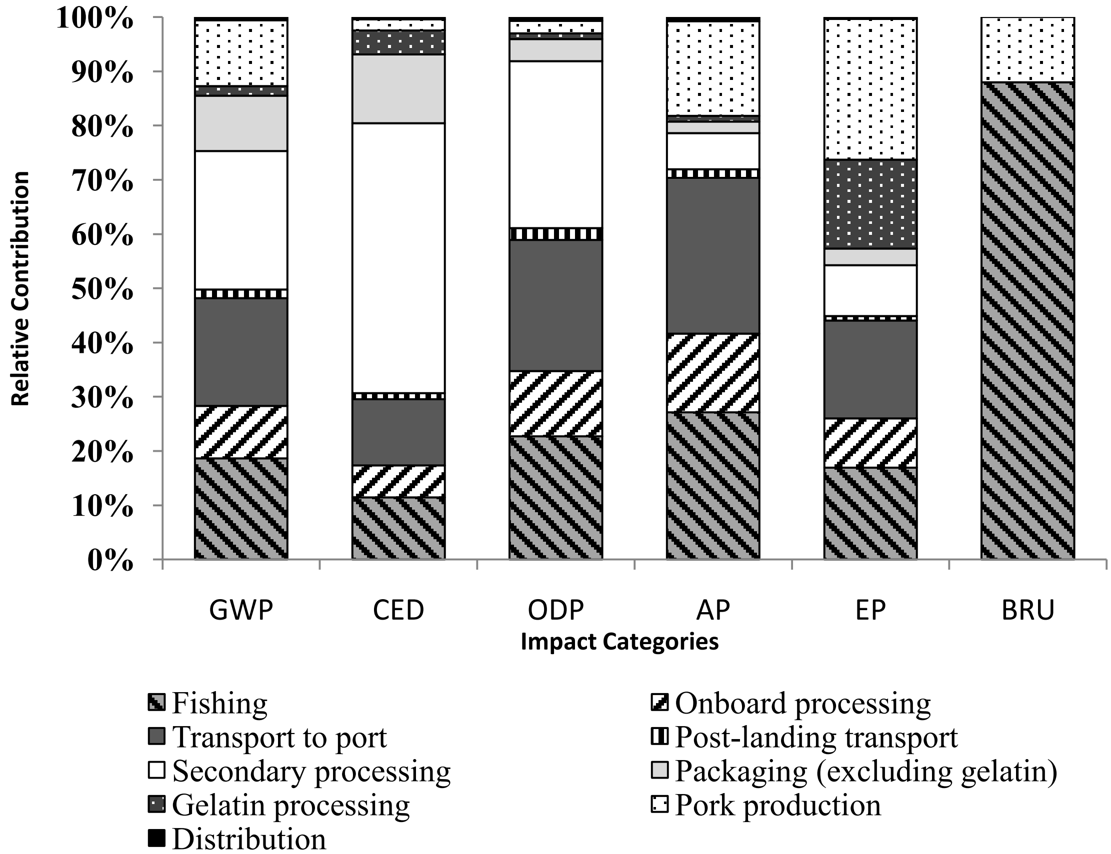

Figure 13. Life cycle impact assessment contribution analysis – 60-capsule bottle of omega-3 krill oil capsules.

Packaging accounts for a much larger portion of the overall impacts of omega-3 krill oil capsules than those of meal and oil, contributing an average of 22 per cent to emissions-based impact categories and 19 per cent of total energy use. Gelatin manufacturing and pork production are both noteworthy sources of these impacts. Pork production accounts for 12 per cent of GWP, 17 per cent of AP, and 26 per cent of EP associated with omega-3 krill oil capsules. Meanwhile, waste streams of nitrogen and phosphorous from gelatin manufacturing account for a surprising 16 per cent of life cycle eutrophying emissions.

BRU associated with each krill-derived product is generally a direct reflection of allocated product yields from whole krill. The fishing stage, therefore, accounts for all BRU associated with krill meal and krill oil, and the majority of BRU associated with omega-3 krill oil capsules. However, a small portion of the BRU burden of omega-3 krill oil capsules (12 per cent) also results from crop-derived inputs to pork production in the gelatin supply chain (Figure 13).

3.4.5 Scenario Analysis

Not surprisingly, decreasing fuel consumption by the fishing and resupply vessels would be expected to yield significant improvements across most impact categories, particularly in the case of meal and oil (Table 14). Reductions in fuel consumption on either vessel would be expected to provide an almost equal reduction in life cycle energy use and emissions. Increasing meal yield would also result in substantial improvements across impact categories, although not to the extent that a reduction in fuel use would (Table 14). Substantial improvement in AP would be realized by switching to a low-sulfur fuel: transitioning to a fuel mix of all MDO on both vessels would result in modeled reductions in life cycle acidifying emissions of 36 per cent for krill meal and 25 per cent for omega-3 krill oil capsules (Table 14). Interestingly, by far the most significant overall changes to the life cycle environmental costs of krill-derived products would be the increase in energy use and emissions if products were distributed by air. Shipping krill meal by air rather than by container vessel, for example, would more than triple the life cycle GHG emissions and energy use (Table 14).

Importantly, modeled potential improvements to BRU in the life cycles of both krill meal and omega-3 krill oil capsules follow different patterns than those modeled for other impact categories, because BRU is not related to fuel use. The only scenario modeled here that would see improvements in BRU is an increase in meal yield per tonne of krill harvested. A 10 per cent increase in meal yield would translate to a 9.1 per cent decrease in BRU associated with meal and a 7.9 per cent decrease in BRU associated with omega-3 krill oil capsules (Table 14).

Table 14. Modeled changes in emissions and energy use as a result of potential changes made to krill meal and omega-3 krill oil capsule supply chains, relative to baseline analysis.

Scenario	Resulting Change in Meal Impacts (%)						Resulting Change in Capsule Impacts (%)					
	GWP	ODP	AP	EP	CED	BRU	GWP	ODP	AP	EP	CED	BRU
1	-9.4	-9.7	-9.7	-9.6	-9.5	0.0	-4.7	-5.8	-7.0	-4.8	-2.3	0.0
2	0.2	0.2	0.0	0.0	-0.2	0.0	0.0	-0.2	-0.1	0.0	0.0	0.0
3	0.2	0.0	0.0	0.0	-0.2	0.0	-2.4	-0.8	-2.2	-3.4	-1.6	0.0
4	-4.6	-4.8	-5.2	-5.1	-4.7	-9.1	-4.8	-5.8	-4.2	-3.4	-5.4	-7.9
5	-2.0	-3.1	-36.0	-3.2	-3.2	0.0	-0.9	-1.9	-25.5	-1.4	-0.8	0.0
6	243.5	261.8	36.0	54.4	257.7	0.0	58.6	74.5	12.5	11.7	37.1	0.0

Note: Scenario 1 – 10% reduction in fishing/transport to port fuel use; Scenario 2 – 10% reduction in distribution distance; Scenario 3 – 10% reduction in packaging materials; Scenario 4 – 10% increase in krill meal yield; Scenario 5 – 100% MDO fuel mix on fishing/resupply vessels; Scenario 6 – distribution by air freight.

3.5 Discussion

Fisheries for Antarctic krill represent a potentially important source of nutritionally valuable products for a number of uses. However, products derived from this fishery are associated with a number of challenges and concerns regarding the environmental implications of fishing and processing krill.

3.5.1 Fuel Use

Energy use and related GHG emissions in the krill product life cycle are largely dominated by the fishing and transport-to-port stages. This is consistent with previous fishery-related LCAs, which have identified the fishing stage (which typically includes both fishing and transporting unprocessed fish to port) to account for between 65 and 90 per cent of life cycle GHG emissions (Ziegler *et al.*, 2003; Hospido & Tyedmers, 2005; Thrane, 2006; Ziegler & Valentinsson, 2008). Interestingly, in the supply chain of Antarctic krill products, fuel consumption by a secondary resupply vessel used to transport meal and oil from the fishing vessel to port accounts for roughly the same energy use and emissions as fuel consumption on the fishing vessel (Figures 11-13; see Appendix I). This suggests that the distance between the fishing vessel and port plays a significant role in the life cycle environmental impacts of krill products.

FUI can be used as one way to compare relative performance of fisheries and track changes in performance over time (Tyedmers, 2001; Tyedmers, 2004; Schau *et al.*, 2009). On the basis of litres of fuel burned per tonne wet weight landings, unprocessed and transported to port, the FUI of Antarctic krill is relatively low when compared to many high-value commercial species such as cod, tuna or lobster (Tyedmers, 2001; Ziegler *et al.*, 2003; Tyedmers, 2004; Hospido & Tyedmers, 2005; Ziegler & Valentinsson, 2008; Winther *et al.*, 2009), but markedly higher than has been documented for other fisheries targeting species for reduction into meal and oil (Table 15).

Table 15. Reported fuel use intensities of fisheries targeting species for reduction.

Fishery	Gear (if known)	Fishing locale (if known)	Fuel Use Intensity (L/t)
Capelin/Atlantic herring[a]	Trawl	North Atlantic Ocean	80
Sand eels/Atlantic herring[a]	Trawl	North Atlantic Ocean	95
Atlantic herring/mackerel[a]	Trawl	North Atlantic Ocean	110
Atlantic herring[b]	Trawl	Northwest Atlantic Ocean	118
Antarctic krill	Trawl	Atlantic sector of Southern Ocean	191[g]
Capelin/Atlantic herring[a]	Purse seine	North Atlantic Ocean	20
Atlantic herring[b]	Purse seine	Northwest Atlantic Ocean	21
Gulf menhaden[a]	Purse seine	North Atlantic Ocean	32
South American pilchard[c]	Purse seine	Indian Ocean	42-112[h]
Atlantic mackerel[d]	Purse seine	Northeast Atlantic Ocean	80
Blue whiting[a]	Purse seine	North Atlantic Ocean	85
Atlantic herring/sand eels[a]	Purse seine	North Atlantic Ocean	100
Atlantic Herring[d]	Purse seine	Northeast Atlantic Ocean	140
Peruvian anchovy[e]			19
Atlantic herring[e]			91
Atlantic mackerel[e]			94
Atlantic herring[f]		Northeast Atlantic Ocean	106
Blue whiting[f]		Northeast Atlantic Ocean	106
Capelin[f]		Northeast Atlantic Ocean	106
Atlantic mackerel[f]		Northeast Atlantic Ocean	106

a. Tyedmers (2004).
b. Driscoll and Tyedmers (2010).
c. Penn (2000).
d. Thrane (2004).
e. Winther and colleagues (2009).
f. Schau and colleagues (2009).
g. Fuel use intensity for Antarctic krill reflects fuel consumed during fishing (65% of total fuel use by the fishing vessel) and transport by the resupply vessel, and excludes fuel burned for onboard processing on the fishing vessel.
h. Range shows variation of fuel use intensity between three years of fishing

Reductions in fuel consumption in the Antarctic krill fishery could be realized by reducing the number of trips between the fishing vessel and port, reducing the distance of fishing grounds to port, improving engine efficiency, or increasing either krill catch or processed yield relative to fishing effort. The GHG and other emissions associated with the fishery can also be effectively improved without necessarily decreasing fuel consumption. Ziegler and Hansson (2003), for example, found that technological changes made at the fishing stage as well as changes in fishing effort could decrease emissions of CO_2 by 40 per cent and emissions of several other gases by between 70 and 98 per cent, for cod fisheries in the Baltic. Perhaps one of the most effective long-term options to reduce GHG emissions from the Antarctic krill fishery would be a transition to a cleaner energy carrier, such as natural gas, which has been modeled to reduce emissions of nitrous oxides (NO_X) and CO_2 from fisheries by 85 and 20 per cent, respectively (Ellingsen & Lonseth, 2005), though the provision of natural gas to a fishing vessel in the Southern Ocean may be impractical.

3.5.2 Packaging and Distribution of Fishery Products

Packaging and distribution contribute very little to the overall life cycle environmental impacts of Antarctic krill products, particularly bulk-packaged meal and oil for the aquafeed market which take advantage of economies of scale to maximize efficiency. However, packaging is a significant driver of impacts associated with omega-3 krill oil capsules because of the high packaging-to-product ratio. In particular, gelatin processed from pig skin was here shown to be a significant contributor to overall impacts. It is possible that alternative animal- or plant-based sources of gelatin could result in improved energy use and emissions, particularly EP, though the scale of these potential improvements has not been modeled.

The distances final products need to be transported to reach clients in the aquaculture and nutraceutical industries were found to be relatively insignificant. Overall, distribution contributed very little to the total environmental burdens of krill-derived products, and decreasing distribution distance was found to have the least effect of all improvement scenarios. However, the mode of distribution, particularly the hypothetical use of air freight, can dramatically influence the overall energy use and emissions associated with krill products. This is consistent with other studies which have demonstrated that the mode of transport plays a greater role in the transport-related impacts of seafood products than the actual distance traveled (Andersen, 2002; Fulton, 2010).

3.5.3 Biotic Resource Use

BRU is the one impact category included in this study which is not associated with the burning of fossil fuels, and it is interesting that the relative performance of Antarctic krill products should differ so greatly between comparisons based on BRU and those based on energy use and emissions-based impact categories. It is important to note that, while BRU is a measure of dependence on ecological productivity, it does not take into account a number of ecological considerations that are often of key concern in fisheries, including actual target stock populations and destruction or alteration of marine habitat.

BRU has been measured previously for meal and oil products derived from numerous fisheries, as well as several culture systems (Papatryphon *et al.*, 2004; Aubin *et al.*, 2006; Pelletier *et al.*, 2009; see Chapter 2) (Table 16). Antarctic krill products are associated with relatively low BRU when compared to those derived from other species targeted for reduction, largely as a result of Antarctic krill's low trophic level (see Chapter 2). The BRU associated with culture systems is typically assumed to be driven entirely by feed ingredients, and there is wide variation within culture of a single species depending on the composition of feeds (Papatryphon *et al.*, 2004; Pelletier *et al.*, 2009). Clearly, the source fishery for fish-derived feed inputs greatly influences the BRU of these systems.

Table 16. Biotic resource use associated with reduction fisheries and culture systems.

Species	BRU per live weight tonne	BRU per 100 GJ meal and oil
Species for reduction into meal and oil		
Gulf menhaden[a]	1,721	16,349
Antarctic krill[a]	1,761	45,786
Peruvian anchovy[a]	5,569	99,681
Atlantic herring[a]	18,869	215,111
Blue whiting[a]	113,699	2,694,672
Aquaculture species		
Atlantic salmon culture, Canada[b]	18,400	
Rainbow trout culture, fed mostly plant-derived feed ingredients[c]	19,100	
Rainbow trout culture, fed mostly Norwegian and Peruvian fish meal[c]	41,300	
Atlantic salmon culture, Chile[b]	56,600	
Turbot culture, France[d]	60,900	
Atlantic salmon culture, Norway[b]	111,100	
Atlantic salmon culture, UK[b]	137,200	

a. See Chapter 2.
b. Pelletier and colleagues (2009).
c. Papatryphon and colleagues (2004).
d. Aubin and colleagues (2006).

3.5.4 Environmental Burden of Aquaculture Feeds

Currently, the major use for Antarctic krill-derived products is in aquafeeds. Farming of salmon and other carnivorous fish species relies on inputs from reduction fisheries (Naylor *et al.*, 2000; Papatryphon *et al.*, 2004; Naylor & Burke, 2005; Tacon, 2008; Pelletier *et al.*, 2009; Pelletier & Tyedmers, 2010b). While concerns regarding this relationship tend to be focused on the ecological consequences of fishing, reliance on fisheries also drives many emissions and energy-related environmental impacts of aquaculture production (Pelletier *et al.*, 2009). LCAs of culture systems have found that feed provision accounts for upwards of 90 per cent of total energy use and related impacts for intensive Atlantic salmon culture, and is also a key driver of many emissions-based impacts (Pelletier *et al.*, 2009). Feed is also a significant driver of NPP appropriation associated with aquaculture of carnivorous species (Papatryphon *et al.*, 2004; Aubin *et al.*, 2006; Pelletier *et al.*, 2009).

The important role that fish inputs play in the life cycle environmental performance of many aquaculture systems suggests that the choice of feed inputs may be a potential opportunity to improve the performance of farmed fish products. This includes both the choice of source fishery for fish-based inputs, and the option of replacing fish-based products partially or entirely with alternative plant-based ingredients. The replacement of fish ingredients with soy and vegetable oil has been modeled to show significant potential improvements in energy use, emissions, and BRU associated with culture systems (Papatryphon *et al.*, 2004; Pelletier & Tyedmers, 2007; Pelletier *et al.*, 2009). Feasibility studies of transitioning to new feed compositions, though, must consider differences in nutritional content between different species and between plant- and fish-based ingredients.

3.5.5 Study Limitations

Analysis in this study was limited to a single krill product supply chain, and as such is not necessarily representative of the entire Antarctic krill industry. The primary data provider, Aker BioMarine, however, has accounted for one third to half of fishery landings in recent years. Additional data limitations are inherent in the analysis of omega-3 krill oil capsule packaging: the source of gelatin was assumed to be porcine, and environmental costs of pig skin were inferred from a single study of pork systems in the United States. Because of the importance of gelatin production to the overall life cycle environmental performance, future studies examining the comparative impacts of encapsulated nutraceutical products would benefit from the analysis of multiple gelatin sources, including bovine and fish-based sources.

Analysis was also limited by the exclusion of certain life cycle stages and impact categories. Specifically, the use and disposal life cycle stages were excluded, which have been shown to contribute significantly to the overall impacts of some fishery-derived products (Ziegler *et al.*, 2003; Thrane, 2006). However, because the krill products examined here are considered to be ready-to-use and do not require further preparation or cooking as many fish products do, it is unlikely that the use stage would contribute significantly. Several important environmental impacts associated with fisheries were also excluded either because data quality did not allow for conclusive results or because the nature of the impact does not lend itself to quantification. These impacts include marine aquatic ecotoxicity, bycatch and discard, and destruction and alteration of marine habitats.

3.6 Conclusions

We quantified the energy use, emissions, and BRU associated with meal, oil, and omega-3 capsules derived from the Antarctic krill fishery. These elements of environmental sustainability are increasingly important but often overlooked characteristics of food systems and fisheries systems in particular. The environmental performance of the Antarctic krill fishery is of particular interest to many stakeholders, and the environmental implications of the fishery are at the heart of much debate; it is critical that these discussions be well informed from a variety of angles, to bring forward the most holistic understanding of fisheries sustainability.

We found that fuel consumption during fishing and transportation to port dominated the life cycle environmental impacts of Antarctic krill meal and oil and, to a lesser extent, omega-3 krill oil capsules. Fuel use intensity during these activities is very high for krill-derived products when compared to products derived from other reduction fisheries as well as substitutable products sourced from agriculture. Opportunities to improve fuel consumption and related emissions exist, with the most dramatic potential improvements resulting from transitions to fuels with lower sulfur contents or to cleaner energy carriers such as natural gas. Conversely, Antarctic krill was found to have a relatively low measure of BRU when compared to other reduction fisheries, primarily as a result of krill's low trophic level.

LCA can communicate environmental information that has not been traditionally considered in the context of fisheries sustainability and management. It allows us to compare products based on globally significant environmental issues, highlight hotspots of environmental impact and identify opportunities to improve production systems. This is the first comprehensive study of the energy use and emissions associated with the Antarctic krill fishery, and findings here will contribute to broadening our understanding of the environmental implications of using Antarctic krill as a resource.

Chapter 4. Discussion

The research undertaken in this thesis began with three broad goals: 1) to measure and communicate the environmental burden of Antarctic krill-derived products; 2) to compare the environmental costs of Antarctic krill-derived products to products derived from several other reduction fisheries, on the basis of multiple criteria; and 3) to further expand the application of EF and LCA to fisheries and aquaculture systems and explore some of the methodological issues encountered in their application. These three goals were related, as the quality and applicability of results generated in the EF and LCA case studies hinge on the understanding of the methodological choices made and the transparency with which the implications of those methodological choices are communicated.

Chapter 2 explored the methodology of EF analysis in the context of marine resources, to answer the questions ‘What are the drivers underpinning MF results?’, ‘What are the sources and magnitude of variability and uncertainty in MF studies?’ and ‘How do variability and uncertainty affect our ability to draw meaningful conclusions from MF?’. Measures of natural variability and uncertainty, while generally agreed to be important considerations in the application of any ecological indicator, do not typically accompany EF results. It was found here, however, that they actually play a critical role in interpreting the results of EF studies of fishery-derived products. When compared to products from four other reduction fisheries, meal and oil derived from Antarctic krill have a relatively low MF, although the results assume that actual ecological conditions and yields reflect typical, average, or expected values, and a positive or negative change in any input variable, particularly trophic level or trophic transfer efficiency, can alter results significantly. It was recommended in this paper that further work be pursued to address uncertainty and natural variability more formally for other land use categories in EF measurements.

Chapter 3 assessed the resource (biotic and energy) use and emissions associated with AB’s krill-derived products in an LCA case study. It was found that fuel use was the primary driver behind the energy use and emissions-based impacts of krill products. This was not surprising, as LCAs examining other fisheries have come to similar conclusions. Comparisons of the krill fishery to other reduction fisheries on the basis of FUI yielded very different results from those based on dependence on marine ecosystem area reported in the EF study: the FUI of Antarctic krill, landed and unprocessed, is markedly higher than those of other reduction fisheries whose energy use has been measured. This is an important conclusion, because of the critical role that fuel consumption plays in contributing to the overall life cycle impacts of these systems.

The analysis of omega-3 krill oil capsules actually became one of the most interesting elements of the LCA case study, as the domination of impacts by fuel use subsided and different drivers began to emerge as a result of further processing and a high packaging-to-product ratio. However, omega-3 supplements derived from Antarctic krill could not be compared to other similar products, as little work has been done to measure the material and energy demands of nutraceutical products. Nor did the structure of the study lend itself to answering the question 'Are omega-3 krill oil capsules a more or less environmentally costly use of Antarctic krill than meal and oil for aquafeeds', as the products have very different functions and there is no information available as to supplementary products for omega-3 capsules.

4.1 Fuel Use in Fisheries and Marine Fuels

Modern fishing vessels are characterized by heavy reliance on combustion of fossil fuels for propulsion, fishing, and a range of secondary activities (Tyedmers, 2001). For many contemporary fisheries, these energy inputs exceed the output of edible energy from derived products. Broad analyses of fisheries have identified a number of patterns in fuel consumption, including differences between fisheries targeting different species, fishing with different gears, or operating in different regions (Watanabe & Okubo, 1989; Tyedmers, 2001; Schau *et al.*, 2009).

This thesis examined the operations of a single fishing vessel, as well as a secondary resupply vessel, representing a large share of total fishing of Antarctic krill in recent years. It was found that the FUI of Antarctic krill products is high relative to other fisheries targeting species for reduction into meal and oil. Fuel consumption onboard the fishing and resupply vessels was found to be a major driver of the life cycle environmental impacts of all Antarctic krill products, particularly krill meal and krill oil for use as inputs to aquafeeds. This was not surprising, as the fishing stage has consistently been identified as a major driver of energy use and emissions of fishery products (Ziegler *et al.*, 2003; Hospido & Tyedmers, 2005; Ellingsen & Aanondsen, 2006; Thrane, 2006; Ziegler & Valentinsson, 2008; Boyd, 2008; Vásquez-Rowe *et al.*, 2010; Fulton, 2010; Driscoll *et al.*, *in review*).

There are a number of reasons for fishing companies and other stakeholders to seek ways to reduce fuel consumption by fishing vessels. The environmental reasons are clear: reduction of fuel consumption translates into improvements in overall energy use and emissions. Tyedmers and colleagues (2005) estimated that, globally, marine capture fisheries consumed nearly 42.4 million tonnes of fuel in 2000, or 1.2 per cent of global oil consumption that year, and released approximately 134 million tonnes of CO_2 into the atmosphere. Reducing fuel consumption is also important for the economic viability of fisheries. Fuel consumption tends to be an important driver of the overall operational costs of fishing vessels, particularly in the presence of unpredictable and at times rapidly increasing global fuel prices (Tietze & Lasch, 2005; Sumaila *et al.*, 2008; Miyake *et al.*, 2010; van Marlen & Salz, 2010). Decreasing fuel use and associated emissions can also place fishing companies in a position to more readily respond and adapt to emissions regulations. International regulations already exist for many classes of emissions, including ozone-depleting substances, volatile organic compounds, nitrogen oxides (NO_x) and sulfur oxides (SO_x) (IMO, 2006).

Finally, favourable levels of energy use and emissions relative to other products and evidence of efforts to reduce energy use and emissions can prove to be a valuable competitive advantage for fishery products. A growing number of labeling schemes have been developed in recent years focused on communicating the relative environmental performance of seafood products (Wessells *et al.*, 2001; Thrane *et al.*, 2009), and recently it has been increasingly suggested that communications of the environmental costs of fisheries should consider energy- and emissions-based criteria (Pelletier & Tyedmers, 2008; Thrane *et al.*, 2009). A competitive advantage can be achieved by fishery products via comparisons with products from other fisheries or comparisons with land-based animal and plant products. While capture fisheries have been criticized as being the "most energy-intensive food production method in the world" (Wilson, 1999), estimates of global energy use by fisheries suggest that many fish products are actually a far more energy- and emissions-efficient source of protein than many land-based animal products (Pimental & Pimental, 2003; Tyedmers *et al.*, 2005; Sonesson *et al.*, 2010; Pelletier *et al.*, *in review*).

Fuel use in fisheries LCAs is not commonly measured at the resolution of individual types of marine fuels. Fuel use data used in this thesis were available for both MDO and IFO, and differences between the properties, emissions and life cycle environmental costs of both were explored. The clearest difference between the two marine fuels is the sulfur contents, 11 g per litre of MDO and 46 g per litre of IFO, although other less substantial differences also exist (see Appendix E). Scenario analysis in Chapter 3 found that adopting a fuel mix with higher MDO content would translate into improvements in all energy and emissions-based impact categories considered, particularly AP. The life cycle environmental benefits of MDO have been questioned in the past because of the increased upstream processing required relative to IFO and Bunker C (Corbett & Winebrake, 2008), but that increased processing was found here to be outweighed by the benefits of improved emissions when burned, supporting the conclusions of Corbett & Winebrake (2008). These findings may be of particular interest because of SO_2 regulations already in place and the plan for even stricter regulations on sulfur content of marine fuels in the future (IMO, 2006). It is recommended to other fisheries LCA practitioners that, particularly when AP is of interest, future LCAs of fisheries products should consider these differences between marine fuels.

4.2 Carbon Footprint

The CF is a reflection of the GHG emissions associated with an individual, organization, region, activity, product or service (Wackernagel & Rees, 1996; Wiedmann & Minx, 2007). When measured at national and global scales, it often accounts for the largest portion of the total EF (Ewing *et al.*, 2010; Pollard *et al.*, 2010). The CF was not considered in the analysis of Chapter 2, which focused instead on the marine portion of the EF. However, the CF, being a measure of GHG emissions, is closely related to the GWP impact category of LCA. Because the GWP impact category for fisheries is typically dominated by fuel consumption during the fishing stage, FUI is generally a good indicator of the CF of fisheries.

Antarctic krill products, while they were found to have a relatively low MF, have a high CF when compared to meal and oil products derived from other species (Table 17). This is directly related to the high FUI of the Antarctic krill fishery examined in this thesis. Comparisons of reduction fisheries on the basis of CF follow a very different pattern from those based on MF (Table 17). Interestingly, in spatial terms, the CF is largely overshadowed by the MF, and does not have much influence on the total EF of reduction fisheries products (Table 17).

The fact that the importance of differences in the CF of fisheries products appears to be lost when examined together with the MF, and the fact that the CF and MF measure two very different types of environmental burden (aquatic biotic resource extraction and the area of global average forest land required to mitigate GHG emissions via carbon sequestration) calls for caution when aggregating these different portions of the EF and drawing conclusions regarding the relative importance of CF compared to MF. While the CF is still often measured in spatial terms at national and global scales (Ewing *et al.*, 2010), communicating the CF in terms of CO_2-e emissions rather than land area is becoming more common (Wiedmann & Minx, 2007). Communicating the carbon footprint in terms of CO_2-e emissions – basically the GWP impact category of LCA – would avoid the confusion associated with comparing CF to MF when evaluating the EF of fisheries.

Table 17. Marine and carbon portions of the EF associated with the provision of 100 GJ combined meal and oil product from five fisheries. For detailed analysis, see Chapter 2 and Appendix J.

Fishery	Tonnes wet weight required for 100 GJ	Marine footprint	Carbon footprint	Total ecological footprint
Gulf menhaden	9.5	8.4	0.6	9.0
Antarctic krill	26.0	18.7	3.5	22.2
Atlantic herring	11.4	26.9	1.1	28.0
Peruvian anchovy	17.9	35.5	0.9	36.4
Blue whiting	23.7	989	2.2	991.2

4.3 Challenges and Limitations

A number of challenges were encountered in this thesis, including research-related frustrations, issues concerning methodological choices, and challenges related to the scope and applicability of findings. The first challenge encountered was one typical of many LCA studies: frustrations experienced during data collection. LCA is a data-intensive method that often relies heavily on the participation of industry to volunteer information. In many cases, surveys can be distributed to a number of industry contacts to gather data from multiple sources. However, for this study, data collection relied on one single company, AB. While the study benefited enormously from the fact that the primary source had a clear interest in ensuring research results were robust, the pace of data collection was largely dependent on the ability of the company to provide information in a timely fashion. In this regard, data acquisition was sometimes delayed when my contacts at the AB office in Norway did not have immediate access to data and/or sufficient human resources to devote time specifically to compiling and communicating data. A related challenge emerged when it became apparent that my understanding of the entire production system grew gradually over time, and on more than one occasion I was introduced to a new product, process or input material that I was not previously aware of, demanding additional data collection. Ultimately, the data collection process would have benefitted from better communication with AB from the start, and from an initial screening survey to better understand the entire production system prior to the main data collection instrument.

Challenges were also encountered in comparing krill products to broadly comparable products from other reduction fisheries. These comparisons became an important element of the thesis, both because they are useful in placing results in the context of wider food production systems, and because they are valuable gauges to understand the relative performance of krill-derived products. Comparisons in Chapter 2 were made on the basis of energy content, and were accompanied by comparisons based on wet-weight mass and protein content. The choice of energy content as the primary basis of comparison was made because energy, rather than mass, was considered to be the primary function of the products, and because protein-based comparisons completely exclude the nutritional value of oil and therefore would not recognize the full importance of differences in nutritional value between, for example, Gulf menhaden and Antarctic krill (see Appendix A). The use of any of these bases of comparison excludes many nutritional properties of the products, including omega-3 fatty acid content and Astaxanthin amino acid content, an important component of krill and a marketing advantage for krill-based products. In Chapter 3, comparisons were made on the basis of FUI, which measures fuel consumption per wet-weight landed mass, ignoring all differences in nutritional content; FUI is a typical form of comparison between fisheries when energy use and GHG emissions are the focus of concern, and does not require substantial collection of additional data to estimate. As became clear in the EF study, the choice of basis of comparison is paramount and can create bias to favour one product over another; therefore, it was argued that the differences between bases of comparison need to be addressed, including what is and is not considered by each method, and sensitivity analyses, such as that undertaken in Chapter 2, should be used to highlight the influence of these differences on comparative results.

Another challenge that commonly arises in LCA work is the issue of co-product allocation. This issue was faced when assessing several processes in the krill production system: allocating burden from fishing and onboard processing between meal, oil and paste produced on Saga Sea; allocating burden from transportation on La Manche between meal, paste and oil; allocating burden from transportation to France between capsules and lower grade meal; and allocating burden from France-based processing between capsules and lower grade meal. According to ISO 14044:

> Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and output are changed by quantitative changes in the products or functions delivered by the system (ISO, 2006b, p. 14).

Because the function of the products here was seen to be the provision of energy, it was decided that the most appropriate form of allocation to meet this guideline was allocation based on relative energy content of the products. Energy content was used as the basis of allocation for fishing and processing activities on Saga Sea and for processing activities in France. Emissions associated with transportation on La Manche were allocated based on mass, because mass and volume, rather than energy content, are the primary limiting factors of transport: larger products demand more tonne kilometers of transportation service than smaller products. It is important to recognize that allocation based on biophysical characteristics such as mass or energy content is not typical in LCAs of fisheries: in a review by Ayer and colleagues (2006), it was found that economic allocation was the most common method used in LCAs of seafood products. Economic allocation is applied widely in LCAs, particularly in studies carried out in Europe; in fact, the PAS 2050 standards specifically call for economic allocation for calculating the CF of products (BSI, 2009). This significant disparity between methods applied in different studies makes it difficult to compare results from different LCAs, and it is unlikely that this methodological issue will be resolved definitively in the near future. When possible, it is appropriate, and common practice, to provide sensitivity analyses in studies to demonstrate the influence of this methodological choice on the results. Here, allocation factors for both mass-based and energy-based allocation were presented in Chapter 3. It is also important to note that the issue most commonly faced in fisheries LCAs which requires allocation is the presence of bycatch or multiple target species (Ziegler *et al.*, 2003; Ellingsen & Aanondsen, 2006; Thrane, 2006; Ziegler & Valentinsson, 2008). This study differs in that only a single species was harvested and no bycatch was reported, and allocation efforts were instead focused on dividing burdens between multiple products from the same species. Ziegler (2006) suggests that allocation between meal and oil based on economic criteria would not differ significantly from that based on energy content, because the two are more or less correlated. Allocation of burden towards omega-3 krill oil capsules, however, would likely change significantly as a result of using economic criteria, and in that case capsules would likely be allocated much more burden than they were in this study, assuming they have a much higher value per unit mass/energy. While it was recognized that the application of economic allocation in this thesis would be likely to have a profound effect on some results, in was not possible to perform sensitivity analysis to quantify that effect due to the unavailability of data pertaining to AB's revenue streams.

The applicability of the results of this thesis depends largely on what was chosen to be included and excluded from analysis. Limitations of the thesis, particularly the LCA presented in Chapter 3, reflect four important exclusions. First, many ecological issues associated with the krill fishery were not considered. While these issues, including stock status and impacts on predators, are of broad concern, they are better addressed by tools such as CCAMLR stock sustainability studies, MSC assessment, and other methods designed specifically to address ecological impacts. Second, non-environmental aspects of sustainability were excluded entirely from the study. EF does not include socio-economic indicators, and LCA rarely includes socio-economic impact categories; both of these tools rely on quantifiable inputs, and not easily lend themselves to considerations of socio-economic issues. While EF does not seek to include these kinds of issues in analysis, focusing completely on resource use and assimilation of wastes in the case of the CF, there has been some exploration of the inclusion of socio-economic indicators in seafood LCAs (Kruse *et al.*, 2009), but these impact categories have not been commonly applied in actual fisheries and aquaculture case studies. Third, the LCA study was a cradle-to-customer analysis of krill product supply chains and did not consider downstream impacts, including impacts associated with use and disposal of products; while downstream activities for krill meal and oil would be more likely addressed in an LCA of an aquaculture system, downstream activities associated with omega-3 krill oil capsules could have been included, such as recycling of the bottle, but were outside of the scope of the study. Finally, the study uses data pertaining to only one production chain specific to a single company with a single fishing vessel. While AB's activities do account for a significant portion of the contemporary krill industry in the Southern Ocean, LCA results here cannot be considered representative of the entire industry; EF results are more applicable to the industry as a whole, as they are more species-specific than process-specific.

4.4 Significance of Results

Perception of the environmental sustainability of the Antarctic krill fishery seems to be largely driven by ecological concerns regarding stock status and predator-prey relationships and by uncertainty regarding how environmental changes will affect populations. The results presented in this thesis, while providing a new aspect of the BRU associated with the fishery, in both spatialized EF results and in non-spatialized measures of NPP appropriation, do not directly assess the fishery on the basis of these ecological issues. However, results do provide further insight into the environmental and economic sustainability of the fishery in terms of its contributions to globally-relevant issues which will likely continue to be of importance to governments and consumers, and which may form the basis of future regulations. As well, because products from this fishery are inputs to other production systems, which also face increased awareness and concern regarding these issues, there is likely to be increasing pressure on the fishery to provide environmental information to those customers and to improve environmental performance if those customers demand it. Feed production accounts for a significant portion of both the EF of aquaculture systems (Folke, 1988; Tyedmers, 2000) and of the energy use and GHG emissions resulting from aquaculture systems (Tyedmers, 2000; Tyedmers *et al.*, 2007; Pelletier & Tyedmers, 2010). Consequently, the results of both analyses presented in this thesis provide relevant information to the aquaculture industry regarding the influence of the use of krill and other fishery inputs on the environmental performance of farmed fish products.

Aquaculture is growing to become an important source of protein in the world, and meal and oil products from reduction fisheries are required for much of this seafood production, particularly of high-value carnivorous species often destined for wealthy consumers. The question must be asked, should krill be considered a suitable source of these products? While a comprehensive answer to this question is beyond the scope of this thesis, the research undertaken here does provide insight into the relative environmental performance of krill products when compared to several other reduction fisheries, and demonstrates that the performance of a fishery largely depends on the methods and indicators used to evaluate it. On the basis of EF results, the krill fishery can be considered a relatively sustainable use of marine resources when compared to higher trophic level species. On the basis of energy use and emissions, krill products appear to have substantially higher environmental costs when compared to other reduction fisheries. If compared on the basis of other indicators, including other measures of environmental performance and of socio-economic performance, results may lead to different conclusions again. However, ultimately, it is the ecological issues described above which will likely drive perception of this fishery as well as any significant limits on krill fishing activities.

Appendix A. Nutritional Content of Fish/Krill Meal

Table A1. Nutritional values used to calculate the energy densities of meal derived from Antarctic krill and four fish species.

Species	Moisture (%)	Crude Protein (%)	Ether Extract (%)	Crude Fibre (%)	Ash (%)
Peruvian anchovy	8.0	64.2	5.0	1.0	21.7
Atlantic herring	7.0	72.3	10.0	0.7	10.2
Blue whiting	9.0	62.6	4.6	0.7	22.6
Gulf menhaden	8.0	60.1	9.4	0.7	21.4
Antarctic krill	6.5	56.0	23.0	-	10.5

a. Nutritional content of meal derived from Peruvian anchovy, Atlantic herring, blue whiting and Gulf menhaden taken from NRC (1994).

b. Nutritional content of meal derived from Antarctic krill taken from Aker BioMarine (2008).

Appendix B. Detailed Marine Footprint Sensitivity Analysis Results

Table B1. Correlation coefficients of marine footprint input parameters and outcomes.

Input variable	**Peruvian anchovy**	**Atlantic herring**	**Blue whiting**	**Gulf menhaden**	**Antarctic krill**	**Average**
Trophic transfer efficiency	-0.732	-0.763	-0.772	-0.832	-0.769	**-0.774**
Trophic level	0.562	0.551	0.574	0.201	0.439	**0.465**
Regional productivity	-0.207	-0.174	-0.129	-0.349	-0.299	**-0.232**
Carbon to wet weight ratio	0.182	0.159	0.118	0.311	0.263	**0.207**
Oil yield	-0.034	-0.033	-0.008	-0.082	-0.027	**-0.037**
Meal yield	-0.028	-0.029	-0.026	-0.003	-0.049	**-0.027**
Meal energy content	-0.018	-0.013	-0.007	-0.036	-0.032	**-0.021**

Appendix C. Energy Use and Emissions Associated with Pork Production

Table C1. Life cycle impact assessment results of pork production used to inform upstream processes of pig skin inputs to gelatin (Pelletier *et al.*, 2010). Data relate to the production of 1.85 kg live weight 'average commodity pig'.

Impact category	Units	Value
Global warming potential	kg CO_2-e	4.916
Ozone depletion potential	kg CFC-11-e	9.35E-8
Acidification potential	kg SO_2-e	0.123
Eutrophication potential	kg PO_4-e	0.034
Cumulative energy demand	MJ	20

Appendix D. EcoInvent 2.0 Unit Processes Used to Construct Krill Life Cycle Inventory

SimaPro models for this thesis were taken from the EcoInvent 2.0 database compiled and distributed by the Swiss Centre for Life Cycle Inventories. When system-specific information was known and EcoInvent did not contain appropriate unit processes, new processes were modeled by adapting existing EcoInvent processes. In the absence of system-specific information, and when numerous EcoInvent processes were present, average processes were created from existing EcoInvent processes. Note: RER refers to European average data.

Table D1. EcoInvent 2.0 unit processes used to represent material and operational inputs to fishing vessel (Saga Sea) and resupply vessel (La Manche) construction, maintenance and gear manufacturing.

Category	Input	Unit Process
Vessel Construction and maintenance material inputs	Steel[a]	Steel, converter, low-alloyed, at plant/RER U
		Steel, converter, chromium steel 18/8, at plant/RER U
		Steel, converter, unalloyed, at plant/RER U
		Steel, electric, chromium steel 18/8, at plant/RER U
		Steel, electric, un- and low-alloyed, at plant/RER U
	Copper	Copper, at regional storage/RER U
	Aluminum	Aluminum alloy, AlMg3, at plant/RER U
	Glass[a]	Flat glass, coated, at plant/RER U
		Flat glass, uncoated, at plant/RER U
	Wood[a]	Sawn timber, hardwood, planed, air / kiln dried, u=10%, at plant/RER U
		Sawn timber, hardwood, raw, air/kiln dried, u=10%, at plant/RER U
		Sawn timber, softwood, planed, air dried, at plant/RER U
		Sawn timber, hardwood, raw, kiln dried, u=10%, at plant/RER U
	Fibreglass	Glass fibre, at plant/RER U
	Polyethylene[a]	Polyethylene, HDPE, granulate, at plant/RER U
		Polyethylene, LDPE, granulate, at plant/RER U
		Polyethylene, LLDPE, granulate, at plant/RER U
Vessel construction and maintenance operational inputs	Transport[b]	Transport, lorry >16t, fleet average/RER U
		Transport, freight, rail/RER U
	Energy[b]	Electricity, Chile[c]
		Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER U
Gear	Polyethylene[a]	Polyethylene, HDPE, granulate, at plant/RER U
		Polyethylene, LDPE, granulate, at plant/RER U
		Polyethylene, LLDPE, granulate, at plant/RER U
	Rubber	Synthetic rubber, at plant/RER U

a. Averaged values for multiple unit processes, because material specifications specific to actual production were not available.

b. Adapted from EcoInvent 2.0 process 'Transoceanic freight ship/OCE/I U'.

c. Average of low, medium and high voltage using Brazilian processes from EcoInvent 2.0 processes adapted to reflect Chilean energy mix (22.7% coal, 24.6% oil, 7.9% gas, 5.3% biomass, 39.5% hydroelectric) from http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=CL

Table D2. EcoInvent 2.0 unit processes used to represent material inputs to packaging.

Category	Input	Unit Process
Meal packaging	Nylon	Nylon 6, at plant/RER U
		Nylon 6, glass-filled, at plant/RER U
		Nylon 66, at plant/RER U
		Nylon 66, glass-filled, at plant/RER U
	Polyethylene	Polyethylene, HDPE, granulate, at plant/RER U
		Polyethylene, LDPE, granulate, at plant/RER U
		Polyethylene, LLDPE, granulate, at plant/RER U
Oil packaging	Polyethylene	Polyethylene, HDPE, granulate, at plant/RER U
		Polyethylene, LDPE, granulate, at plant/RER U
		Polyethylene, LLDPE, granulate, at plant/RER U
Capsule packaging[a]	Cardboard	Corrugated board, fresh fibre, single wall, at plant/RER U
		Corrugated board, mixed fibre, single wall, at plant/RER U
		Corrugated board, recycling fibre, double wall, at plant/RER U
		Corrugated board, recycling fibre, single wall, at plant/RER U
	Polyethylene	Polyethylene, HDPE, granulate, at plant/RER U
		Polyethylene, LDPE, granulate, at plant/RER U
		Polyethylene, LLDPE, granulate, at plant/RER U
	Polypropylene	Polyproylene, granulate, at plant/RER U
	Polyethylene Terephthalate	Polyethylene terephthalate, gransulate, bottle grade, at plant/RER U

a. Excluding inputs to gelatin.

Table D3. EcoInvent 2.0 unit processes used to represent inputs to gelatin production, excluding the input of pig skin.

Category	Input	Unit Process
Gelatin Production	Sulphuric acid	Sulphuric acid, liquid, at plant/RER U
	Sodium hydroxide	Sodium hydroxide, 50% in H2O, production mix, at plant/RER U
	Electricity	Electricity, medium voltage, at grid/FR U

Table D4. EcoInvent 2.0 unit processes used to represent inputs to secondary processing for omega-3 krill oil capsules.

Category	Input	Unit Process
Processing	Ethanol	Ethanol, 99.7% in H2O, from biomass, at distillation/RER U
	Energy	Heat, light fuel oil, at industrial furnace 1MW/RER U
		Electricity, medium voltage, at grid/FR U

Table D5. EcoInvent 2.0 unit processes used to represent transportation inputs to distribution.

Category	Input	Unit Process
Freight transport	Container vessel	Transport, transoceanic freight ship/OCE U
	Truck	Transport, lorry >16t, fleet average/RER U
	Air freight[a]	Transport, aircraft, freight/RER U

a. For the purposes of scenario analysis.

Appendix E. Properties and Emissions Associated with Marine Fuels

This study employed emissions data that reflect characteristics of different fuel types, MDO and IFO, to highlight differences between energy carriers and identify potential changes as a result of using alternative fuel mixes. However, the EcoInvent 2.0 database includes only one unit process for heavy fuel oil, based on average for several different fuels (Spielmann *et al.*, 2007). In order to allow comparisons, new unit processes were constructed using EcoInvent unit processes as a template. This required adjusting both upstream emissions associated with fuel production (Table E1) and emissions associated with burning of fuels (Table E3). Emissions associated with transportation and distribution of fuels were assumed to be equal on a mass basis for all marine fuels, and the EcoInvent unit process 'heavy fuel oil, at regional storage/RER U' was used to represent these activities.

Table E1. CO_2 emissions associated with extraction, processing and refining of marine fuels.

Emissions	Units	EcoInvent[a]	MDO[b]	IFO 180[b]	Bunker C[b]
High population density	g/kg	171.51	197.24	145.78	138.92
Low population density	g/kg	190.72	219.33	162.11	154.48
Stratospheric and Tropospheric	g/kg	1.26E-05	1.45E-05	1.07E-05	1.02E-05
Other	g/kg	16.34	18.79	13.89	13.24
Land Transformation	g/kg	1.40E-02	1.40E-02	1.40E-02	1.40E-02
Total	g/kg	378.58	435.36	321.78	306.64

a. EcoInvent 2.0 unit process 'heavy fuel oil, at refinery/RER S'.

b. Adjusted by adding 15% for MDO, subtracting 15% for IFO, and subtracting 19% for Bunker C, following Corbett and Winebrake (2008).

Differences also exist between the density and energy content of marine fuels. This study assumed the purpose of marine fuels to be the provision of energy, and so all emissions modeled were converted to account for differences in energy density. Fuel densities were taken from Environment Canada (1999), and energy densities were acquired from the United States Energy Information Administration (EIA, 2010) (Table E2).

Table E2. Properties of marine fuels.

Property	Units	MDO	IFO 180	Bunker C
Density (15 °C)[a]	kg/L	0.863	0.957	0.926
Energy density[b]	MJ/L	38.969	41.421	41.727
Energy density[b]	MJ/kg	45.155	43.282	45.062

a. Fuel-specific densities taken from Environment Canada (1999).

b. Energy density calculated from EIA (2010).

Table E3. Emissions associated with burning marine fuels.

Category	Emission species	Units	MDO	IFO 180	Bunker C
Fuel-dependent emissions	CO_2[a]	g/L	2728	3079	3123.40
	SO_2[b]	g/L	11	46	48.15
	HCl[c]	g/L	4.00E-02	6.40E-02	6.35E-02
	HF[d]	g/L	5.18E-03	5.74E-03	5.56E-03
Diesel engine emissions	NO_X[e]	g/L	69.4	76.9	74.45
	CO[e]	g/L	6.4	7.1	6.85
	N_2O[e]	g/L	6.90E-02	7.66E-02	7.41E-02
	Methane[e]	g/L	4.32E-02	4.79E-02	4.63E-02
	Benzene[e]	g/L	4.06E-02	4.50E-02	4.35E-02
	Toluene[e]	g/L	1.73E-02	1.91E-02	1.85E-02
	Xylene[e]	g/L	1.73E-02	1.91E-02	1.85E-02
	Ammonia[d]	g/L	2.07E-06	2.30E-06	2.22E-06
	Other NMVOC[d]	g/L	2.24E-06	2.49E-06	2.41E-06
Particulate emissions	<2.5 µm[e]	g/L	1.24	1.38	1.33
	2.5-10 µm[e]	g/L	1.42	1.57	1.52
	10-100 µm[e]	g/L	1.78	1.97	1.91
Heavy metals	As[f]	g/L	8.20E-05	4.35E-04	4.63E-04
	Cd[f]	g/L	1.04E-05	2.68E-05	2.78E-05
	Cr[f]	g/L	4.83E-05	1.76E-04	1.85E-04
	Cu[f]	g/L	8.20E-05	4.35E-04	4.63E-04
	Ni[f]	g/L	2.64E-03	2.58E-02	2.78E-02
	Pb[f]	g/L	9.49E-05	1.82E-04	1.85E-04
	Se[f]	g/L	1.90E-04	3.64E-04	3.70E-04
	Zn[f]	g/L	4.66E-04	8.23E-04	8.33E-04
	Hg[f]	g/L	4.06E-05	2.20E-05	1.85E-05
Toxic substances	Dioxins[e]	g/L	9.E-10	1.E-09	9.26E-10
	PAH[e]	g/L	2.E-03	2.E-03	1.85E-03
Other outputs	Disposal, bilge[e]	g/L	0.5	0.6	0.6
	Heat, waste[e]	MJ/L	35	38	37

a. United States Energy Information Administration (2010).

b. Corbett and Winebrake (2008).

c. Miller and colleagues (1996).

d. Based on EcoInvent 2.0 unit process 'operation, transoceanic freight ship/OCE U'.

e. Spielmann and colleagues (2007).

f. Spielmann and colleagues (2007), assuming residual/distillate ratios of 10%/90% for MDO, 90%/10% for IFO 180, and 100%/0% for Bunker C, following Environment Canada (1999).

Appendix F. Method for Calculating Biotic Resource Use

Biotic resource use was here defined as the appropriation of net primary productivity, such that NPP was not available for other uses in the ecosystem. Marine NPP appropriation was estimated by calculating the amount of krill harvested to supply the functional unit, applying energy-based allocation, and following the formula used for the calculation of marine footprint (Chapter 2) (Table F1).

Table F1. Calculation of NPP appropriation from krill harvest.

Product	Krill required	Allocation factor[a]	Allocated krill	NPP
1 kg krill meal	6.9 kg	.9612	6.68 kg	11.8 kg C
1 L krill oil	1,470.6 kg	.0075	11.0 kg	19.4 kg C
60 krill oil capsules	342.4 g[b]	.9612	329.1 g	579.5 g C

a. Allocation factors do not add to 1. The remainder is allocated to krill paste produced for development purposes.

b. 60 capsules requires the input of 150 g krill meal; only 49.3 g are allocated to the production of capsules; the remainder is allocated to lower grade meal product, on an energy basis. 49.3 g of meal requires the harvest of 342.4 g of krill.

To estimate the BRU of krill oil capsules, the NPP associated with the pork product input to gelatin manufacturing also needed to be established. While Pelletier and colleagues (2010) did include an ecological footprint impact category in the LCA of pork, NPP data were not provided, and so needed to be calculated here. Soy and corn inputs to pork production were taken from Pelletier and colleagues (2010), and converted to NPP assuming a 45% carbon content of feedstock.

Table F2. Calculation of NPP appropriation from feeding pigs, for functional unit of 60 omega-3 krill oil capsules (13.5 g gelatin; 25 g pig skin)

Input	Per kg pork[a]	Per 60 capsules	% carbon	NPP
Soy	951.1 g	23.8 g	45%	10.7 g
Corn	2,684.5 g	67.1 g	45%	30.2 g
Total	3,635.6 g	90.9 g	45%	40.9 g

a. Based on average values for four pork production systems, including feed consumed by finishing pigs and feed consumed by gestating and lactating sows (Pelletier *et al.*, 2010).

Appendix G. Aker BioMarine Fuel Use and Production Data for 2007-2009.

This research made use of data from Aker BioMarine for the years 2007-2009. Fuel use intensities used average values from 2007-2009 for the fishing vessel (Saga Sea) and from 2007-2008 for the resupply vessel (La Manche).

Table G1. Saga Sea krill harvest, 2007-2009 (tonnes).

Month	**2007**	**2008**	**2009**
January	4,470	4,650	3,535
February	4,787	6,947	5,003
March	6,018	11,542	4,366
April	6,266	6,163	7,736
May	9,687	5,626	9,297
June	3,393	4,743	6,436
July	2,059	8,225	3,205
August	1,996	4,799	3,649
September	0	1,156	0
October	0	0	0
November	0	0	0
December	1,260	135	0
Total	**39,937**	**53,986**	**43,227**

Table G2. Saga Sea production, 2007-2009 (kg).

Product	**2007**	**2008**	**2009**
Meal	6,814	8,590	6,236
Oil	26	35	36
Paste	0	120	272

Table G3. Saga Sea fuel use, 2007-2009 (L).

Fuel type	**2007**	**2008**	**2009**
MDO	977,000	1,873,000	1,355,000
IFO	4,774,000	4,830,000	4,656,000

Table G4. La Manche fuel use, 2007-2008 (L).

Fuel type	**2007**	**2008**
MDO	1,290,000	1,360,000
IFO	4,260,000	3,920,000

Appendix H. Calculating Distribution Distances for Krill Meal and Oil

Distribution distances for meal and oil from Montevideo were based on four distribution scenarios from Aker BioMarine, with destinations: Florø, Norway; Vancouver, Canada; Brisbane, Australia; and Puerto Montt, Chile. Estimated truck travel distance was provided by Aker BioMarine. Container ship travel distance was estimated using the port distance calculator at www.portworld.com/map (Table H1).

Table H1. Breakdown of distribution scenarios for krill meal and oil.

Transport Scenario	Mode	Origin	Destination	Distance (km)
1	Container ship	Montevideo, UY	Rotterdam, NL	11,579
	Container ship	Rotterdam, NL	Florø, NO	1,083
	Truck	Florø, NO		2
	Total			12,664
2	Container ship	Montevideo, UY	Valparaiso, CL	4,858
	Container ship	Valparaiso, CL	Los Angeles, US	9,023
	Container ship	Los Angeles, US	Vancouver, CA	2,035
	Truck	Vancouver, CA		15
	Total			15,593
3	Container ship	Montevideo, UY	Brisbane, AU	13,216
	Truck	Brisbane, AU		10
	Total			13,226
4	Container ship	Montevideo, UY	Valparaiso, CL	4,915
	Truck	Valparaiso, CL	Puerto Montt, CL	586
	Total			5,501
Average	Container ship			11,677
	Truck			153
	Total			11,830

Appendix I. Characterization Results for Krill Meal and Oil and Omega-3 Krill Oil Capsules

Table I1. Characterized environmental burden associated with 1 kg krill meal.

	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication Potential	Cumulative Energy Demand	Biotic Resource Use
	kg CO_2-e	kg CFC-11-e	g SO_2-e	g PO_4-e	MJ	NPP (kg C)
Fishing	**1.950**	**2.35E-07**	**49.00**	**5.71**	**28.60**	**11.6**
(%)	**(35.8%)**	**(36.5%)**	**(36.6%)**	**(36.5%)**	**(35.7%)**	**(100.0%)**
Fuel	1.880	2.32E-07	48.61	5.66	27.43	…
Vessel construction	0.057	2.42E-09	0.34	0.04	0.93	…
Vessel maintenance	0.014	5.73E-10	0.07	0.01	0.22	…
Gear	0.001	7.73E-11	0.00	0.00	0.02	…
Processing	**1.01**	**1.25E-07**	**26.20**	**3.05**	**14.80**	…
(%)	**(18.6%)**	**(19.4%)**	**(19.6%)**	**(19.5%)**	**(18.5%)**	**(0.0%)**
Primary, onboard	1.01	1.25E-07	26.20	3.05	14.80	…
Transport to port	**2.200**	**2.67E-07**	**55.30**	**6.50**	**32.30**	…
(%)	**(40.4%)**	**(41.4%)**	**(41.3%)**	**(41.5%)**	**(40.3%)**	**(0.0%)**
Fuel	2.132	2.64E-07	54.91	6.45	31.20	…
Vessel construction	0.055	2.36E-09	0.34	0.04	0.90	…
Vessel maintenance	0.013	5.58E-10	0.07	0.01	0.21	…
Packaging	**0.137**	**1.29E-11**	**0.50**	**0.09**	**2.18**	…
(%)	**(2.5%)**	**(0.0%)**	**(0.4%)**	**(0.6%)**	**(2.7%)**	**(0.0%)**
Nylon	0.133	1.24E-11	0.47	0.09	2.02	…
Polyethylene	0.004	3.64E-13	0.04	0.00	0.14	…
Distribution	**0.144**	**1.72E-08**	**2.90**	**0.30**	**2.31**	…
(%)	**(2.7%)**	**(2.7%)**	**(2.2%)**	**(1.9%)**	**(2.9%)**	**(0.0%)**
Container vessel	0.125	1.41E-08	2.79	0.27	1.98	…
Truck	0.019	3.10E-09	0.11	0.03	0.33	…
TOTAL	**5.441**	**6.44E-07**	**133.9**	**15.65**	**80.19**	**11.6**
(%)	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**

Table I2. Characterized environmental burden associated with 1 L krill oil.

	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication Potential	Cumulative Energy Demand	Biotic Resource Use
	kg CO_2-e	kg CFC-11-e	g SO_2-e	g PO_4-e	MJ	NPP (kg C)
Fishing	**3.151**	**3.81E-07**	**79.34**	**9.24**	**46.30**	**19.1**
(%)	**(44.5%)**	**(45.0%)**	**(45.2%)**	**(45.2%)**	**(43.5%)**	**(100.0%)**
Fuel	3.037	3.76E-07	78.67	9.17	44.40	…
Vessel construction	0.091	3.92E-09	0.56	0.06	1.50	…
Vessel maintenance	0.022	9.30E-10	0.11	0.01	0.36	…
Gear	0.001	1.25E-10	0.00	0.00	0.04	…
Processing	**1.640**	**2.02E-07**	**42.30**	**4.93**	**23.90**	…
(%)	**(23.2%)**	**(23.9%)**	**(24.1%)**	**(24.1%)**	**(22.5%)**	**(0.0%)**
Primary, onboard	1.640	2.02E-07	42.30	4.93	23.90	…
Transport to port	**2.030**	**2.46E-07**	**50.80**	**5.97**	**29.70**	…
(%)	**(28.7%)**	**(29.0%)**	**(28.9%)**	**(29.2%)**	**(27.9%)**	**(0.0%)**
Fuel	1.967	2.43E-07	50.44	5.93	28.69	…
Vessel construction	0.051	2.17E-09	0.31	0.03	0.83	…
Vessel maintenance	0.012	5.14E-10	0.06	0.01	0.20	…
Packaging	**0.125**	**2.14E-09**	**0.49**	**0.24**	**2.13**	…
(%)	**(1.8%)**	**(0.3%)**	**(0.3%)**	**(1.2%)**	**(2.0%)**	**(0.0%)**
Cardboard	0.006	3.00E-10	0.03	0.03	0.22	…
Steel	0.031	4.12E-10	0.12	0.05	0.36	…
Polyethylene	0.088	4.12E-10	0.34	0.16	1.55	…
Distribution	**0.133**	**1.58E-08**	**2.63**	**0.05**	**4.38**	…
(%)	**(1.9%)**	**(1.9%)**	**(1.5%)**	**(0.3%)**	**(4.1%)**	**(0.0%)**
Container vessel	0.115	1.30E-08	2.53	0.05	3.75	…
Truck	0.018	2.84E-09	0.10	0.00	0.63	…
TOTAL	**7.079**	**8.47E-07**	**175.55**	**20.43**	**106.41**	**19.1**
(%)	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**

Table I3. Characterized environmental burden associated with a 60-capsule bottle of omega-3 krill oil capsules.

	Global Warming Potential	Ozone Depletion Potential	Acidification Potential	Eutrophication Potential	Cumulative Energy Demand	Biotic Resource Use
	kg CO_2-e	kg CFC-11-e	g SO_2-e	g PO_4-e	MJ	NPP (kg C)
Fishing	**0.102**	**1.23E-08**	**2.57**	**0.30**	**1.50**	**0.579**
(%)	**(18.6%)**	**(22.6%)**	**(27.1%)**	**(17.0%)**	**(11.5%)**	**(88.0%)**
Fuel	0.098	1.21E-08	2.55	0.30	1.44	…
Vessel construction	0.003	1.27E-10	0.02	0.00	0.05	…
Vessel maintenance	0.001	3.00E-11	0.00	0.00	0.01	…
Gear	0.000	4.05E-12	0.00	0.00	0.00	…
Processing	**0.193**	**2.34E-08**	**2.00**	**0.33**	**7.30**	…
(%)	**(35.2%)**	**(43.0%)**	**(21.1%)**	**(18.4%)**	**(55.7%)**	**(0.0%)**
Primary, onboard	0.053	6.56E-09	1.37	0.16	0.78	…
Secondary, France	0.140	1.68E-08	0.63	0.17	6.52	…
Transport to port	**0.11**	**1.31E-08**	**2.72**	**0.32**	**1.59**	…
(%)	**(20.1%)**	**(24.2%)**	**(28.7%)**	**(18.1%)**	**(12.1%)**	**(0.0%)**
Fuel	0.106	1.30E-08	2.70	0.32	1.54	…
Vessel construction	0.003	1.16E-10	0.02	0.00	0.04	…
Vessel maintenance	0.001	2.74E-11	0.00	0.00	0.01	…
Additional transport	**0.009**	**1.17E-09**	**0.14**	**0.01**	**0.15**	**…**
(%)	**(1.6%)**	**(2.1%)**	**(1.5%)**	**(0.6%)**	**(1.1%)**	**(0.0%)**
Transport to France	0.007	8.15E-10	0.13	0.01	0.11	…
Transport to distributor	0.002	3.53E-10	0.01	0.00	0.04	…
Packaging, non-gelatin	**0.055**	**2.2E-09**	**0.2**	**0.05**	**1.67**	…
(%)	**(10.0%)**	**(4.0%)**	**(2.1%)**	**(2.8%)**	**(12.7%)**	**(0.0%)**
Cardboard	0.000	9.17E-13	0.00	0.00	0.00	…
Polyethylene	0.001	1.36E-13	0.00	0.00	0.05	…
PE terephthalate	0.048	2.20E-09	0.18	0.00	1.38	…
Polypropylene	0.006	5.15E-13	0.02	0.05	0.24	…
Packaging, gelatin	**0.076**	**1.84E-09**	**1.76**	**0.75**	**0.85**	**0.079**
(%)	**(13.9%)**	**(3.4%)**	**(18.6%)**	**(42.4%)**	**(6.5%)**	**(12.0%)**
Gelatin processing	0.010	5.62E-10	0.10	0.29	0.58	…
Pork production	0.066	1.28E-09	1.66	0.46	0.27	0.079
Distribution	**0.003**	**3.62E-10**	**0.07**	**0.01**	**0.05**	…
(%)	**(0.5%)**	**(0.7%)**	**(0.7%)**	**(0.3%)**	**(0.4%)**	**(0.0%)**
Container vessel	0.003	2.97E-10	0.07	0.01	0.04	…
Truck	0.000	6.52E-11	0.00	0.00	0.01	…
TOTAL	**0.548**	**5.44E-08**	**9.48**	**1.77**	**13.11**	**0.658**
(%)	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**	**(100%)**

Appendix J. CO_2-e Emissions and Carbon Footprint of Meal and Oil.

Table J1. Energy inputs to fishing and associated CO_2-e emissions per 100 GJ combined meal and oil product.

	Units	Peruvian anchovy	Atlantic herring	Blue whiting	Gulf menhaden	Antarctic krill[e]
Fuel use intensity[a]	L/t	19	98	96	32	191
Direct fuel inputs[b]	L	340.1	1117.2	2275.2	304.0	4966.0
CO_2-e emissions from fuel use[c]	kg	1163.1	3820.8	7781.2	1039.7	16884.4
Indirect CO_2-e emissions[d]	kg	246.7	810.5	1650.6	220.5	586.4
Total CO_2-e emissions	kg	1409.9	4631.3	9431.7	1260.2	17470.8

a. Fuel use intensities taken from Table 15, representing those fisheries which primarily caught the specified species.

b. Direct fuel inputs calculated according to the tonnages required to provide 100 GJ combined meal and oil: 17.9 tonnes Peruvian anchovy, 11.4 tonnes Atlantic herring, 23.7 tonnes blue whiting, 9.5 tonnes Gulf menhaden, and 26.0 tonnes Antarctic krill (see Table 6).

c. CO_2-e emissions for fish species calculated as 3.4 kg per L fuel, assuming all fisheries to use similar fuel mixes to that of the Antarctic krill fishery.

d. Including emissions from vessel construction, vessel maintenance, and gear manufacturing. Assumed to account for 17.5 per cent of total CO_2 emissions in fisheries targeting species other than krill, following Tyedmers (2004).

e. Antarctic krill yields consistent with those reported in Chapter 2 (i.e. assuming production of only meal and oil products); CO_2-e emissions per kg meal/oil adapted from those reported in Chapter 3 to reflect the difference in yield when paste is not considered.

Table J2. Energy inputs to processing and associated CO_2-e emissions per 100 GJ combined meal and oil product.

	Units	Peruvian anchovy	Atlantic herring	Blue whiting	Gulf menhaden	Antarctic krill
Energy from natural gas[a]	MJ	29373.9	18707.4	38891.7	15589.5	
CO_2-e emissions from use of natural gas[b]	kg	2094.4	1333.8	2773.0	1111.5	
Energy from electricity[a]	MJ	1707.7	1087.6	2261.0	906.3	
CO_2-e emissions from electricity use[c]	kg	283.5	10.9	22.6	190.3	
Energy from fuel oil[a]	MJ	9415.4	5996.4	12466.2	4997.0	
CO_2-e emissions from fuel oil use[d]	kg	891.6	567.9	1180.5	473.2	4238.7
Total CO_2-e emissions	kg	3269.5	1912.6	3976.1	1775.1	4238.7

a. Energy inputs in the form of natural gas, electricity, and fuel oil are based on average energy demands by several reduction plants: energy demands to process one tonne of fish were 1,641 MJ from natural gas, 95.4 MJ from electricity, and 526 MJ from fuel oil (Pelletier, 2009, pers. comm.).

b. 0.0713 kg/MJ natural gas (EcoInvent process 'Heat, natural gas, at industrial furnace >100kW/RER U').

c. Processing was assumed to take place in Chile for products derived from Peruvian anchovy, the United States for products derived from Gulf menhaden, and Norway for products derived from Atlantic herring and blue whiting. CO_2-e emissions rates used were 0.166 kg/MJ in Chile (based on EcoInvent process 'Electricity, high voltage, at grid/BR U' adapted using electricity mix for Chile); 0.21 kg/MJ in the United States (EcoInvent process 'Electricity, high voltage, at grid/US U') and 0.01 kg/MJ in Norway (EcoInvent process 'Electricity, high voltage, at grid/NO U').

d. 0.0947 kg/MJ fuel oil (EcoInvent process 'Heat, heavy fuel oil, at industrial furnace 1MW/RER U').

Table J3. Material inputs to packaging and associated CO_2-e emissions per 100 GJ combined meal and oil product.

	Units	Peruvian anchovy	Atlantic herring	Blue whiting	Gulf menhaden	Antarctic krill
Packaging inputs to meal[a]	kg	69.7	43.3	87.8	39.7	79.0
CO_2-e emissions from meal packaging	kg	502.7	312.4	633.1	286.3	569.9
Packaging inputs to oil[a]	kg	60.1	92.4	31.1	111.7	1.5
CO_2-e emissions from oil packaging	kg	112.0	172.1	58.0	208.0	2.8
Total CO_2-e emissions	kg	614.7	484.5	691.2	494.3	572.7

a. Inputs to packaging of fish meal and oil were assumed to be similar to those for Antarctic krill products: 19 g per kg meal, and 73 g per kg oil. Packaging inputs were calculated depending on the meal and oil quantities required to provide 100 GJ of energy (see Table 6).

b. CO_2-e emissions for all products were assumed to be consistent with Antarctic krill products: 0.137 kg CO_2-e per kg meal, and 0.136 kg CO_2-e per kg oil.

Table J4. Distribution distances and associated CO_2-e per 100 GJ combined meal and oil product.

	Units	Peruvian anchovy	Atlantic herring	Blue whiting	Gulf menhaden	Antarctic krill
Distance transported by container ship[a]	km	11,677	11,677	11,677	11,677	11,677
Container vessel freight	tkm	52463.6	41399.6	58946.7	42264.9	48819.2
CO_2-e emissions from container ship transport[b]	kg	561.6	443.2	631.0	452.4	522.6
Distance transported by truck[a]	km	153	153	153	153	153
Truck freight	tkm	687.4	542.4	772.4	553.8	639.7
CO_2-e emissions from truck transport[b]	kg	85.4	51.4	95.9	68.8	70.9
Total CO_2-e emissions	kg	647.0	494.6	726.9	521.2	593.5

a. Distribution distances for all products were assumed to be similar to those for Antarctic krill.

b. CO_2-e emissions for distribution are 0.01 kg CO_2-e per tkm by container vessel (EcoInvent process 'Transport, transoceanic freight ship/OCE U') and 0.12 kg CO_2-e per tkm by truck (EcoInvent process 'Transport, lorry >16t, fleet average/RER U').

Table J5. Total CO_2-e emissions and carbon footprint of 100 GJ combined meal and oil product.

	Units	Peruvian anchovy	Atlantic herring	Blue whiting	Gulf menhaden	Antarctic krill
CO_2-e emissions from fishing	kg	1409.9	4631.3	9431.7	1260.2	17470.8
CO_2-e emissions from processing	kg	3269.5	1912.6	3976.1	1775.1	4238.7
CO_2-e emissions from packaging	kg	614.7	484.5	691.2	494.3	572.7
CO_2-e emissions from distribution	kg	647.0	494.6	726.9	521.2	593.5
Total CO_2-e emissions	kg	5941.4	7523.0	14825.9	4050.8	22875.7
Carbon to be sequestered[a]	t	1.62	2.05	4.04	1.10	6.23
Carbon footprint[b]	ha	0.90	1.14	2.24	0.61	3.46

a. Using a CO_2-to-carbon molecular weight ratio of 3.67:1.

b. Using an average global forest sequestration rate of 1.8 tonnes carbon per hectare per year (Wada, 1994).

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