FISH AND FUEL: LIFE CYCLE GREENHOUSE GAS EMISSIONS ASSOCIATED WITH ICELANDIC COD, ALASKAN POLLOCK, AND ALASKAN PINK SALMON FILLETS DELIVERED TO THE UNITED KINGDOM

by

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ABSTRACT

Seafood is a global commodity of growing importance. The present study examined contributions to global warming from three significant seafood product chains. Each of these systems were relatively fuel efficient compared to fuel intensities reported for other fisheries globally. As such, processing and transportation phases made relatively important contributions to the overall global warming impact of these systems. Energy inputs to processing were important, as was the emission-intensity of the energy format used. In the context of interest regarding the food miles concept as an indicator of sustainability, results revealed that rather the mode of transport, not the distance travelled, was the most important factor in determining overall greenhouse gas emissions from transportation. Results indicate that further research evaluating the complete supply chain of seafood products (not only the fishing phase) may reveal important opportunities for emission reductions.

LIST OF ABBREVIATIONS USED

ADFG	Alaska Department of Fish and Game
AP	Acidification Potential
BRU	Biotic Resource Use (see NPP)
BSi	British Standards
C	Carbon (see NPP)
CED	Cumulative Energy Demand
CFC	Chlorofluorocarbon
CML	Institute of Environmental Sciences (Universiteit Leiden)
EEA	European Environment Agency
EIA	Energy Information Administration
EP	Eutrophication Potential
FAO	Food and Agriculture Organization (United Nations)
Findus	The Findus Group, parent of Findus, Young's and The Seafood Company
FHF	Fishery and Aquaculture Research Fund
g	gram
GHG	Greenhouse Gas
GT	Gross tonnage
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HP	Horsepower
IEA	International Energy Agency
IFC	International Finance Corporation

IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
J	Joule
kg	kilogram
km	kilometre
kWh	kilowatt hour
l	litre
LCA	Life Cycle Assessment, also Life Cycle Analysis
m	metre
MJ	mega joule
MSC	Marine Stewardship Council
NPP	Net Primary Productivity
PAS	Publicly Available Specification (i.e. PAS 2050)
SE	Standard Error
SETAC	Society of Environmental Toxicology and Chemistry
t	metric tonne
TAC	Total Allowable Catch
tkm	tonne kilometre
UK	United Kingdom
US	United States of America

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM & RESEARCH QUESTION

Recently, human society has come to appreciate limits to growth, that is, the concept of a finite biophysical environment which will limit the ability of a growing human population to meet their increasing material and energy demands (Barnett & Morse, 1963; Boulding, 1966; Ehrlich, 1968; Georgescu-Roegen, 1971; Meadows et al., 1972). These limits apply both in terms of access to resources, such as fossil fuels, as well as the ability of the environment to assimilate the wastes produced by human activities.

Anticipating and avoiding resource scarcity is particularly crucial in the case of food resources. Malthus famously and controversially predicted that eventually the human population would exceed its own capacity to produce food, and starvation would result (Malthus, 1798). Even in the case of technological advances which increased our agricultural capacity, Malthus argued, such improvements could only proceed arithmetically, while population increased exponentially, and thus population would inevitably outpace food production.

In the western world, we have not yet faced such a “Malthusian catastrophe.” Our supply of food has more than kept up with the growth in our population. However, this increase in food supply has relied upon methods (e.g. greenhouses and irrigation) and materials (e.g. fertilizers and pesticides) that require large inputs of both renewable and nonrenewable resources. Indeed, meeting our demand for food is now considered a primary driver of anthropogenic environmental impacts (Eshel & Martin, 2005; Tukker & Jansen, 2006).

Seafood satisfies a significant portion of this demand globally: ninety-two million tonnes of fish were landed by capture fisheries in 2006, of which approximately 77% was destined for human consumption (FAO, 2009a). This accounts for approximately 15% of the world’s animal protein supply (FAO, 2009a). From an environmental perspective, the provision of seafood by fishing is associated with a variety of impacts unique to this last major wild-caught food source. These impacts include bycatch (the capture of non-target species of fish or other marine organisms) (Alverson et al., 1994; Hall et al., 2000), damage to marine habitats by fishing gear (Auster & Langton, 1999; Chuenpagdee et al., 2003; Hiddink et al., 2006), and depletion of wild fish stocks (Jackson et al., 2001; Myers & Worm, 2003). Furthermore, like any other food production system, the energy and materials consumed by the seafood supply chain necessarily contribute to a number of other environmental impacts, such as climate change. Indeed, as the most highly traded food commodity worldwide (FAO, 2009a), seafood is associated with potentially large transportation related contributions to global warming.

Climate change is an issue of significant concern to both consumers and producers of seafood products. Climate change may negatively affect fish stocks specifically through, for example, increased tropical storms or changes in both the human and biotic components of coastal communities due to sea level rise (Cochrane et al., 2009). Although dispute remains as to how to reduce anthropogenic contributions to climate change (as seen at the COP 15 negotiations in December 2009), most researchers agree that reductions are necessary to maintain the long term stability of both human and animal communities around the globe (Stern, 2006; IPCC, 2007a).

Relatively few studies have undertaken an analysis of the full seafood supply chain emissions of greenhouse gases which contribute to climate change (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Thrane, 2006; Ziegler et al., 2009). Each of these studies found that contributions to various impact categories including climate change are greatest during primary resource production. It is perhaps no surprise then that most studies have focused on impacts associated with primary resource production from both fisheries (Tyedmers, 2000; Tyedmers, 2001; Ziegler & Hansson, 2003; Thrane, 2004; Hospido & Tyedmers, 2005; Tyedmers, Watson, & Pauly, 2005) and aquaculture (Tyedmers, 2000; Paptryphon et al., 2004; Mungkung, 2005; Grönroos et al., 2006; Pelletier & Tyedmers, 2007). However, given the diversity of the seafood supply chain in terms of capture and processing methods as well a transportation network that may span the world, research which examines the complete supply chain is necessary to confirm these findings and draw a more complete picture of the greenhouse gas intensity of seafood.

1.1.1. This Study

In the interest of increasing our understanding of the contributions made to climate change by seafood systems, a research partnership was forged between Dalhousie University and the Findus Group of companies based in the UK. The Findus Group (Findus) is the parent company of the Young's, Findus, and The Seafood Company brands (Young's Seafood Limited, 2008). Young's and The Seafood Company are primarily based in the UK, while the Findus brand operates mainly in Scandanavia and France. Overall, Findus (the parent company) employs over 6,000 people and produces 345,000 tonnes of food each year, 70% of which (by sales value) is fish and seafood (Findus Group, 2010a). The products produced include fish fingers, fish cakes, ready-to-eat meals such as fish pies, as well as breaded and unbreaded fillets (Findus Group, 2010b).

Findus have made a corporate commitment to acting ethically to reduce the environmental impact of their business (Young's Seafood Limited, 2008). The present research seeks to examine the scale and sources of contributions to climate change made by the catching, processing, and transportation of seafood products to the Findus headquarters and site of secondary processing in Grimsby, UK. Climate change was chosen as the impact of interest because of its global significance, and its importance to representatives at Findus and the consumers of Findus products. The climate change impact category may also serve as a good proxy for a variety of other environmental impacts (Ziegler, 2001; Thrane, 2006). This is because many environmental impacts, including climate change, are related to energy use (Krozer & Vis, 1998).

Although the focus of this study is contributions of the seafood supply chain to climate change, with the data collected to examine contributions to climate change it was possible to calculate potential contributions to other environmental impacts. It was decided that including an assessment of these potential impacts (such as eutrophication and acidification) would help us describe a more complete picture of the environmental impacts associated with the seafood industry.

The products chosen for study represented both important (i.e. high profile and/or high volume) products in the UK market, and diverse products in regards to several key variables: species, source locale, fishing gear, processing option, product form and transportation mode(s). A comparison of the three systems selected is provided in Table 1. Each product system is described in more detail in Chapters 2-4.

Table 1. Summary of target species.

Target Species	**Alaskan pollock (*Theragra chalcogramma*)**	**Pink salmon (*Oncorhynchus gorbuscha*)**	**Atlantic cod (*Gadus morhua*)**
Source locale	U.S. waters of the Bering Sea	Alaskan waters of Northeast Pacific	Icelandic waters of North Atlantic
Main Gear Type	Mid-water Trawl	Purse seine	Set Longline
Seasonality	Seasonal (December-April, July-September)	Seasonal (May-August)	Year-round
Management System	Quota	License	Quota
Sustainability Certification	MSC	MSC	None
Processing	Machine At-Sea, and Mothership/ Manual (China)	Manual (China), and Machine (Alaska)	Machine (Iceland)
Product form upon import to UK	Frozen Fillet	Frozen Fillet	Fresh and Frozen Fillet
Major transport modes	Bulk tramper sea, Containerized sea	Containerized sea	Air freight or ferry

This study will examine three questions in relation to each seafood product system:

(1) What are the life cycle contributions to climate change that result from the delivery of one kilogram of fillet to the UK?
(2) Which phases of the products’ life cycle contribute most to total greenhouse gas emissions and hence present the greatest opportunities for emission reductions?
(3) How do contributions to climate change compare with contributions to other important global scale environmental concerns at each stage of the life cycle?

Answering these research questions required a quantitative understanding of the inputs and outputs to these systems over the complete life cycle of each product. Furthermore, these inputs and outputs needed to be characterized in terms of contributions to various impact categories, including climate change. For this reason, a life cycle assessment methodology was applied.

1.2 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is an appropriate tool for this study because it facilitates study of the supply chain from fishing through to delivery of the product in Grimsby. Furthermore, LCA offers a useful framework to describe impacts which may be quantified, such as contributions to climate change in terms of greenhouse gas emissions. LCA has also previously been used to understand the environmental impacts (including contributions to climate change) associated with a number of seafood product systems, thus providing a basis of comparison with our results as well as an opportunity to reflect on challenges and opportunities for future studies.

1.2.1 A Brief History of LCA

The genesis of life cycle assessment occurred amidst the heightened environmental awareness of the 1960s (beginning, perhaps, with the publication of Rachel Carson’s classic “Silent Spring” in 1962), followed by the oil crisis of the early 1970s. The concerns of this time are reflected in the “first” LCA, conducted by the Coca-Cola company in 1969 (Baumann & Tillman, 2004). The makers of Coke wanted to identify the most energy efficient and least material intensive form of packaging for their product (Baumann & Tillman, 2004). A few years later in 1972, a similar study was conducted in the UK to evaluate energy inputs to various beverage containers (Boustead, 1996).

Following the resolution of the oil crisis, LCA entered a gestation period: immediate interest in its use for identifying energy efficient alternatives waned, but gradually the tool's utility for evaluating performance relative to a variety of other inputs and (importantly) outputs (i.e. emissions and waste, overlooked in the first LCA-style studies) was realized (EEA, 1997). By the late 1980s and early 1990s, LCA was identified as one of the most promising "new" tools for environmental managers (EEA, 1997). Results from early efforts to employ a life cycle approach seemed to be a step forward for environmental management, offering quantitative and thus seemingly objective data regarding the environmental impacts of a product and its alternatives. However, concerns began to arise that excessive flexibility in the methodology of the time served to undermine the credibility of results (Baumann & Tillman, 2004). Controversy regarding the use of research results in marketing claims led to the push for methodological standardization (Baumann & Tillman, 2004).

Life cycle assessment was formally named in 1991 following the first conference held to discuss and define the methodology, hosted by the Society of Environmental Toxicology and Chemistry (SETAC) (Garbathuler, 1997). Debate during these early years of LCA focused on the need to establish both a consistent approach for applying the tool and more robust impact assessment methodologies (Garbathuler, 1997). These meetings of both American and European scientists (Garbathuler, 1997) culminated initially in the production of SETAC's Code of Practice (Consoli et al., 1993). The Code of Practice stipulated that a LCA must include the four steps that persist today: goal and scope definition, inventory analysis, impact assessment, and interpretation (initially termed improvement assessment). Since then, discussion among international researchers and practitioners has aimed to define the terminology of LCA practice, and continue to increase the rigour of LCA methodology (Garbathuler, 1997). To this end in 1997 the first ISO standard for LCA methodology was published, and the standard was formally updated to reflect current best practice in 2006 (ISO, 2006a; ISO, 2006b).

Today, LCA is used in a variety of industries and circumstances, from describing impacts associated with carbon dioxide capture for enhanced oil recovery (Hertwich et al., 2008), to evaluating the materials used to build a house (Asif et al., 2007), to comparing organic and conventional farmed salmon products (Pelletier & Tyedmers, 2007). A variety of databases and software packages exist to support the research, and indeed have been integral to the present study. Methodological standards, both formal and informal on a national (e.g. PAS 2050 in the UK) or industry (e.g. seafood) basis have increased. There has been some disillusionment with the tool due to ongoing challenges related to the difficulty and expense of conducting comprehensive studies, and the persistent potential for variable results (owing in part to the necessity of making value judgments during the course of any LCA) (EEA, 1997). However, when applied judiciously LCA continues to show promise as a tool to quantify and compare the environmental impacts of competing products and services. As such, LCA continues to be refined as a tool for research and management.

1.2.2 Structure of LCA

As discussed, conducting a life cycle assessment requires completion of four iterative steps (Figure 1): definition of the goal and scope, inventory analysis, impact assessment, and interpretation (ISO, 2006a). LCA is iterative in that discoveries made during consecutive steps may provide cause for a return to a previous step, and thus each step may be refined as the assessment proceeds.

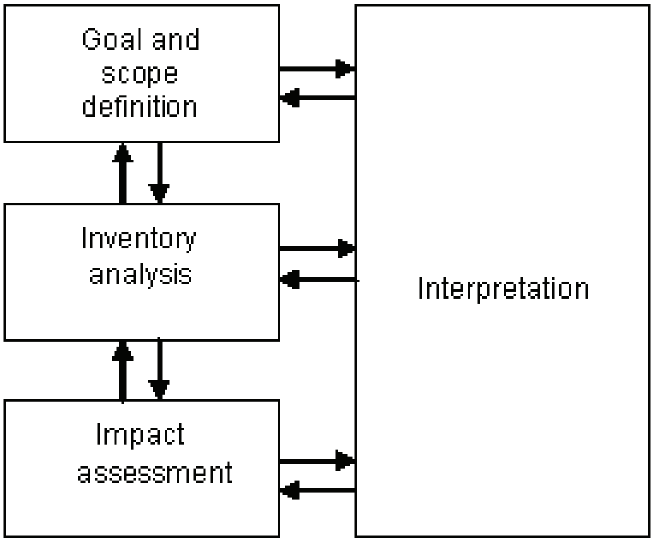

Figure 1. The Life Cycle Assessment Framework as per ISO 14040 standards. (ISO, 2006a)

Goal and Scope Definition

The goal of the study describes the purpose for conducting the LCA. ISO guidelines require that the goal of the study should be specific in several respects including: the intended application of the study and it's results, the reasons for carrying out the study, the intended audience for the results of the study, and whether the results will be communicated as a comparative assertion to the public (ISO, 2006b).

The scope of analysis describes everything about how the LCA should be conducted (Guinée et al., 2001). The ensuing steps are a matter of executing what is described in the scope, modifying the goal or scope if necessary, and repeating this procedure until the LCA is considered to be complete. In all cases, the scope of the study must remain consistent with the goal (ISO, 2006a). ISO guidelines require that this description includes: the product system, the function of the system, the functional unit, the system boundary, allocation procedures, impact assessment methodology, impact categories, data requirements (including quality), assumptions, value choices (where applicable), limitations, method for addressing critical review, and method for presenting results (ISO, 2006b). The scope may include cut-off criteria, which describe the limit at which information is expected to contribute negligibly to results (i.e. will contribute less than 5% to the total impact), and thus may be excluded from data collection (Baumann & Tillman, 2004) .

A few items defined in the goal and scope warrant further explanation. First, the functional unit is intended to closely represent the function performed by the product or activity of interest. The function of a vacuum cleaner, for example, may be to clean a certain unit of space. The impacts associated with a vacuum cleaner can therefore be compared to other products that perform the same function, i.e. clean the same unit of space to the same level of cleanliness. In this way, LCA allows us to examine various methods of meeting a given need, without acknowledging the necessity of using a particular product to meet that need. The product itself would be termed a reference flow in LCA terminology. A reference flow is a "measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit."(ISO, 2006a)

The selection of impact categories and associated assessment methodologies is another area of particular importance in goal and scope definition. Specifically, the practitioner must choose between mid- and end- point indicators (Pennington et al., 2004). Mid-point indicators refer to impacts more proximal to activities considered part of the system (ISO, 2006b). For example, the life cycle may include the burning of fuel, which leads to air emissions which may contribute to climate change (mid-point), which may in turn lead to biodiversity loss, sea level rise, infrastructure damage, etc. (all end-points). End-point indicators can be described in terms of four "areas of protection": human health, natural environment, natural resources (ISO, 2006b), and the man-made environment (Udo de Haes et al., 1999). Areas of Protection describe the categories of items which have value to human decision-makers (ISO, 2006b). For this reason, end-point categories may be favored because of their relevance for decision-makers. For example, "human health risk" may seem more compelling than less-tangible "climate change potential". However, considerable uncertainty is introduced in making the leap from mid-point to end-point category indicators (Bare et al., 2000). The causal links between contributions to climate change and biodiversity loss, for example, are much less certain than the links between certain air emissions and climate change. For this reason mid-point category indicators may be favored for the greater reliability of their results.

Describing the boundaries of analysis can also be controversial. Boundaries function to delineate a reasonable scope of work for the study, and to focus data collection on inputs and outputs most likely to contribute significantly to the impact categories of interest. By necessity, data must be excluded as part of boundary definition, which can lead to a sense that any LCA is somehow “incomplete.” However boundary definition, when done in line with the goals of the study, should ensure that significant contributors to the environmental impact(s) of interest are represented by the best available information. As such, LCA results represent the best available approximation of the true impacts of a given system.

Inventory Analysis

Following definition of the goal and scope, the second step in LCA is inventory analysis. During inventory analysis data are collected regarding the major material and energy inputs to and outputs from the product system of interest, including information regarding the production of co-products and recycling of inputs and outputs. Both foreground (i.e. data related to the particular system under study) and background (data drawn from databases or other studies, usually for indirect inputs to the system, such as manufacture of capital goods) is collected at this stage.

The data collected are often organized in terms of processes and subprocesses. For example, a seafood system may be described in terms of the distinct processes of catching, processing and final transportation. In turn, the catching “process” may include subprocesses such as bait provision, vessel construction, maintenance, etc. The impacts of the system can then be assessed in terms of the data related to each of the processes and subprocesses. The identification of processes and subprocesses allows LCA practitioners to organize data and more easily identify hot spots in the life cycle of a product during the Interpretation phase.

Inventory analysis is often the most time consuming stage of life cycle assessment, depending on the level of detail required by the LCA and how readily available the necessary information is.

Impact Assessment

Having collected the necessary data, the third step in LCA is impact assessment. The purpose of impact assessment is to make LCA results more understandable and facilitate comparison among impact categories (Baumann & Tillman, 2004). During impact assessment, inventory data are classified based on their contributions to various impact categories (defined as part of the goal and scope), and characterized (using assessment methodologies) in terms of an impact potential. For example, the input of diesel to a fish catching process is likely to result in the emission of CO_2, NO_2 and other gases. The quantities of both CO_2 and NO_2 emissions would be grouped with other greenhouse gas emissions from this activity, and used to calculate the "climate change potential" of that process. The climate change potential would be calculated based both on the quantities of the gases emitted and their capacity for radiative forcing relative to the reference gas CO_2. The sum of the quantities of gases emitted multiplied by their impact potential (relative radiative forcing in this case) represents the climate change potential of that process.

At various points in a products' life cycle, subprocesses may result in the production of more than one product. At such points, impacts associated with that subprocess must be distributed (allocated) among the various co-products on some basis. The choice of allocation methodology is one of the more controversial elements of LCA due to the potentially large impact this choice has on results.

As part of impact assessment results may be normalized (for example, in terms of relative national or global contributions to a given impact category). Results may also be grouped to help simplify the results. In this case, results may be weighted in terms of relative importance to the "grouped" impact category. For example, climate change potential and ozone depletion may each be grouped in a “human health impact potential” category, however the contribution of climate change potential may be weighted more heavily if the LCA practitioner judges this impact to be more important to the human impact potential category result. Normalization, grouping and weighting are all optional steps in LCA, and may be performed depending on the goal and scope of the study.

Interpretation

The final, but in many ways continuous “step” in LCA is interpretation. As the LCA nears completion interpretation involves presenting the results and discussing implications of the findings. Interpretation at this stage may involve secondary analysis, or making comparisons. Interpretation occurs throughout the LCA process to ensure the methods and results correspond with the goal and scope.

1.2.3 Types of LCA

As LCA has evolved from a generalized life cycle approach into a standardized methodology, diversity of opinion remains as to the purpose of conducting a LCA and thus how LCA is applied. LCA may follow one of two general theoretical approaches (Russell et al., 2005). An attributional LCA (also called a descriptive or retrospective LCA) looks to account for the impacts associated with a system at a particular point in time. In contrast, consequential LCA (also called change-oriented or prospective LCA) seeks to examine the effect changes in the system might have on the overall environmental impact of society. Consequential LCAs may be undertaken at the design stage of a proposed product to inform strategic decisions on product development. Whether an attributional or consequential LCA approach is undertaken depends largely on the goals of your study; i.e. whether you intend to study the baseline environmental impacts of a system, or if you intend to examine the potential impacts of a change to that system. However each approach can lead to different results, due to the alternative approach each suggests for drawing system boundaries and dealing with co-product allocation. (Thomassen et al., 2008) For example, attributional LCA will tend to suggest allocation is dealt with by partitioning, in order to maintain the system boundaries around a particular system of interest. Partitioning refers to dividing the process into subprocesses and including in the assessment only those processes which correspond to the co-product of interest. Consequential LCA on the other hand will tend to be interested in the connections of co-products with other systems, and thus system expansion will tend to be used (Baumann & Tillman, 2004; Ekvall et al., 2005). System expansion involves including in the analysis other systems which produce the co-products described, and “subtracting” the impacts avoided (that theoretically result from not carrying out this alternative process) from the impacts associated with the primary process of interest.

The foregoing discussion illustrates that there continues to be a great deal of possible variation in how LCA is executed. While LCA has been standardized, the standards do not prescribe all aspects of the methodology to be employed, but rather specify the range of issues that must be taken into account during a LCA. As a result, the normative principles of the practitioner come into play when choices are made about how systems are defined and impacts allocated (Weidema, 1998).

1.2.4 Limitations & Challenges

As LCA methodology continues to develop, several items stand out as points of ongoing debate.

Allocation

ISO recommends avoiding allocation either by partitioning or system expansion (ISO, 2006b). Often, however, this is not practicable or possible due to the indivisibility of the processes, the lack of appropriate alternative processes (which produce any of the co-products exclusively), and/or a lack of available data or resources to obtain such data. In this case, ISO recommends allocating impacts according to physical relationships among co-products (ISO, 2006b). If physical relationships cannot be used, allocation may be conducted using other relationships among the products, such as relative economic value (ISO, 2006b).

Debate regarding the preferred method of allocation in the many cases where partitioning or system expansion is not possible remains active. Due to the possible variability in methods and approach taken by different LCA practitioners, or even the same practitioners conducting studies with various goals and scopes, a variety of results are possible using LCA methodology and as such it can be difficult to compare LCA results (Krozer & Vis, 1998; Weidema, 2000; Ekvall & Finnveden, 2001). Variation in the possible results of LCAs remains a potential threat to the credibility of LCA results; however practitioners may minimize this risk through transparency in reporting and the use of sensitivity analysis to test the effect of methodological decision-making on results.

Assessment methods: Impact "Potentials"

Although the sophistication of assessment methods has increased over the years of LCA's development, LCA practitioners still struggle to describe impacts according to the particular sensitivities of regions where emissions are made. Many modern production chains involve activities spanning the globe, and as such emissions are made across a wide area. As a result, describing the overall eutrophication (for example) that may result from such a system can be exceptionally difficult. It is for this reason that most impacts are described in terms of "potentials" to suggest the level of uncertainty inherent in describing impacts.

Fortunately, greenhouse gas emissions contribute equally to the global-scale phenomena of climate change regardless of where they occur. As such the degree of uncertainty in this impact category is likely to be less than in other impact categories.

Striving for Holism

LCA is often valued for offering a potential solution to the lack of information regarding the relative "sustainability" of various alternatives. LCA does provide a systematic approach to describing contributions to a wide range of resource depletion and emission related impacts associated with a given product. However, results are also bracketed by a potentially high degree of uncertainty due to variation in methodological choices and imperfect assessment methods. Furthermore, even detailed LCAs struggle to describe all the possible environmental and social impacts of a given system (Pelletier et al., 2007). Few robust methods exist to describe impacts on biodiversity or human health, for example. In addition, tradeoffs also often exist among impact categories, such that no product may perform universally “better” than its alternative. As such, LCAs are unlikely to ever provide a complete answer to the question of how to achieve sustainability. Human decision makers are still required to weigh the evidence provided by LCA and make appropriate decisions on behalf of their community as to which option is preferable given their particular concerns and priorities.

1.3 LCA OF SEAFOOD

Several key findings have resulted from previous work applying LCA methodology to the study of seafood products that provide relevant context for the current study. First, vessel construction, maintenance and gear have not been found to be important contributors to climate change in the context of the wild-caught seafood life cycle (Hayman et al., 2000; Tyedmers, 2000; Huse et al., 2002; Ziegler et al., 2003; Tyedmers, 2004). A majority of the greenhouse gas emissions do appear to occur at the capture stage however, and result from direct fuel inputs to fishing (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006) with larger boats tending to consume more fuel per unit of fish caught (Tyedmers, 2001; Thrane, 2004). Although not under examination here, there is some evidence that the health of the fished stock is important in this regard, as healthy stocks will not require capture vessels to fish as widely or as vigorously in order to obtain the same quantity of fish (Tyedmers et al., 2005). The skills of individual skippers may also play a role in the efficiency of the fishing fleet (Ruttan & Tyedmers, 2007). Regulatory schemes, such as quotas, length limits on boats, or limits on the minimum size of fish can have important and sometimes perverse effects on the energy efficiency of the fishery (Driscoll & Tyedmers, 2009). For example, quotas may eliminate the “race to fish”, however length limits may encourage the use of wider and thus less fuel efficient boats to maintain deck space while respecting the length limit.

Moving on to the processing stage, capital goods are again not particularly important relative to the impacts made by direct energy inputs to processing (Ziegler, 2001). Packaging can make processing one of the most impactful stages if packaging materials are particularly energy intensive (Thrane, 2006). Following processing, transport mode (particularly if the mode is air freight) can have an important influence on impact contributions (Karlsen & Angelfoss, 2000; Andersen, 2001; Horvath, 2006).

Refrigerants used throughout the life cycle may also play an important role in the climate change impact category depending on the refrigerant used, as some refrigerants are powerful greenhouse gases (Winther et al., 2009). Other important factors for impacts in all categories include product yield from processing and product loss between capture and market, due to the allocation of impacts preferentially on those products which complete their journey to the consumer (Ziegler & Hansson, 2003; Boyd, 2008).

1.4 STRUCTURE OF THE THESIS

The following three chapters examine each of the three product systems under study in more detail. Chapter 2 focuses on Atlantic cod, Chapter 3 on Alaskan pollock, and Chapter 4 on pink salmon. Finally, Chapter 5 consists of a discussion of the results including comparisons of the three systems under study, implications of results, lessons learned and recommendations for future research. The author intends to modify one or more of these chapters in order to pursue publication. Findings will also be communicated directly to representatives at Findus.

CHAPTER 2 ATLANTIC COD

Atlantic cod caught in Icelandic waters are an economically significant product for both Iceland and the UK. Here we examine the contributions to climate change and other related environmental impact categories associated with the supply of both fresh and frozen cod fillets caught by longline gear in Iceland and delivered to Grimsby, UK. The scope of analysis includes the provision of bait, vessel and gear, catching effort, processing effort, as well as packaging, storage and final transportation of the fillets. Prior to final transport, results confirm those of previous studies that fishing potentially contributes the most to climate change, and indeed to most other impact categories studied (acidification, eutrophication, abiotic resource use and cumulative energy demand). When final transport is included, within the fresh fillet supply chain air freighting to market was found to make a substantial contribution. As such, transport was the most impactful stage for all categories except eutrophication, where fishing and transportation phases made almost equal contributions. In contrast, the frozen fillet supply chain, in which product is shipped from Iceland to the UK via sea, final transport made a relatively small contribution to all impact categories relative to fishing. These results indicate that while Icelandic line-caught cod may be a relatively low-impact seafood product due to the relative fuel efficiency of the fishing phase, fresh versions of these products should be avoided to minimize contributions to climate change and many other impact categories.

2.1 INTRODUCTION

Atlantic cod (*Gadus morhua*) are demersal fish that typically weigh between one and four kilograms and grow to between 45 to 85 cm in length (Icelandic Fisheries, 2009a). They feed on both invertebrates and other fish, and range across the continental shelves of the North Atlantic (FAO, 2010a). Global landings of Atlantic cod have ranged between 764,000 and 1,094,077 tonnes over the last decade (Figure 2), approximately one third of which has been caught by each of Norway, Russia, and Iceland (FAO, 2010a).

While a historical mainstay of commercial fisheries in all coastal nations bordering the North Atlantic, concern regarding the health of many cod stocks has been piqued in recent decades due to collapse of the Atlantic cod stock off the eastern coast of Canada in 1991. Although Icelandic stocks have not faced such a collapse, their numbers have declined since the 1970s (Brander, 2007). This decline has not been consistent, however, and a range of factors including climate change, stock demographics, and fishing activity have all be thought to play a role in the variation (Lilly et al., 2008). Icelandic cod stocks are managed using a quota system (Kristofersson & Rickertsen, 2005), however landings often exceed the total allowable catch (TAC) by a small margin (Figure 2). Overall, Icelandic landings are much reduced from historical highs within the last 50 years of 470,000 tonnes/year (Icelandic Fisheries, 2010b).

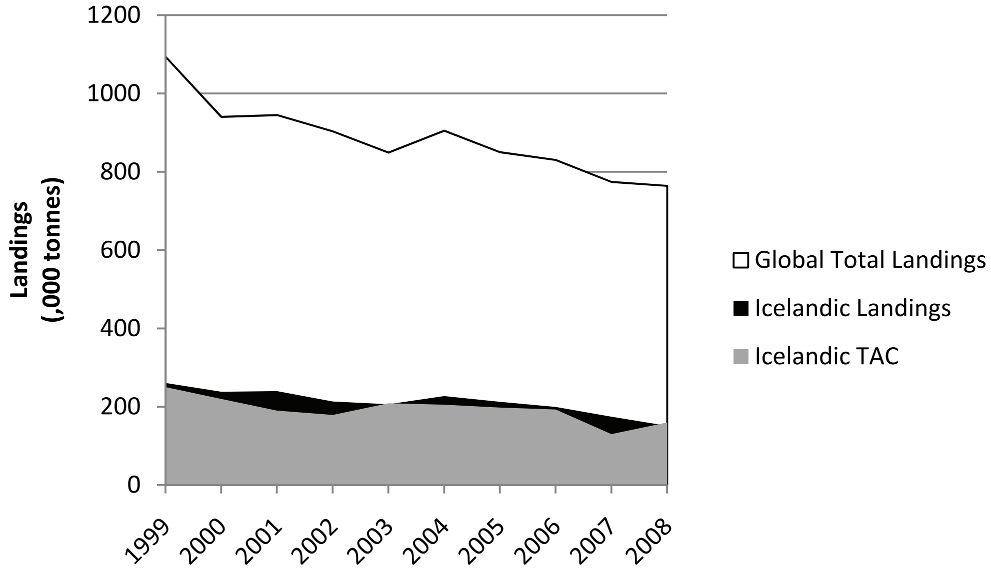

Figure 2. Global catches and Icelandic landings of cod over the last decade (Statistics Iceland, 2008).

Although overfishing is not clearly the culprit in the declining catch figures, historically Icelandic cod stocks have been subject of concern due to perceived overfishing. In the 1970s, such concerns led to a face-off between Iceland and the UK in what became known as "the cod war." The conflict began when Iceland extended its maritime jurisdiction and claimed an exclusive economic zone for fishing (Bilder, 1973). Iceland claimed the jurisdictional expansion was necessary to limit overfishing in their waters, however the UK attempted to ignore the extension until Iceland threatened to remove a valuable NATO base from the country (Bilder, 1973). The stand off ended with Iceland successfully extending its jurisdiction and securing access to the associated fisheries (Bilder, 1973).

Responsible management of their fisheries may be a particularly sensitive issue in Iceland due to the historical centrality of this industry to the Icelandic economy. Once responsible for 15.2% of the country's GDP, the seafood industry (both fishing and processing) has declined in importance over the last 30 years to contribute 7.8% of GDP in 2008 (Statistics Iceland, 2008). It is interesting to note in the context of this study however that there is some evidence that fishing activity contributes a disproportionate amount to Iceland's greenhouse gas emissions, accounting for 64% of the total in 1990 (United Nations, 1996).

Of all species, cod is the most important economically in Iceland, accounting for 35-40% of total seafood export revenue (Icelandic Fisheries, 2009c). In general, frozen fish accounts for 50% of exports by mass, while fresh (chilled) products made up only 16% (the remainder being salted products or used to make fish meal or oil) (Fiskerifond, 2004). Notably, fresh cod fillets are typically of greater value than their frozen counterparts (Fiskerifond, 2004).

The UK is the largest single destination for exported Icelandic cod products (16%), where cod is the second most imported seafood product by weight after tuna (Icelandic Fisheries, 2009c). One hundred and eight thousand tonnes of cod were imported to the UK in 2008 (Marine and Fisheries Agency, 2009), 30% of which originated in Iceland (Seafood Choice Alliance, 2007). Though cod is also caught in UK waters, imports greatly exceed domestic landings and exports. In 2008, only 20,000 tonnes of cod was landed in the UK in 2008 (Marine and Fisheries Agency, 2009).

Cod is caught all around Iceland throughout the year, however landings are highest in the winter and along the southwestern coast, in the area around the cod's major spawning grounds (Icelandic Fisheries, 2009b). Icelandic cod fishermen use trawl, Danish seine, longline and handline gears, however longline is the most popular (Kristofersson & Rickertsen, 2005). Longline is a relatively labour and time intensive form of fishing, however fish caught in this way are generally of higher quality than fish caught using other gear (Gabriel et al., 2005). Another benefit is that longline tends to catch only larger fish (the quota system also specifies a minimum size limit for landed cod), however the gear is not species selective (Engas et al., 1996). Haddock *(Melanogrammus aeglefinus*), Atlantic catfish (*Anarhichas lupus*), tusk (*Brosme brosme*) and ling (*Molva molva*) are common bycatch in the Icelandic longline cod fishery (Icelandic Fisheries, 2009b). Individual longlines may be up to 20 km in length with 16,000 hooks. In Iceland, the bait is most commonly herring (*Clupea harengus*), mackerel (*Scomber scombrus*), caplin (*Mallotus villosus)* or squid *(Illex argentinus*), although artificial bait has also been tried in recent years (Icelandic Fisheries, 2009b). Lines are typically set mechanically and left to soak for one to four hours. Longlines may be deployed from a wide range of fishing vessels in Iceland, from small undecked boats under 10 GT, to large decked vessels up to 500 GT, some of which use multiple gears throughout the year (not exclusively longline) (Icelandic Fisheries, 2009b). Smaller boats have a crew of 1-3 people and typically land their catch daily, while larger vessels may stay at sea for several days at a time (Icelandic Fisheries, 2009b).

Cod may be landed whole, gutted, or headed and gutted depending on the number of days at sea and the facilities available on the fishing vessel. The landed cod is then sent for processing. The cod fillets and related products are then shipped to a wide range of international markets as well as consumed domestically. We sought to describe the contributions to climate change and other related impact categories associated with the life cycle of one kilogram of fresh and frozen cod fillet caught and processed in Iceland and delivered into Grimsby, UK.

2.2 METHODS

We employed a life cycle assessment methodology, comprised of four steps (Figure 1): goal and scope, inventory analysis, impact assessment, and interpretation (ISO, 2006a).

2.2.1 Goal and Scope

The goals of this project were to:

- quantify the life cycle greenhouse gasses associated with fresh and frozen cod fillets delivered to Grimsby;
- identify hot spots in the supply chain of these two products;
- identify opportunities for greenhouse gas emission reductions; and
- consider the extent to which other key resource use and emission impacts vary with greenhouse gas emissions.

The scope of analysis encompassed material and energy inputs to three broad subsystems (and their associated component systems) (Figure 2): fishing, processing and packaging, and final transportation. The functional unit of analysis is one kilogram of fillet delivered in Grimsby. Fresh and frozen product forms were considered separately.

Certain assumptions were made in order to simplify the system under study or fill data gaps, in light of time constraints and the difficulty in collecting data. Due to our focus on climate change, items deemed unlikely to contribute significantly to this impact category (particularly given the functional unit of 1 kg of fillet) were excluded from study. For example, the material and energy inputs to the engine and fixtures of the fishing vessel as well as infrastructure related to the processing plant were excluded due to their small mass relative to the cod caught or processed during their service.

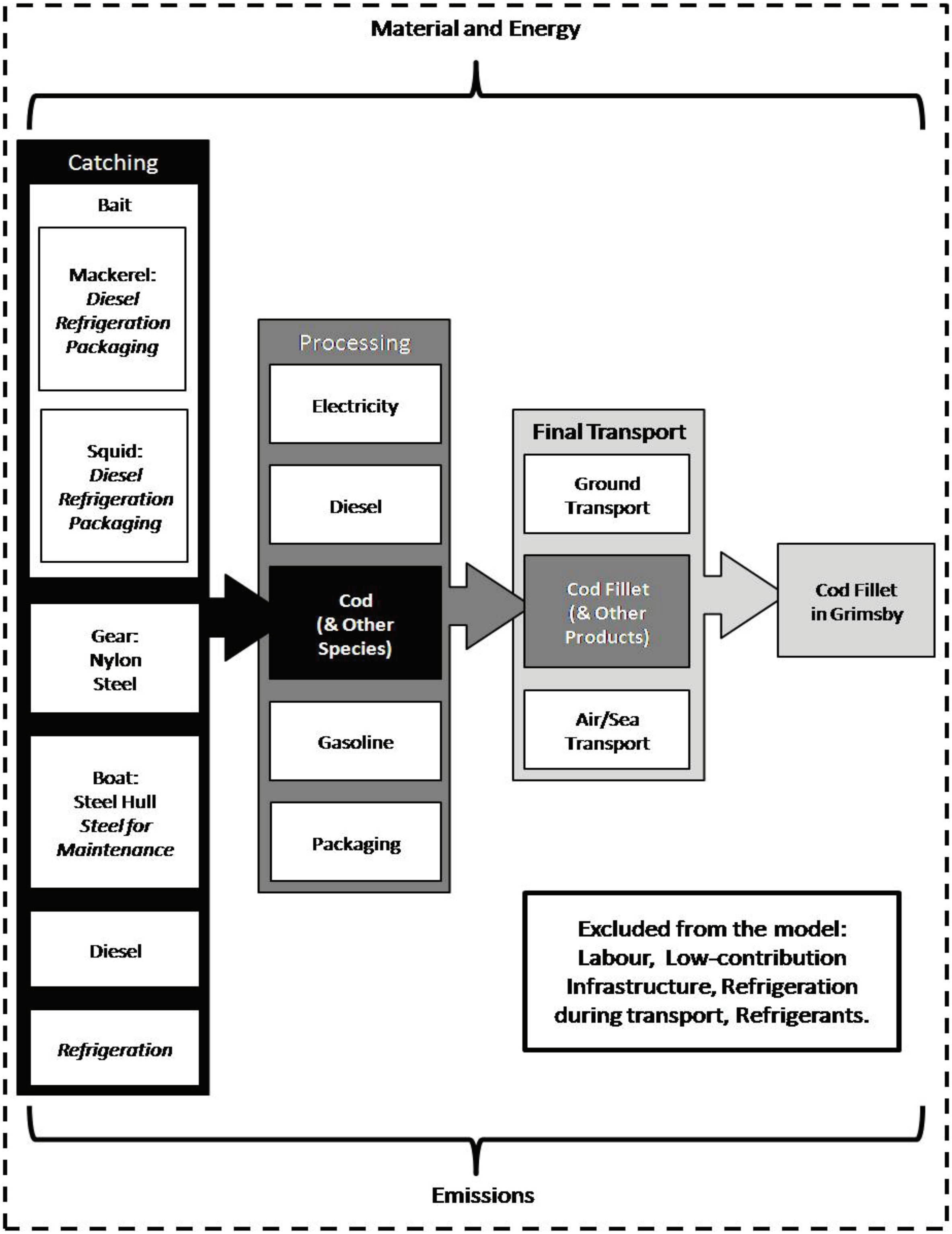

Figure 3. System boundaries for the LCA of one kilogram of fresh or frozen Icelandic cod fillet from capture through to delivery in Grimsby, UK. Italicized font denotes background data as indicated in Table 2-4.

2.2.2 Inventory Analysis

Primary data were collected via a detailed English-language survey covering material and energy inputs to fishing, processing and final transportation anticipated to make non-trivial contributions to greenhouse gas emissions based on insights from earlier research (Tyedmers, 2000; Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Hospido et al., 2006; Thrane, 2006). Questions included annual catch and fuel inputs to fishing, the size of the fishing boat and engines, as well as fillet yield and energy inputs to processing, among other details (see Appendix A and B). The survey was issued to a representative from the primary Icelandic provider of cod fillets to Findus. This company was then asked to distribute the survey widely to their processing facilities and fish providers (i.e. skippers of vessels targeting cod by longline). However, given factors beyond our control, surveys were only distributed to a select group of vessels and processing plants. Uncertainties and ambiguities regarding resulting data were clarified through subsequent e-mail and telephone correspondence with the cod supply company.

Inputs to vessel construction and maintenance were estimated from data elicited from a commercial shipyard. Inputs to bait provision (direct fuel inputs, packaging and storage energy) were drawn from previous research. Energy inputs to refrigeration, where this was not clearly accounted for in general fuel inputs to a vessel or processing facility, were also drawn from previously published research. Types and quantities of packaging typically used to package fresh and frozen cod fillets were derived from an industry contact. Final transportation scenarios for both fresh and frozen supply chains were characterized through industry informants and online transport-mode specific mileage calculators.

All foreground inventory data were compiled in an Excel workbook where quantities of all inputs were organized on the basis of inputs to individual sub-processes. The LCA software package SimaPro 7.1, developed by PRé Consultants based in the Netherlands, was then used to calculate impact potentials for each sub-process and for the system as a whole. The calculation was based on the data regarding specific inputs to the system, a set of databases reflecting the provision and use of these inputs, and standardized impact assessment methodology.

2.2.3 Impact Assessment

Contributions to climate change were calculated using the IPCC 2007 method with a time horizon of 100 years (IPCC, 2007b). The IPCC 2007 method uses equivalency factors for various greenhouse gas emissions to describe total contributions to climate change in terms of kilograms of CO_2 equivalent. The method was modified to eliminate "carbon credits" due to the appropriation of biogenic material in the system. For example, the use of wood in the manufacture of an item of gear would not be considered to offset CO_2 emissions elsewhere in the system. Other impact categories were also quantified including acidification and eutrophication potentials, abiotic resource use, cumulative energy demand and biotic resource use. These categories encompass a relatively diverse set of environmental emission and resource depletion concerns and are underpinned by robust methodologies. Acidification (in terms of kg SO_2 equivalent), eutrophication (in terms of kg PO_4 equivalent) and abiotic resource use (in terms of kg Sb equivalent) were assessed using the CML 2001 method developed by scientists at the Centre of Environmental Science Leiden University. Cumulative Energy Demand (in terms of MJ equivalent) was calculated using the EcoInvent method (Frischknecht, 2005). All of the impact categories with the exception of biotic resource use were calculated with the assistance of SimaPro.

Biotic resource use is a measure of the net primary productivity (NPP) required to sustain the production of the given mass of biotic resources consumed while accounting for typical metabolic demand and losses within ecosystems. Following previous seafood LCAs (Paptryphon et al., 2004; Pelletier & Tyedmers, 2007; Boyd, 2008), it was calculated here in terms of tonnes of carbon (C) using the method described by Pauly and Christensen (1995):

$$NPP = (M/9) \times 10^{\wedge(T-1)}$$

where M= wet weight of animal biomass;
and T= tropic level of species

Both bait and catch contribute to the biotic resource use of the fishery. Average trophic levels of finfish inputs were drawn from Fishbase while the average trophic level of squid was drawn from SeaLifeBase.

Co-product Allocation

When quantifying impacts other than BRU, allocation of impacts among co-products was necessary in reference to two activities: fishing (allocating among target and non-target species that are also landed) and processing (allocating among fillets and marketed co-products). The allocation of environmental burdens among co-products of an indivisible process in seafood LCAs is most commonly done using economic value (Ziegler, 2001; Ziegler et al., 2003; Paptryphon et al., 2004; Mungkung, 2005; Hospido et al., 2006) or physical relationships, such as the relative mass (Eyjólfsdóttir et al., 2003; Ellingsen & Aanondsen, 2006; Winther et al., 2009) of those co-products (Ayer et al., 2007). An alternative, relatively novel basis of allocation used in recent seafood LCA studies employs nutritional energy density of co-products (Ayer et al., 2007; Pelletier & Tyedmers, 2007; Pelletier et al., 2009; Pelletier & Tyedmers, 2010). Given the highly variable nature of absolute and relative values of fisheries co-products through time and between locations, and the resulting variability in analytical outcomes that do not reflect any biophysical change in the system (Krozer & Vis, 1998) economic value was rejected as a basis of allocation in this study. Both nutritional energy and mass were considered as the basis for allocation, however there was evidence that there would be little difference in the results regardless of which of these two biophysical methods were chosen (Pelletier & Tyedmers, 2007). Mass allocation was therefore selected based on the increased transparency of results allocated by this well known and understood unit. Furthermore, allocating by mass is consistent with the functional unit of analysis (1 kg of fillet).

2.2.4 Sensitivity and Scenario Analysis

Sensitivity analysis is used to assess how variability or uncertainty in data or assumptions affects LCA results. Scenario analysis is used to assess how possible future modifications of the system would affect results, all else being equal. In this analysis, the effects of decreased fuel efficiency during the catching phase, disposal rather than use of processing co-products, lower fillet yield, and the emission of refrigerants were tested.

2.3 RESULTS

2.3.1 Inventory Data

Despite repeated efforts to secure inventory data from multiple Icelandic longliners and groundfish processing plants, detailed data were only provided for a single vessel and a single processing plant. These data were combined with input from industry experts and data drawn from previously published analyses to characterize inventory data associated with the catching of cod (Table 2), processing and packaging (Table 3) and transport to market in the UK (Table 4).

Table 2. Inventory data for the catching phase of the Icelandic line-caught cod system per tonne of mixed catch.

	Quantity	Source	Background Database
Bait[a]			
Mackerel (kg/tonne)	26.2	Survey	
Fuel to catch (l/tonne)	2.88	Schau et al. (2008)	Franklin: Diesel equipment (gal)
		Duiven & Binard (2002)	
Freezing (MJ/tonne)	9.43	Magnussen (1993)	EcoInvent: Diesel, burned in diesel-electric generating set/GLO S
Storage (kJ/tonne for 6 months)	2.83		EcoInvent: Electricity, hydropower, at power plant/SE S
Packaging		Boyd (2008)	
Paper[b] (kg/tonne)	34.45		EcoInvent: Kraft paper, unbleached, at plant/RER S
Squid[c] (kg/tonne)	39.3	Survey	
Fuel to catch (l/tonne)	21.62	Ishikawa, et al. (1987)	Franklin: Diesel equipment (gal)
Freezing (MJ/tonne)	Included in fuel use	Ishikawa et al. (1987)	Franklin: Diesel equipment (gal)
Storage (MJ/tonne for 6 months)	4.24	Magnussen (1993)	EcoInvent: Electricity, hydropower, at power plant/SE S
Packaging			
Paper[b] (kg/tonne)	34.45	Boyd (2008)	EcoInvent: Kraft paper, unbleached, at plant/RER S
Gear			
Steel (kg/tonne)	0.09	Survey	IDEMAT: X12Cr13(416)I and X10Cr13(mart410)I
Nylon (kg/tonne)	1.87	Survey	EcoInvent: Nylon 6, at plant/RER S; Nylon 66, at plant/RER S
Boat			
Steel[d] (kg/tonne)	3.86	Survey, G. Gerbrandt (pers. comm. January 11, 2010)	EcoInvent: Steel, low-alloyed, at plant/RER ; Reinforcing steel, at plant/RER
Maintenance Steel[e] (kg/tonne)	0.97	Tyedmers (2000)	EcoInvent: Steel, low-alloyed, at plant/RER ; Reinforcing steel, at plant/RER

	Quantity	Source	Background Database
Direct Fuel[f]			
Diesel (l/tonne)	125	Survey	Franklin: Diesel equipment (gal)
Refrigeration[g] (MJ/tonne)	360	Duiven and Binard (2002)	EcoInvent: Diesel, burned in diesel-electric generating set/GLO S
Catch (kg/tonne)			
Cod	550	Survey	N/A
Haddock	160	Survey	N/A
Atlantic catfish	110	Survey	N/A
Ling	70	Survey	N/A
Tusk	50	Survey	N/A
Starry ray	20	Survey	N/A
Spotted catfish	10	Survey	N/A
Redfish	10	Survey	N/A
Other	10	Survey	N/A

[a] The survey, combined with a review of the likely source of supply of a major Icelandic bait provider (FAO, 2009b; Dimon ehf, 2009) revealed that the bait used was Atlantic mackerel (*Scomber scombrus*) and Atlantic squid (*Illex argentinus)*.

[b] The quantity and type of bait packaging material was based on that reported for frozen Atlantic mackerel bait used in the Nova Scotian lobster fishery (Boyd, 2008). No data were available for the packaging of squid as bait so it was assumed to be the same as for mackerel.

[c] Data on energy inputs to Atlantic squid fishing in the vicinity of the Falkland Islands was derived from Ishikawa et al. (1987). Although these data are over 20 years old, no more contemporary data were available.

[d] The longliner was reported to be 39.7 m in length. A value for a similar sized seiner (39 m) built in Canada was used. The ship was assumed to operate for 33 years.

[e] A maintenance factor was added based on Tyedmers (2000), which assumed 25% of the original material and energy inputs would be used over the lifetime of that vessel for maintenance.

[f] Engine emissions were modified using the Lloyd's Register set of emission factors for marine diesel engines (Lloyd's Register, 1995). Lloyd's Register provides a set of emission factors more representative of the likely emissions of fishing vessel engines, and has previously been used in LCAs of seafood (Hospido & Tyedmers, 2005; Boyd, 2008)

[g] These boats are at sea for little more than 3 days at a time. Consequently, it was assumed that ice is produced and loaded aboard prior to each fishing trip. In this case the energy for freezing would not be included in the fuel consumed by the boat engines.

Table 3. Inventory data for the processing phase of cod system in terms of one tonne of cod fillet.

	Quantity	Source	Background Database
Whole Cod (tonnes)	2.2	Survey	N/A
Electricity (kWh)[a,b]	187	Survey	EcoInvent: Average of Electricity, hydropower, at power plant/SK; SE; PL; HU; AT S
Diesel (l)	0.31	Survey	Franklin: Diesel equipment (gal)
Gasoline (l)	0.10	Survey	Franklin: Gasoline equipment (gal)
Marketed co-products (tonnes)[c]	0.21	Survey	N/A
Unmarketed co-products (tonnes)[c]	1.0	Survey	N/A
Packaging (kg)			
Carton (cardboard)	15.66	Survey	EcoInvent: Packaging, corrugated board, mixed fibre, single wall, at plant/RER S
Plastic bag	0.18	Survey	EcoInvent: Packaging film, LDPE, at plant/RER S
Liner (83% cardboard, 17% wax)	10.3	Survey	EcoInvent: Kraft paper, unbleached, at plant/RER S; Paraffin, at plant/RER S

[a] Energy used for refrigeration is assumed to be included in these numbers, and so an additional freezing factor was not added.

[b] The Icelandic energy mix is mainly hydropower and geothermal (International Energy Agency, 2006). There is not a good model for electricity generated from geothermal energy within the suite of life cycle databases available through SimaPro , and given that the contributions to climate change were likely to be similar for both hydropower and geothermal (i.e. negligible), emissions associated with hydropower was substituted. A model for Icelandic hydropower was not available and so an average was used based on a set of European countries.

[c] 2000 tonnes of live-weight fish enter the facility annually. 900 tonnes of fillet (a yield of 45% from live-weight) and 190 tonnes of marketed cod co-products exit the facility annually. Although the remaining 910 tonnes of fish byproduct are not marketed, the survey reported that “nothing is wasted” therefore this mass was not treated as true waste in the base case model.

Table 4. Inventory data for final transportation phase of fresh and frozen cod fillet to the UK per tonne of cod fillet delivered.

	Quantity	Source	Database
Ground (tkm)[a]	600	Survey	EcoInvent: Transport, lorry 16-32t, EURO4/RER S
Air (tkm)[b]	1621	Air Routing International (2010)	EcoInvent: Transport, aircraft, freight/RER S
Sea (tkm)[c]	1670	Dataloy AS, (2010)	EcoInvent: Transport, transoceanic freight ship/OCE S

[a] It was assumed that half of the trips, covering 400 km one way, entail an empty return trip.

[b] Air distance was estimated between Rekjavik, Iceland and Liverpool, UK (the closest airport to Grimsby for which a distance estimate was available).

[c] Sea distance was estimated between Rekjavik, Iceland and Grimsby, UK.

2.3.2 Impact Assessment

Complete details regarding life cycle impacts associated with the fishing, processing, and transportation phases of fresh and frozen fillets appear in Appendix C.

The total greenhouse gas emissions associated with the delivery of one kilogram of frozen fillet to the UK were found to be 0.70 kg CO_2 eq. In line with previous studies on the climate change impact of seafood (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006) the greatest contributions occurred during the fishing phase (Figure 4), and this pattern was mirrored in all other impact categories. The low emission intensity of the electricity generation system in Iceland reduces contributions to all impact categories in the processing phase except cumulative energy demand. As a result contributions to cumulative energy demand appear disproportionately large compared to all other impact categories in this phase (Figure 4).

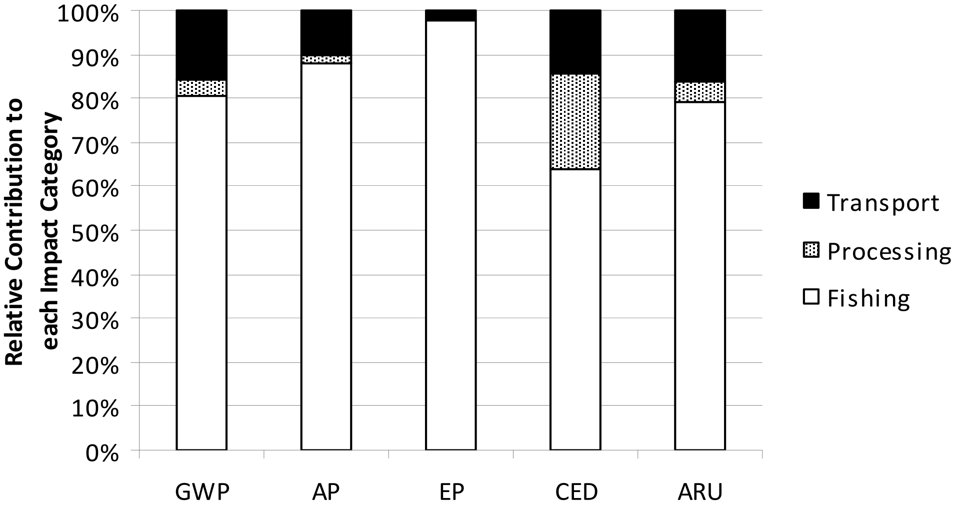

Figure 4. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) made by fishing, processing, and final transportation phases in the life cycle of a frozen cod fillet delivered to Grimsby, UK.

In light of the large contribution made by fishing effort, further analysis was undertaken of the key contributors to impacts made at this stage. Direct fuel inputs far exceed any other input in terms of contributions to all impact categories assessed (Figure 5).

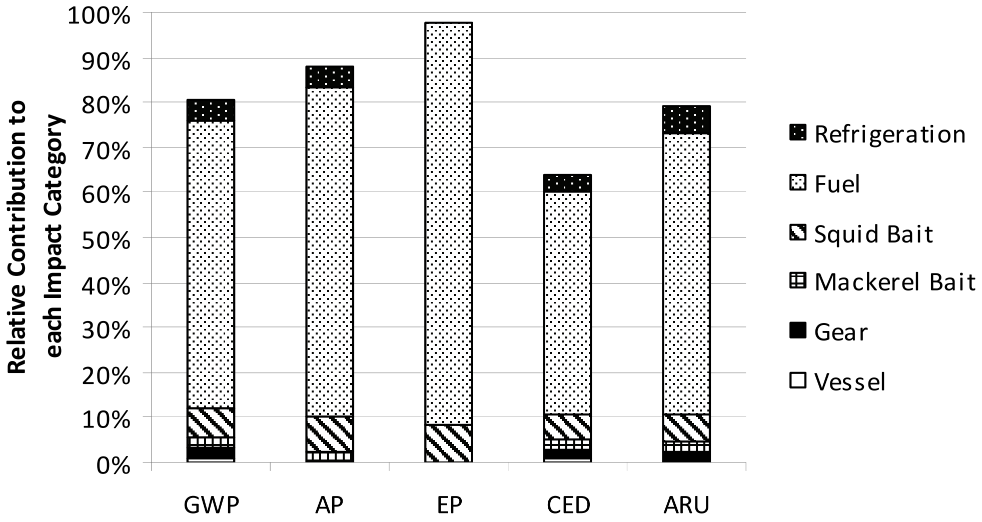

Figure 5. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) made by the fishing phase to one kilogram frozen cod fillet.

The case of fresh fillets however was quite different to that of frozen fillets. In this case air transport outweighed impacts made during the fishing stage in every impact category except eutrophication, where fishing makes slightly greater contributions than air transport (ground transport makes negligible contributions to this impact category) (Figure 6). Overall, a fresh fillet transported by air was found to result in life cycle greenhouse gas emissions of 2.6 kg CO_2 eq, nearly four times that associated with the delivery of frozen fillet transported by sea.

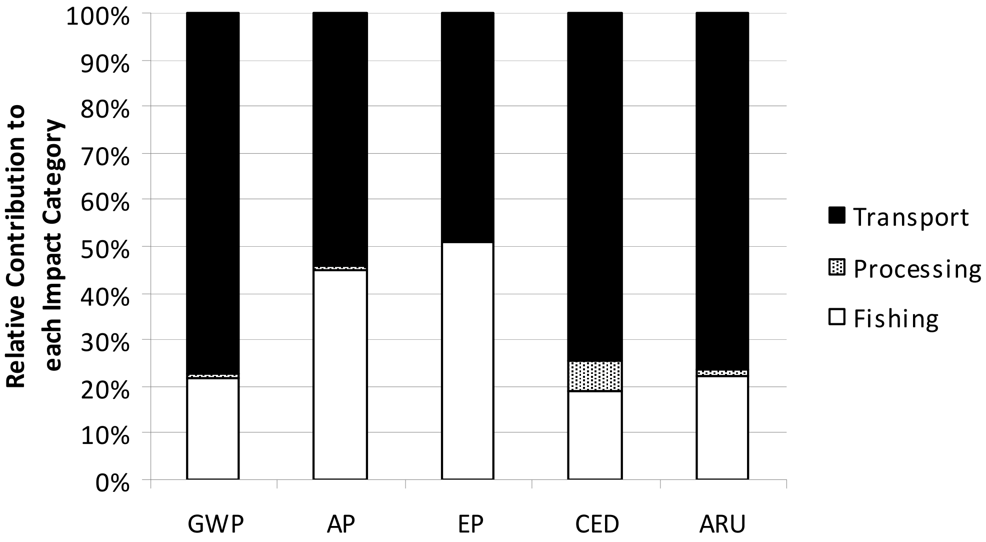

Figure 6. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) made by fishing, processing, and final transportation phases in the life cycle of a fresh cod fillet delivered to Grimsby, UK.

Unlike the other impact categories, biotic resource use is relevant only for the fishing effort. Considering both bait and catch, this fishery appropriates NPP of just over 153.5 tonnes C (Table 5) per tonne of mixed catch landed.

Table 5. Biotic resource use of 1 tonne landed catch in this fishery, given proportions of various species caught. Bait used to catch 1 tonne is also included (see squid and mackerel).

Species	Trophic level (± S.E.)	Proportion per tonne mixed catch (kg)	BRU (kg C)
Cod (*Gadus morhua*)	4.29 ± 1	550	119,157
Haddock (*Melanogrammus aeglefinus*)	3.56 ± 0.67	160	6,455
Atlantic catfish (*Anarhichas lupus*)	3.35 ± 0.47	110	2,736
Ling (*Molva molva*)	4.25 ± 0.69	70	13,831
Tusk (*Brosme brosme*)	4.01 ± 0.66	50	5,685
Starry ray (*Amblyraja radiata*)	3.49 ± 0.56	20	687

Species	Trophic level (± S.E.)	Proportion per tonne mixed catch (kg)	BRU (kg C)
Spotted catfish (*Anarhichas minor*)	3.62 ± 0.51	10	463
Redfish (*Sebastes fasciatus*)	3.16 ± 0.34	10	161
"Other"	N/A	10	N/A
Squid (Bait) (*Illex argentinus*)	3.82 ± 0.56	39	2,863
Mackerel (Bait) (*Scomber scombrus*)	3.73 ± 0.57	26	1,551
Total	N/A	1 tonne catch + bait	153,589

2.3.3 Data Limitations

Only one complete survey was returned, and as such the results of this study are based on one set of data for each of the catching and processing phases. Although every effort was made to confirm and clarify the data obtained, the results cannot be considered representative of an Icelandic fishing fleet that includes 1529 registered vessels, 769 of which are decked boats using non-trawl gear (Statistics Iceland, 2008). It is not known specifically how many of these boats are longliners targeting cod, however the cod caught by our one respondent vessel accounted for less than 1% of all cod landed in Iceland in 2008 (Statistics Iceland, 2008) and 3% of the total catch of all the vessels in its size class (301-500 GT) (Statistics Iceland, 2008).

Regarding processing plants, there are 150 licensed freezing processing plants and 29 fresh processing plants in the Iceland, processing all species of fish (FHF, 2004; FAO, 2009c). Although results are not broadly representative of either Iceland longliners or processing plants, they do provide an initial indicator of the possible impacts of Icelandic cod.

2.3.4 Sensitivity and Scenario Analysis

Fuel Intensity

Direct fuel inputs to fishing have been found to be a significant contributor to a variety of impact categories including climate change in seafood production systems (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006). Furthermore, the fuel intensity reported in this study (125 l/tonne) was lower than that reported recently for another longline fishery targeting demersal species operating in the North Atlantic (Schau et al., 2009). Therefore the effect of decreased fuel efficiency on the environmental performance of the system was tested, using this recently reported value (369 l/tonne).

As a result of an increase in fuel consumption from 125 to 369 l/tonne of fish landed (an increase of approximately three times), contributions to climate change increased by 0.87 kg CO_2 eq / kg fillet (an increase of just over 100% in the case of frozen, but only 30% in the case of fresh product delivered to the UK). As such, where direct fuel inputs to fishing are the most important determinant of the overall performance of the system, an increase in fuel intensity can have an important impact on results.

Fate of Co-Products

In the base case model, impacts were allocated by mass regardless of the fate or value of co-products, provided these products were not a true waste (i.e. disposed of at sea, landfilled, etc.). Although the survey reported that “nothing is wasted” during processing, it was a subjective choice to allocate impacts to all products regardless of economic value, and allocation can have an important impact on LCA results (Boyd, 2008; Ayer et al., 2007). For this reason a sensitivity analysis was conducted where impacts were allocated only to marketed co-products (including fillets).

Understandably, allocating the impacts of the processing phase only to the marketed products significantly increases the per kg impacts of this phase across all impact categories. Contributions to climate change overall increased by 0.49 kg CO_2 eq / kg fillet (an increase of 70% in the case of frozen, and 19% in the case of fresh fillets). Emissions resulting from energy inputs to processing are negligible in both the base case model and this sensitivity analysis, but the emissions resulting from fishing, allocated now only to the 54% of the fish that is marketed, increase by approximately 170% per kg of fillet.

Fillet Yield

Where unmarketed co-products (i.e. co-products that were reportedly "not wasted" but also "not marketed") are excluded from impact allocation, the fillet yield becomes more important to the impact assessment result. Fillet yields can vary from processing, therefore we tested the impact of a fillet yield of 41% from live-weight based on values reported by Winther et al. (2009), reduced from the 45% reported in this study. The quantity of marketed co-products was assumed to be the same as that reported by survey, and the remainder was treated as true waste with impacts only allocated to fillets and marketed byproducts, as above. Reducing fillet yield during this phase and assuming the "lost" mass is waste similarly increases the per kg fillet impacts of this phase, although the change was understandably less. Contributions to climate change increased by an additional 0.084 CO_2 eq / kg fillet, or 12% in the case of frozen and 3% in the case of fresh. Where inputs to the fishing phase are the most important driver of the overall impact of the system (as is the case in the frozen fillet system), we can see that fillet yield is very important in determining contributions to climate change. In this case, product loss of 4% at the processing stage led to an increase of three times that (12%) in terms of the contributions to climate change made per kilogram of frozen fillet.

Refrigerants

Although data regarding the types of refrigerants used at the processing stage were collected for this study, insufficient data were available regarding leakage rates. As such impacts associated with production and loss of refrigerants were not included in our base case model. However, research has found that refrigerant use can contribute significantly to environmental impacts including climate change specifically, as some refrigerants are strong greenhouse gases (Winther et al., 2009). A wide range of leakage rates have been reported for refrigerants (Table 6), and refrigerants differ greatly in terms of their global warming potential.

Table 6. Published rates of leakage for various refrigerants used in catching and processing in the seafood industry.

Refrigerant (global warming potential)	Reported Emission Rate	Normalized kg/tonne fillet
Ammonia NH_3 (0 kg CO_2 eq / kg)	0.187 kg/tonne fillet[a]	0.187
	7.4 g/tonne live weight input[b]	0.0161[c]
R22 (1810 kg CO_2 eq/kg)	0.45 g/ tonne live weight input[b]	0.0098[c]
	0.07 g / kg[d]	0.07[e]
	0.0000378 kg / 9 kg frozen fillet / 21 days storage[f]	0.0042
	0.224 g / kg live weight[g]	0.0001[c]
	0.023 g / kg live weight[g]	0.00001[c]

[a] F. Ziegler, pers. comm. October 1st, 2009
[b] for salmon, gutting only from Winther et al., 2009.
[c] Assumes fillet yield of 46%.
[d] for shrimp, from Ziegler et al., 2009
[e] Normalized per tonne of shrimp (rather than per tonne of fillet)
[f] Eyjólfsdóttir et al., 2003
[g] Winther et al., 2009

Here we quantify impacts associated with the loss of 0.0042 kg of refrigerant HFC 134a per tonne of fillet based on Eyjólfsdóttir et al. (2003). This value was chosen based on the fact that it was reported in a study examining the same fishery (Icelandic cod) as the present study. There are no reported values for the leakage rate of the refrigerant (HFC 134A) reportedly used in the present cod system.

Despite the high global warming potential of HFC 134A (3300 kg CO_2 eq), emission of this refrigerant was found to contribute negligibly to all the impact categories studied. This mirrors the results found by Eyjólfsdóttir et al. (2003), although the refrigerant in this case (R22) had a lower global warming potential.

2.4 DISCUSSION

As with previous studies, direct fuel inputs to fishing were found to be very important in determining contributions to climate change and other impact categories. This was true for the present system despite the fishery being relatively fuel efficient compared to other fisheries targeting cod and/or other demersal species using longline or trawl gear in the North Atlantic (Figure 7).

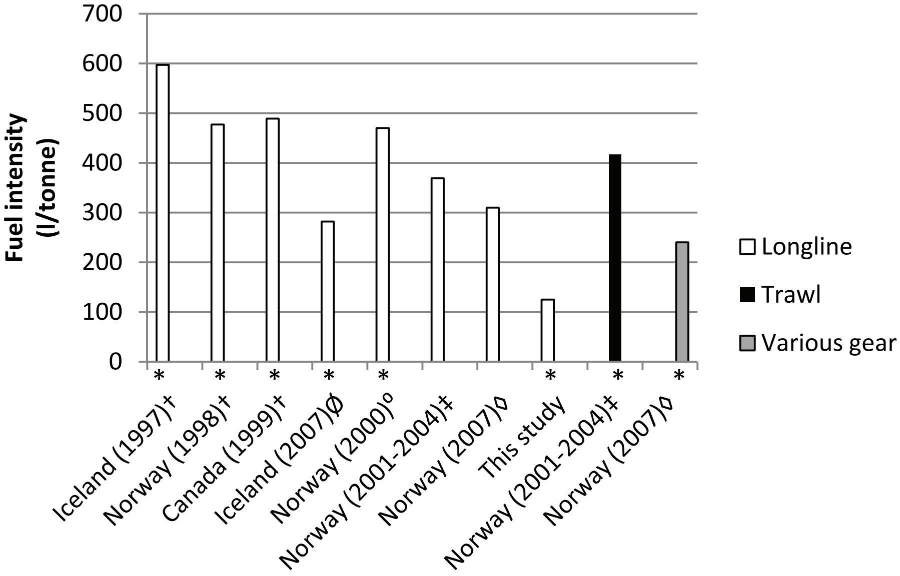

Figure 7. Fuel intensity for fisheries in the North Atlantic targeting cod (*) or other demersal species. †Tyedmers, 2001. ØSund, 2008. °Thrane, 2004. ‡Schau et al., 2008. ◊ Winther et al., 2009.

Although demersal longline is a passive form of gear, it is often still energy intensive on a l/tonne basis (Tyedmers, 2001). The reason for the relative energy efficiency of this fishing vessel is not clear, but may be explained by several factors, such as a particularly skilled skipper (Ruttan & Tyedmers, 2007), a particularly abundant year for stocks on that fishing ground allowing the quota to be met with less effort (Tyedmers et al., 2005), efficient engines, a short distance from this boat's home port to the fishing grounds, etc. (Ziegler, 2001; Thrane, 2004; Tyedmers et al., 2005; Schau et al., 2008).

Although not the most important input to fishing, bait also made non-trivial contributions to several impact categories. Squid, in particular, was found to be a highly energy intensive form of bait and should be avoided to reduce impacts. More recent data regarding inputs to the squid fishery would help confirm these results.

Our results show that where the fishing phase is the most important contributor to a system's overall contributions to climate change, fillet yield and the fate of co-products are key determinants of the extent of the potential impact. To minimize the per kg contributions to climate change made by their products, processing companies should seek to maximize the volume of products extracted from the fish delivered to their door.

The comparison of fresh and frozen product forms offers a key example of the challenge of using food miles as a proxy for sustainability. Although fresh and frozen product forms travel nearly identical distances in this model, the impact of air freight in comparison with sea freight is striking. This demonstrates that mode of transport is at least as important as the distance a given product travels when considering environmental impacts. The issue of transportation related greenhouse gas emissions is particularly relevant as fish is often demanded "fresh" and therefore (as in our model) must be air freighted. As we saw here, air transportation is by far the most energy intensive form of transport, followed by road and rail, with ship transport being the most efficient mode on average (Dutilh & Kramer, 2000; DEFRA, 2005; Horvath, 2006; Forster, 2007). The large contributions of air transportation are also worrying in light of the fact that air transportation is a fast growing mode of food transportation, having doubled within the 1990s (Smith et al., 2005).

The results of this study suggest that Icelandic-caught cod may be a relatively low impact seafood choice, however selecting frozen and therefore sea-freighted products rather than fresh, air-freighted products is important. However these results, based on only a single boat and processing facility, only suggest the possible impacts of this seafood system without being representative of the system in general. Further research may confirm or refine these conclusions.

CHAPTER 3 ALASKAN POLLOCK

Alaskan pollock fillets are a large volume seafood product shipped all over the world. This study examines contributions to climate change and other impact categories that result from the capture, processing, packaging and transport of frozen Alaskan pollock fillets delivered to Grimsby, UK via two possible supply chains. In one case, pollock is caught by a trawler, partially processed on board a floating “mothership” located on the fishing grounds in the Bering Sea before being forwarded frozen to China for further processing, and finally transported by sea to Grimsby. In the other, pollock is caught and processed onboard an at-sea catcher/processor vessel before transport by sea to Grimsby. As with previous studies direct fuel inputs to fishing were an important contributor to all impact categories evaluated. In this regard, data suggested some variability within each supply chain over time. Overall the mothership/Chinese processing supply chain resulted in nearly twice the impacts associated with at-sea caught and processed fillets. The difference between the two systems stems primarily from the fossil fuel inputs to processing on board the mothership, not (as might be suspected) from the additional distance travelled by the Chinese processed fillets. Further data are needed to confirm these results; however findings suggest a high degree of variability in terms of the potential environmental impacts associated with Alaskan pollock fillets.

3.1 INTRODUCTION

Alaskan pollock is said to be the largest food fish resource in the world, with nearly 3 million tonnes caught annually in the waters of the North Pacific and Bering Sea (Seafood Choices Alliance, 2006; Association of Genuine Alaska Pollock Producers, 2009). Over the last 10 years, over a third of this has been caught in U.S. waters of the Bering Sea (FAO, 2010b) (Figure 8). It is therefore not surprising that the Alaskan pollock fishery is the largest fishery in North America, accounting for a third of all U.S. seafood landings by weight (At-sea Processors Association, 2006).

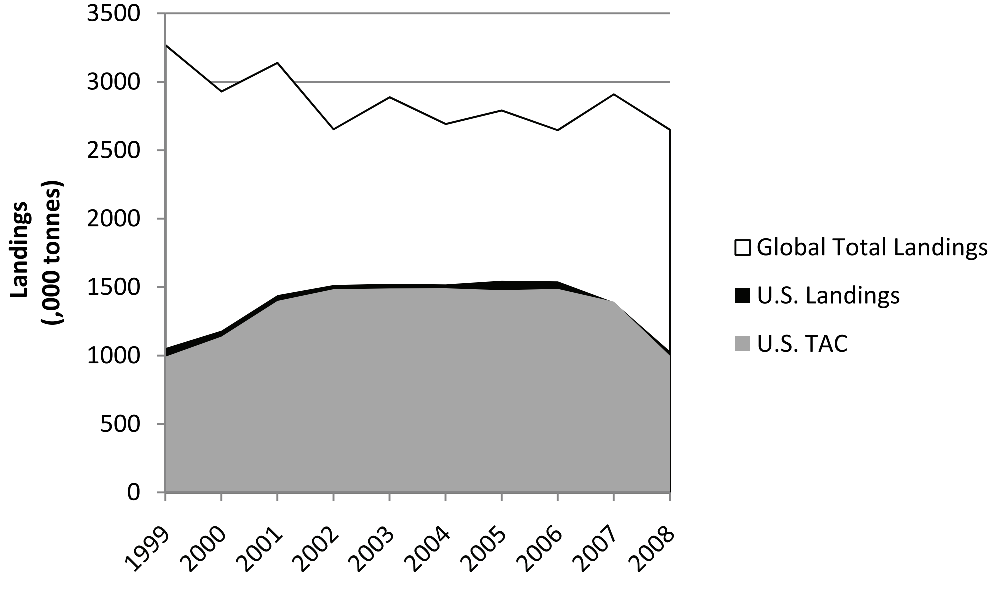

Figure 8. Total global landings, U.S. (Bering Sea) landings and U.S. Total Allowable Catch (TAC) (Bering Sea) for Alaskan pollock (in tonnes) (ADFG, 2010a)

Alaskan pollock are schooling, benthopelagic fish (Fishbase, 2009b). Live adult pollock may weigh up to 7 kg, but typically weigh less than 1 kg and are between 30 and 38 cm in length (FAO, 2010b). Although the Alaskan pollock stock is not thought to be overfished in the Bering Sea (NMFS, 2010), there have been concerns that the fishery has negatively impacted pollock predators, specifically the endangered Steller sea lion (ADFG, 2010a). Restrictions to avoid fishing in sensitive sea lion habitat and during certain times of year have aimed at reducing these impacts.

Although Alaskan pollock is caught and traded internationally by a number of countries, the analysis below focuses entirely on the fishery and products derived from U.S. waters. In U.S. waters the pollock fishery is seasonal, with harvests prohibited for two months in the spring and fall (May/June and October/November respectively), and has a very low bycatch rate (<1%) although total tonnages of some by-catch species of concern (e.g. Chinook salmon) can be substantial (Witherell et al., 2002). As a well managed fishery with a relatively low by-catch rate, U.S.-caught Alaskan pollock is thought to be a relatively “sustainable” seafood choice, and indeed the fishery secured MSC certification in 2005. The U.S. Alaskan pollock fishery entered a standard reassessment for possible re-certification in January, 2009 (MSC, 2009). In contrast, fisheries for Alaskan pollock in other parts of the Bering Sea and North Pacific are generally thought to be more poorly managed and as such are not currently certified by the MSC.

Almost all Alaskan pollock (95%) is caught in U.S. waters using pelagic (mid-water) trawl fishing gear (MSC, 2009; ADFG, 2010a). Mid-water trawling involves towing a cone-shaped net through the water above the surface of the sea floor. Vessels used to trawl for pollock are either dedicated fishing boats without the capacity to process what they catch or specialized “at-sea” catcher-processor vessels. In 2008, there were approximately 90 trawlers, with an average length of 30.5 m, active in the U.S. Alaskan pollock fishery (Association of Genuine Alaska Pollock Producers, 2009). Together these vessels are permitted to take 60% of the annual total allowable catch (TAC) of Alaskan pollock in US waters. The balance of the U.S. TAC is allocated to the catcher-processor fleet. Currently, 19 catcher-processor vessels are active in the fishery. These vessels range in length from 67 to 115 metres and carry combined fishing and processing crews of approximately 140 people each (At-sea Processors Association, 2006).

The fish caught by dedicated trawlers are delivered to either Alaskan shore-based processing facilities, or floating motherships (boats not engaged directly in fishing but equipped with processing and freezing facilities) for processing into various forms and products prior to being sent directly to market or for further processing elsewhere. Whether processed on shore in Alaska or Asia (as is increasingly the case according to S. Rilatt and M. Mitchell pers. comm. February 19th, 2009) or at sea, pollock may be processed into a variety of products including fillets, mince, and surimi or imitation crab meat. Secondary products include roe and where reduction facilities exist, fish scraps are processed into fishmeal and oil. The two primary pollock products, fillets and mince, are typically further processed into a variety of consumer-ready products including breaded fish sticks and fish cakes.

Alaskan pollock is currently not one of the top seafood imports in the UK: Alaskan pollock is one of the 12,130 tonnes of “other” demersal and pelagic species imported in

2008, far outstripped by imports of cod and salmon (Marine Management Organization, 2009). However, as an abundant source of relatively inexpensive whitefish, it is possible this will change in the future. We sought to describe the contributions to climate change and other related impact categories associated with the life cycle of one kilogram of frozen pollock fillet delivered in Grimsby, UK, having been caught in Alaska and processed at-sea (aboard a catcher-processor) or aboard a mothership and on shore in China.

3.2 METHODS

This study followed a life cycle assessment methodology, comprised of four steps (Figure 1): goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a).

3.2.1 Goal and Scope

The goals of this project were to:

- quantify the life cycle greenhouse gas emissions associated with frozen pollock fillets delivered to Grimsby that are derived from two distinct supply chains;
- identify hotspots in their respective supply chains;
- identify opportunities for GHG emission reductions; and
- consider the extent to which other key resource use and emission impacts vary with GHG emissions.

The scope of analysis encompassed all major material and energy inputs to three subsystems (Figure 9): fishing, processing and packaging, and transportation. The functional unit of analysis is one kilogram of packaged frozen fillet delivered in Grimsby. Two process streams were considered separately: fillets captured by trawlers and processed initially aboard motherships and subsequently on shore in China, and fillets captured and processed aboard catcher/processor vessels.

Certain assumptions were made in order to simplify the system under study or fill data gaps, in light of time constraints and the difficulty in collecting data. Due to our focus on climate change, items deemed unlikely to contribute significantly to this impact category (particularly given the functional unit of 1 kg of fillet) were excluded from study. For example, the material and energy inputs to the engine and fixtures of the fishing vessel as well as infrastructure related to the processing plant were excluded due to their small mass relative to the pollock caught or processed during their service.

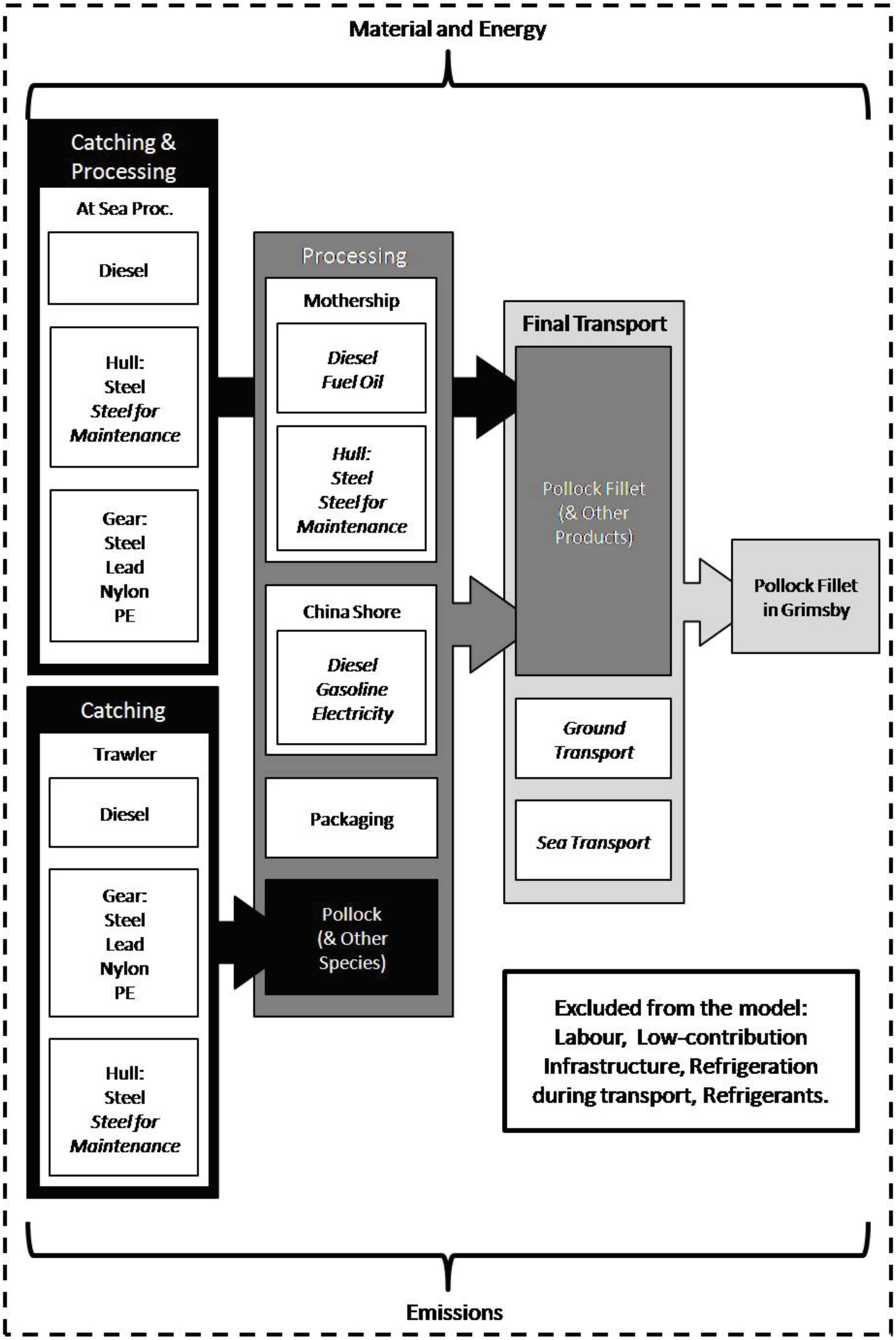

Figure 9. System boundaries for the LCA of one kilogram of frozen Alaskan pollock fillet from capture through to delivery in Grimsby, UK. Italicized font denotes background data as indicated in Tables 8 and 9.

3.2.2 Inventory Analysis

Data were collected from several sources. First, surveys were issued to and returned by one member of each of the trawling and mothership fleets. These surveys included questions regarding annual volume of fish caught and processed, fuel inputs, size of each vessel and its engines, and material inputs to gear among other details (see Appendix A and B). Data related to major energy and packaging-related inputs to Chinese shore-based processing were collected via a survey issued to a major whitefish processor. These data were supplemented with information regarding pollock fillet yield from contacts at Findus. A survey was also issued to all five member companies of the At Sea Processors Association (responsible for operating all nineteen vessels in the fleet), however none were returned. Repeated efforts to solicit detailed data regarding this process chain via phone and email were unsuccessful. As such the researchers opted to employ a technique to estimate fuel use from effort data using an equation and empirical relationship described by Tyedmers (2001):

$Q = R^*(H^*T)$

where Q= quantity of fuel consumed; and
R= rate of fuel consumption in litres/HP*sea-days of fishing effort; and
H= average main engine horsepower of all vessels in the fleet; and
T= total aggregate effort in days at sea

By calculating the slope of the line when effort (in HP*sea-days) was plotted against known fuel consumption for a variety of fishing vessels under normal operation, Tyedmers (2001) estimated the R for boats employing trawl gear to be approximately 2.55. This method was found to correlate well with known fuel use data in the case of Icelandic trawlers (Tyedmers, 2001). For this study data regarding average fleet HP along with total sea-days and catch for the years 2000 to 2008 inclusive were collected from the National Oceanic and Atmospheric Administration (T. Hiatt & R. Felthoven, pers. comm. November 16th, 2009). Resulting estimates of average fuel use intensity for 2008 were communicated to members of the at-sea pollock industry for groundtruthing.

Inputs to vessel construction and maintenance were estimated from secondary sources. Energy inputs to refrigeration, where this was not clearly accounted for in general fuel inputs to a vessel or processing facility, were drawn from previously published research. Final transportation distances and modes were characterized through industry informants and online transport-mode specific mileage calculators.

All foreground inventory data were compiled in an Excel workbook where quantities of inputs were organized on the basis of inputs to individual sub-processes. The LCA software package SimaPro 7.1, developed by PRé Consultants based in the Netherlands, was then used to calculate impact potentials for each sub-process and for the system as a whole. The calculation was based on the data regarding specific inputs to the system, a set of databases reflecting the provision and use of these inputs, and standardized impact assessment methodology.

3.2.3 Impact Assessment

Impact assessment methodology for the pollock system mirrored that used for the cod system. Mass allocation was used. Please refer to Chapter 2 for a detailed discussion.

3.2.4 Sensitivity and Scenario Analysis

In this study the effect of a change in the fuel consumption of both the catcher/processor and the mothership was tested based on historical trends (ten years in the case of the catcher/processors and three years in the case of the mothership).

3.3 RESULTS

3.3.1 Inventory Data

The combination of survey results, communication with industry experts, and data from previously published results contributed to the inventory data presented in regards to the trawler/mothership/Chinese shore-based processing stream (Table 7) and the catcher/processor stream (Table 8).

Table 7. Inventory data for capture of pollock by trawler (per tonne of mixed catch), processing of the whole pollock into headed and gutted product on board a mothership (per tonne of headed and gutted pollock), processing of headed and gutted product into fillets (per tonne of fillet), and final transport to Grimsby.

	Quantity	Source	Background Database
Catching (units per live tonne of catch)			
Gear			
Steel(kg/tonne)	0.006	Survey	IDEMAT: X12Cr13(416)I and X10Cr13(mart410)I
Lead (kg/tonne)	0.008	Survey	IDEMAT: Lead I
Nylon (kg/tonne)	0.052	Survey	EcoInvent: Nylon 6, at plant/RER S; Nylon 66, at plant/RER S
Polyethylene (kg/tonne)	0.008	Survey	EcoInvent: Polyethylene, HDPE; LDPE and LLDPE, granulate, at plant/RER S
Boat[a]			
Steel (kg/tonne)	0.346	Survey, G. Gerbrandt (pers. comm. January 11th, 2010)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Maintenance Steel[b] (kg/tonne)	0.086	following Tyedmers (2000)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Direct Fuel[c]			
Diesel (l/tonne)	36	Survey	Franklin: Diesel equipment (gal)
Refrigeration[d] (MJ/tonne)	Assumed to be included in fuel use.	Survey	Franklin: Diesel equipment (gal)
Catch (kg/tonne)			
Pollock	830	Survey	N/A
Whiting	170	Survey	N/A
Processing (Mothership) (units per tonne headed and gutted pollock)			
Whole pollock (tonne/tonne)[e]	2.78	Survey	N/A

	Quantity	Source	Background Database
Boat[f]			
Steel (kg/tonne)	12.2	Survey, R. Parker (pers. comm. November 25th, 2010)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Maintenance Steel[b] (kg/tonne)	3.04	following Tyedmers (2000)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Diesel[g] (l/tonne)	108	Survey	Franklin: Diesel equipment (gal)
Heavy fuel oil (l/tonne)	268	Survey	EcoInvent: Heavy fuel oil, burned in industrial furnace 1 MW, non-modulating/RER S; burned in refinery furnace/kg/RER S
Transport to China (tkm)[h]	8229	Dataloy AS (2010)	EcoInvent: Transport, transoceanic freight ship/OCE S
Processing (On-shore, China) (units per tonne fillet)			
Headed and gutted pollock[i] (tonne/tonne)	1.43	Survey	N/A
Electricity (kWh/tonne)	390.63	Survey	
Coal	81%	International Energy Agency (IEA) (2007)	EcoInvent: Hard coal, burned in power plant/CN S
Hydro	15%	IEA (2007)	EcoInvent: Electricity, hydropower, at power plant/JP; CS; DK S
Nuclear	2%	IEA (2007)	EcoInvent: Electricity, nuclear, at power plant/US; UCTE S
Gas	2%	IEA (2007)	EcoInvent: Natural gas, burned in power plant/US; UCTE S
Diesel (l/tonne)	6.87	Survey	Franklin: Diesel equipment (gal)
Gasoline (l/tonne)	1.38	Survey	Franklin: Gasoline equipment (gal)
Byproducts (tonne/tonne)	0.3	Survey	N/A
Packaging (kg/tonne)			
Carton (cardboard)	15.66	Survey	EcoInvent: Packaging, corrugated board, mixed fibre, single wall,

	Quantity	Source	Background Database
			at plant/RER S
Plastic bag	0.18	Survey	EcoInvent: Packaging film, LDPE, at plant/RER S
Liner (83% cardboard, 17% wax)	10.3	Survey	EcoInvent: Kraft paper, unbleached, at plant/RER S; Paraffin, at plant/RER S
Transport (units per tonne fillet delivered)			
Ground (tkm)[j]	600	Survey	EcoInvent: Transport, lorry 16-32t, EURO4/RER S
Sea[k] (tkm)	16325	Dataloy AS (2010)	EcoInvent: Transport, transoceanic freight ship/OCE S

[a] The trawler was reported to be 33.5 m in length with an 8.5 m beam. Inputs to the trawler were based on mass and volume estimates provided by a contact in the Canadian ship building industry. The trawler was assumed to be active for 50 years.

[b] A maintenance factor was added based on Tyedmers (2000), which assumes an additional 25% of the original material and energy inputs would be used over the lifetime of that vessel for maintenance.

[c] Engine emissions were modified using the Lloyd's Register set of emission factors for marine diesel engines (Lloyd's Register, 1995). Lloyd's Register provides a set of emission factors more representative of the likely emissions of fishing vessel engines, and has previously been used in LCAs of seafood (Hospido & Tyedmers, 2005; Boyd, 2008).

[d] The trawler reported being at sea for 191 days per year, but did not specify for how many days at a time. It was assumed boats were away for a sufficiently long period that refrigeration would be mainly provided by energy on board the ship, and would therefore be included in the total reported fuel use.

[e] In 2008 50,859 tonnes of live weight fish were delivered to the mothership, resulting in 6,802 tonnes of headed and gutted pollock, 8,058 tonnes of surimi, 595 tonnes of roe, 2,851 tonnes of meal (and 200,400 gallons of fish oil, burned as fuel aboard the ship). The remainder (31,915 tonnes) were disposed of at sea.

[f] The length of the mothership was reported to be 207 m. The steel required to build this vessel was estimated based on the closest sized vessel for which data were available: a 92 m trawler which required 4,848 tonnes of steel. Steel inputs for the mothership were scaled up linearly from this value. The ship was assumed to be active for 49 years based on data provided via survey.

[g] Fish oil is also burned on the ship, displacing diesel on a 1:1 basis based on (Anonymous, pers. comm. September 8th, 2009). Engine emissions were modified using the Lloyd's Register set of emission factors for marine diesel engines (Lloyd's Register, 1995). Lloyd's Register provides a set of emission factors more representative of the likely emissions of fishing vessel engines, and has previously been used in LCAs of seafood (Hospido & Tyedmers, 2005; Boyd, 2008).

[h] Headed and gutted pollock are shipped from the mothership in Alaskan waters to Qingdao or Bangkok, and then (in this model) on to Grimsby. An average of shipping from Akutan, Cordova or Sitka to Bangkok or Qindao was used to approximate this shipping distance.

[i] Data were for cod and haddock processing, however it was assumed energy inputs for processing were the same regardless of species. Pollock fillet yield (70% from headed and gutted fish) was obtained from representatives at Findus. The remaining 30% is assumed to be used for animal feed.

[j] No data were available for the distance travelled from processing plant to shipping facility in China. An average distance based on the cod system was therefore used, representing a 400km trip with half of these trucks returning empty.

[k] An average of shipping from Qindao or Bangkok to Grimsby was used to approximate the shipping distance from Asia to the UK.

Table 8. 2008 Inventory data for catching and processing by at sea processor (per tonne mixed product) and final transport to Grimsby.

	Quantity	Source	Background Database
Catching/Processing (units per tonne mixed product)			
Gear[a]			
Steel(kg/tonne)	0.006	Survey (trawler)	IDEMAT: X12Cr13(416)I and X10Cr13(mart410)I
Lead (kg/tonne)	0.008	Survey (trawler)	IDEMAT: Lead I
Nylon (kg/tonne)	0.052	Survey (trawler)	EcoInvent: Nylon 6, at plant/RER S; Nylon 66, at plant/RER S
Polyethylene (kg/tonne)	0.008	Survey (trawler)	EcoInvent: Polyethylene, HDPE; LDPE and LLDPE, granulate, at plant/RER S
Boat[b]			
Steel (kg/tonne)	5.6	Survey, R. Parker (pers. comm. November 25th, 2010)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Maintenance Steel[c] (kg/tonne)	1.4	following Tyedmers (2000)	EcoInvent: Steel, low-allowed, at plant/RER; Reinforcing steel, at plant/RER
Direct Fuel[d]			
Diesel (l/tonne) OR	101 (estimate)	T. Hiatt & R. Felthoven, (pers. comm. November 16th, 2009), Tyedmers, (2001)	Franklin: Diesel equipment (gal)
Diesel l/tonne	108 (reported)	Anonymous (pers. comm. April 12th, 2010); Anonymous (pers. comm. April 20th, 2010)	N/A
Refrigeration	Assumed to be included in fuel use.		

	Quantity	Source	Background Database
Total Catch (kg/tonne catch)			
Pollock	902	T. Hiatt & R. Felthoven (pers. comm. November 16th, 2009)	N/A
Other	98	T. Hiatt & R. Felthoven (pers. comm. November 16th, 2009)	N/A
Product Outputs (kg/tonne)[e]			
Pollock Whole	negligible	T. Hiatt & R. Felthoven (pers. comm. November 16th, 2009)Hiatt and Felthoven (2010)	N/A
Pollock Headed & Gutted	5	As above.	N/A
Pollock Roe	55	As above.	N/A
Pollock Fillet	365	As above.	N/A
Pollock Surimi	290	As above.	N/A
Pollock Mince	77	As above.	N/A
Pollock Meal	63	As above.	N/A
Pollock Oil	10	As above.	N/A
Pollock Other	9	As above.	N/A
Other	126	As above.	N/A
Packaging (kg/tonne)			
Carton (cardboard)	15.66	Survey	EcoInvent: Packaging, corrugated board, mixed fibre, single wall, at plant/RER S
Plastic bag	0.18	Survey	EcoInvent: Packaging film, LDPE, at plant/RER S
Liner (83% cardboard, 17% wax)	10.3	Survey	EcoInvent: Kraft paper, unbleached, at plant/RER S; Paraffin, at plant/RER S

	Quantity	Source	Background Database
Final Transport (units per tonne fillet delivered)			
Ground[f] (tkm)	600	Survey (Cod)[f]	EcoInvent: Transport, lorry 16-32t, EURO4/RER S
Sea[g] (tkm)	15240	Dataloy AS, 2010	EcoInvent: Transport, transoceanic freight ship/OCE S

[a] Inputs to the catcher/processor trawling gear were scaled up from the trawler gear data based on relative volume of catches. Gear was assumed to be used for 5 years.

[b] The length of the catcher/processor was reported to be on average 87.5 m (T. Hiatt & R. Felthoven, pers. comm. November 16th, 2009). The steel required to build this vessel was estimated based on a 92 m trawler which required 4,848 tonnes of steel. The ship was assumed to be active for 30 years following Tyedmers (2000).

[c] A maintenance factor was added based on Tyedmers (2000), which assumed 25% of the original material and energy inputs would be used over the lifetime of that vessel for maintenance.

[d] "Reported" refers to average of two highly disparate numbers provided anonymously by industry contacts. In the model, engine emissions were modified using the Lloyd's Register set of emission factors for marine diesel engines (Lloyd's Register, 1995). Lloyd's Register provides a set of emission factors more representative of the likely emissions of fishing vessel engines, and has previously been used in LCAs of seafood (Hospido & Tyedmers, 2005; Boyd, 2008).

[e] The yield of each of these products from live-weight and the quantity of waste left over from processing were unavailable. The data presented indicates the relative proportion of various products produced by the at-sea catcher-processor. In our model, it was assumed no byproducts from processing were wasted.

[f] In the absence of system-specific data, an average distance based on the cod system was used, representing a 400 km trip with half of these trucks returning empty.

[g] It was not clear specifically where in Alaska pollock are landed, therefore an average was used for shipping from Akutan, Cordova or Sitka to Grimsby. Some catch is landed in Seattle but overall this is reported to be minimal compared to landings in Alaska (Anonymous, pers. comm. April 24th, 2010).

Base case impacts were calculated using estimated 2008 fleet-wide fuel consumption data (101 litres per live tonne caught). Limited historical timeseries data were also available for both systems (Figure 12).

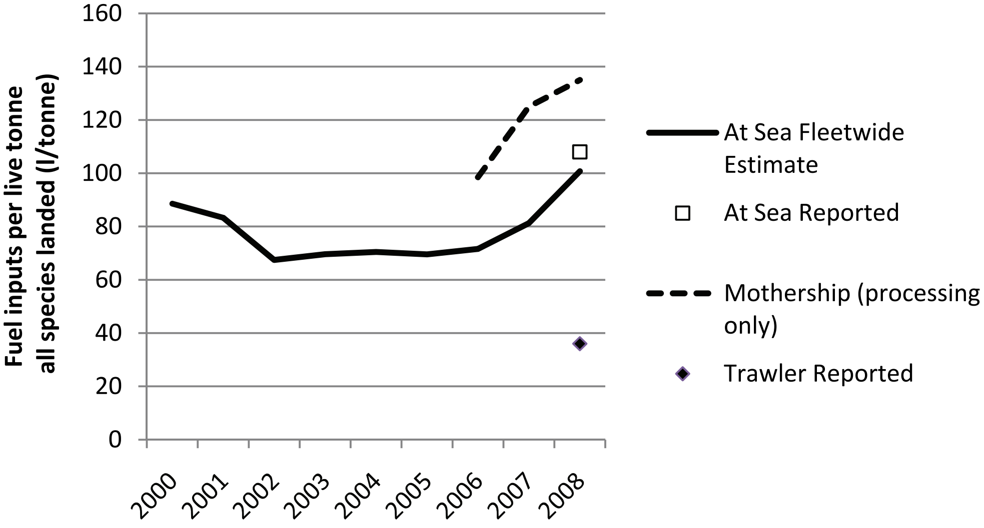

Figure 10. Fuel inputs to catcher processor vessels (solid line and box data point) and separate catching and mothership-based processing supply chain (diamond data point and dashed line). Fleet-wide catcher-processor fuel use estimated from effort data, all others reported by industry contacts.

The estimated fuel use data for the catcher-processor fleet in 2008 is in close agreement with that reported by industry contacts, although the confidential data provided representing two vessels suggests a large degree of variability within the fleet. Interestingly despite not engaging directly in fishing, the mothership is the least fuel efficient per live weight tonne handled of the three vessel types examined.

3.3.2 Impact Assessment

Complete details regarding life cycle impacts associated with the fishing, processing, and transportation phases of frozen pollock fillets may be found in Appendix C.

In the case of pollock caught by trawl, headed and gutted on a mothership, transported to China for processing into fillets, and finally delivered into Grimsby, processing makes the largest contribution to all impact categories (Figure 11). The majority of the potential contributions to climate change in this phase (58%) originate with the mothership. Total contributions to climate change from this supply chain were found to be 1.1 kg CO_2 eq / kg frozen fillet.

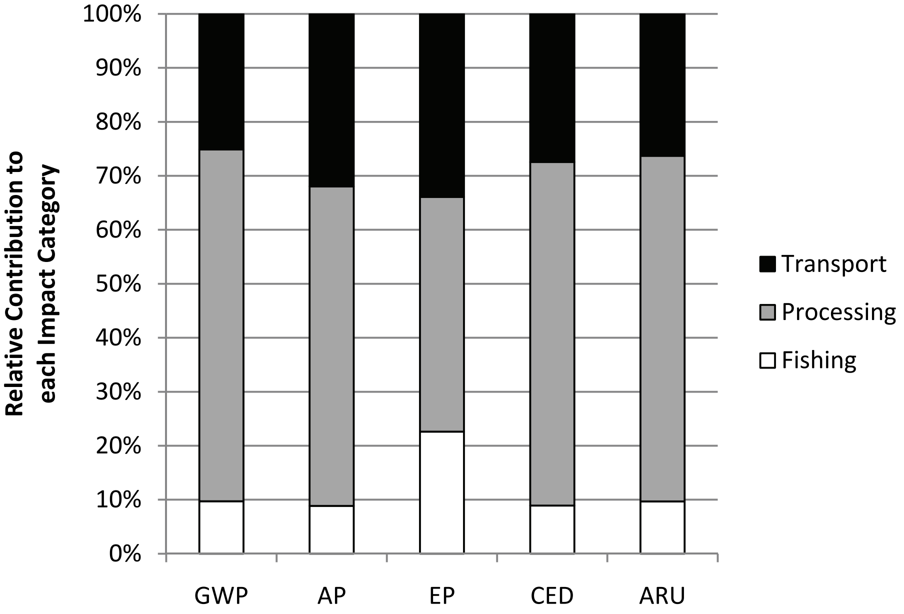

Figure 11. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) impact categories made by fishing, processing aboard a mothership and in China, and final transportation phases in the life cycle of a frozen pollock fillet delivered to Grimsby, UK.

Contributions to all impacts are lower in the case of fillets derived from fish caught and processed by at-sea catcher/processors, and so the role of transport makes a relatively larger contribution (Figure 12). Total greenhouse gas emissions from this process stream were found to be 0.59 kg CO_2 eq / kg frozen fillet, nearly half that of the alternative.

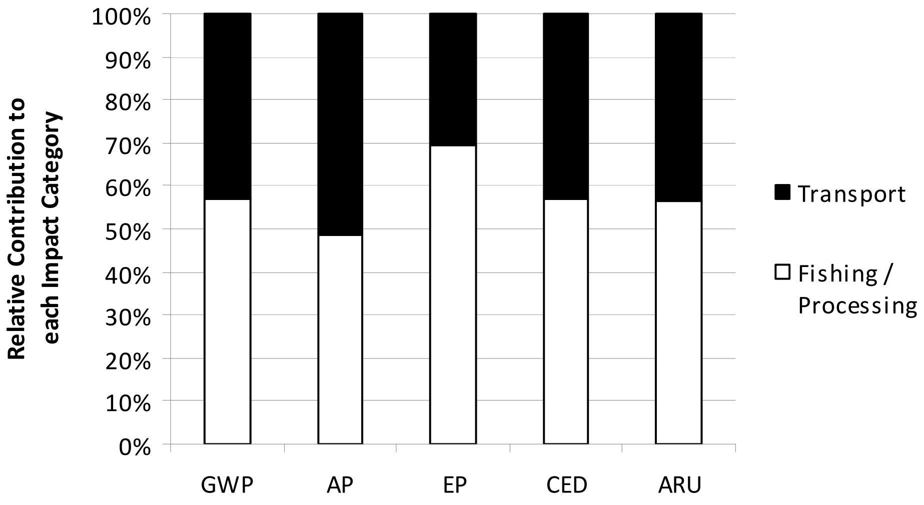

Figure 12. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) impact categories made by the at-sea catcher/processor and final transportation to Grimsby, UK.

Specific details regarding the species of bycatch in the pollock fishery were only available from the trawler (bycatch was reported as “other” in the at-sea processor catch data). Using these data, the fishery was found to require NPP totaling over 62 tonnes C per tonne of mixed catch landed (Table 9).

Table 9. Biotic resource use for the pollock fishery per tonne live-weight catch.

Species	Trophic level (± S.E.)	Proportion per tonne mixed catch (kg)	BRU (kg C)
Pollock (*Theragra chalcogramma*)	3.68 ± 0.62	828	44,034
Whiting (*Merluccius productus*)	3.98 ± 0.69	172	18,251
Total	N/A	1000	62,285

3.3.3 Data Limitations

Despite efforts to secure data from multiple sources, only one survey was returned for each of the trawler and mothership fleets, as well as for Chinese-based secondary processing. This mothership, however, is responsible for 50% of the quota processed by such vessels in 2008. The single trawler represents only 1% of the fleet, but was responsible for catching 17% of the pollock processed by this mothership in 2008.

No surveys were returned by any of the at-sea catcher-processor fleet, although limited data regarding fuel intensity were provided by anonymous sources within the industry and these sources were able to confirm that our fuel consumption estimates were sound. Although every effort was made to confirm and clarify data obtained throughout the study, additional data would have been welcome to further refine the analysis.

3.3.4 Sensitivity and Scenario Analysis

Fuel intensity of fisheries are known to vary year over year (Tyedmers, 2004, Schau et al. 2009) and this has been observed in the present study (Figure 12). In order to test the sensitivity of our overall results to changes in fuel inputs to both catching and processing at sea, both supply chains were evaluated using the average fuel intensity for the period for which data were available (three years in the case of the mothership, ten years in the case of the at-sea catcher/processor). This represented a decrease in fuel intensity of 23% in the case of the at-sea processor (from 101 l/tonne of catch to 78 l/tonne), and 11% in the case of the mothership (from 135 l/tonne of input to 120 l/tonne). Resulting contributions to climate change of the entire at-sea processor stream decreased by 12% to 0.5 kg CO_2 eq per kg frozen fillet delivered to the UK. Climate change contributions associated with the mothership mediated processing stream also decreased, by 5% to a total of 1.0 kg CO_2 eq per kg frozen fillet delivered to the UK.

3.4 DISCUSSION

Previous research has shown that direct fuel inputs to fishing are very important contributors to a range of environmental impacts of seafood systems (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006). Given this, it is noteworthy that the dedicated trawler was found to consume just 36 l/tonne of all fish landed, one of the lowest fuel inputs to a food fishery reported in the literature (see for example Watanabe & Okubo, 1989; Tyedmers, 2004; Schau et al. 2009) and far lower than any fuel inputs previously reported for an Alaskan pollock fishery (Table 10). Meanwhile, the at-sea catcher/processors burn almost three times as much fuel at 101 litres per tonne of all fish caught but clearly these values are not directly comparable. In addition to the energy requirements of processing pollock on board, catcher/processors may be less able to optimize activity for fishing, leading to lower catch per unit effort (Dorn, 1998). Despite this, overall fuel inputs to the at-sea processing fleet remain among the very lowest reported for a food fishery and are far lower than fuel inputs of 600 litres per tonne reported for Japanese catcher-processor vessels operating in the 1980s (Watanabe & Okubo, 1989).

Table 10. Reported direct energy inputs to fishing effort (in all cases with trawl gear) in the fishery for Alaskan pollock in various parts of the Pacific.

Source	Fishery locale and year	Type of vessel	Energy intensity (l/tonne live weight)
This study	U.S. waters of Bering Sea, 2008	Trawler	36
This study	U.S. waters of Bering Sea, 2008	Catcher-processor	101
Nomura (1980)	North Pacific, 1975	Trawler	200
Watanabe & Uchida (1984)	North Pacific, early 1980s	Trawler	580 - 2310
Watanabe & Okubo (1989)	North Pacific, early 1980s	Catcher-processor	600

A variety of factors may contribute to the remarkably low fuel inputs associated with the modern Alaskan-based pollock fishery. The skill of skippers has been found to influence fuel efficiency (Ruttan & Tyedmers, 2007), perhaps through optimizing speed and haul depth, or by managing fishing activity around target species behaviour (Battaile & Quinn, 2004). Pollock, for example, school more tightly during the day, and as such may be more efficiently caught at this time (Battaile & Quinn, 2004). The age of the engine is also found to influence fuel efficiency (Ziegler & Hansson, 2003), and as such results from the last few years are perhaps unsurprisingly better than those from the 1980s. As well, the ability to stay on the fishing grounds for extended periods of time by either offloading to a mothership (in the case of the trawler) or finishing and freezing products at sea (in the case of the catcher-processors) would also help reduce fuel inputs. However, the extent of this last benefit is less clear in the case of the at-sea processors as much of this fleet is harboured in Seattle and must travel a significant distance to and from Alaska at the start and end of each season. Fuel inputs for this travel are included in our assessment, but they must mitigate the advantage of staying on the fishing grounds throughout the season without the need to shuttle back and forth to shore.

Another likely factor explaining the relative fuel efficiency of the fleet is the abundance of the pollock stock (Tyedmers, 2004). In this vein, it is notable that estimated fuel inputs to the catcher-processor fleet show a marked increase in recent years (Figure 12) at the same time that the total TAC has been reduced (Figure 8) apparently to address concerns regarding the size of the stock (Ianelli et al., 2009). It is therefore advisable that the managers of the pollock fishery continue to manage the resource conservatively in order to safeguard stocks for the future, as this may also serve to minimize contributions to climate change made by the fishery. Further research regarding the relationship between fish stock abundance and fuel inputs to fishing would be useful in confirming this theory.

Although not directly involved in fishing activity, it is possible that stock levels may influence fuel consumption by the mothership, as this ship is able to spend less time at sea in years when the quota can be met quickly (Anonymous, pers. comm. September 8th, 2009). Overall, our results show the mothership as being the most energy intensive phase of the pollock supply chain, but it should be noted that a variety of factors make this particular mothership unique (e.g. size, age, fuel type according to Anonymous pers. comm. September 8th, 2009). As such, it is unlikely that these results are representative of the other two motherships responsible for processing approximately 5% of the total pollock catch. Although the mothership studied here is responsible for approximately half of the quota allocated to the mothership supply chain, it is only expected to remain active for another 5-10 years (Anonymous, pers. comm. September 8th, 2009). At that time the emissions profile of this supply chain will likely change as it is replaced with a more fuel efficient modern vessel, however without data for the other motherships in the fleet the details of that emissions profile are unclear.

Due to a lack of available data, our results are also not representative of the performance of the supply chain employing a fleet of trawlers delivering to Alaskan shore-based processors. This supply chain is currently responsible for catching and processing 50% of the pollock caught in Alaskan waters of the Bering Sea, and as such this system represents a good opportunity for future research.

This study suggests that there may be a great deal of variability in terms of the environmental impact associated with an Alaskan pollock fillet, due both to the methods employed for processing and variation in fuel intensity (both among the various members of the fleet and for the fleet as a whole over time). In the context of this variability, we see again that food miles are only a partial indicator of the greenhouse gas emission performance of a supply chain. A greater proportion of the total emissions of the mothership-processed fillet originated with the mothership (36%) than from all the transportation modeled in that chain (33%, including transport to and from Asia). Energy inputs to processing overall were much more important (53% of the total). Furthermore, a relatively short trip by truck in Asia (600 km) was responsible for essentially equivalent greenhouse gas emissions (0.092 kg CO_2 eq compared to 0.088 kg CO_2 eq) as a relatively long trip by sea from Alaskan waters to China (8,229 km). Uncovering the reality of the source and extent of greenhouse gas emissions required a much more detailed analysis than can be encompassed by the food miles approach. In general, more data would be very useful in revealing the complete picture of greenhouse gas emissions associated with the provision of an Alaskan pollock fillet, and confirming the preliminary results presented here.

CHAPTER 4 ALASKAN PINK SALMON

Alaskan pink salmon fillets are a relatively inexpensive, high profile seafood product. This study examines the contributions to climate change and other related impact categories made by Alaskan pink salmon fillets caught by purse seine gear, processed on shore in either Alaska or China, and shipped by sea to Grimsby, UK. The pink salmon purse seine fishery is relatively fuel efficient, and as such the processing and transportation phases become more important in determining the overall potential climate change impact of the system. In this regard, results indicate that the decreased energy efficiency of processing in China, the higher emission intensity of electricity generation there, and the impact of transporting salmon from Alaska to the Chinese processing facility all led to greater impacts associated with Chinese-processed fillets. However, results are based on limited data for the processing phase, and as such further study will be needed to confirm these conclusions.

4.1 INTRODUCTION

There are five species of commercially important Pacific salmon: sockeye (*Oncorhynchus nerka*), chum (*Oncorhynchus keta*), chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*) and pink (*Oncorhynchus gorbuscha*). Pink salmon are the smallest species of salmon (3 kg on average) and also have shortest residency at sea, typically living only 2 years (Fishbase, 2009c). Pink salmon range throughout the northern and central Pacific (Fishbase, 2009c). All salmon are anadromous, living a portion of their life in the salt water environment of the ocean, bookended by life in the freshwater of rivers where they are hatched and where they return to spawn.

Pink salmon accounts for about 50% of global wild-caught salmon consumption, half of which originates in North America (Figure 13). Most pink salmon is canned for U.S. consumption, however twenty one percent of Alaskan pink salmon is exported frozen (Knapp et al., 2007). This study examines frozen Alaskan pink salmon fillets imported into Grimsby, UK. In 2005 salmon was the most consumed seafood product overall in the UK (Seafood Choices Alliance, 2007). Although most of this salmon is farmed domestically, salmon of all kinds and from all sources is still the third largest seafood import in the UK after cod and haddock. Over 63,000 tonnes were imported in 2008, 10% of which originated in the U.S. (Marine Management Organization, 2009).

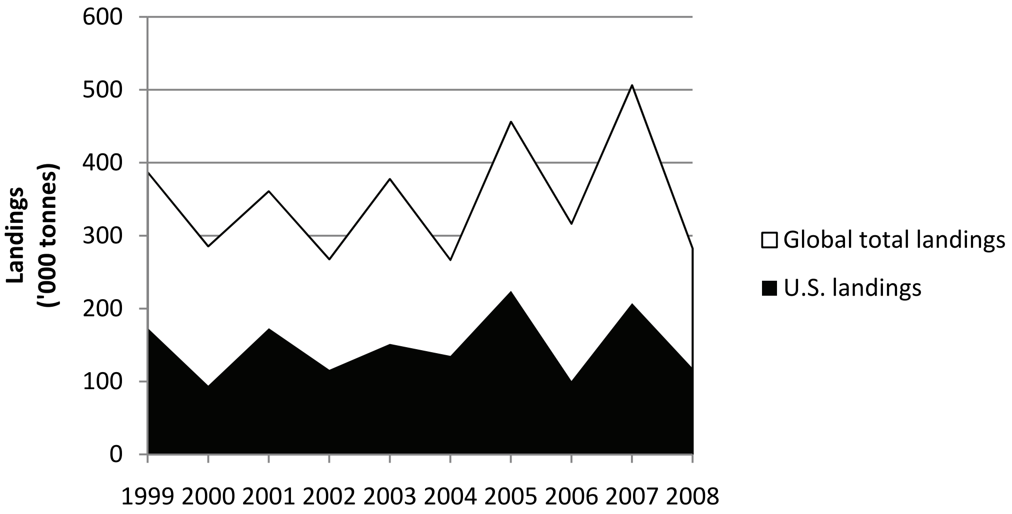

Figure 13. Pink salmon landings over the last decade (ADFG, 2009; FAO, 2009b).

Salmon are caught during their return for spawning in the summer, May through August. In Alaska, they are managed to ensure a sufficient number of salmon successfully reach the spawning grounds – the remainder are available to be captured by the commercial fishery. Importantly however, approximately forty-four percent of contemporary wild-caught Alaskan pink salmon originate not in wild spawning grounds but in hatcheries, where fish are raised from eggs to fry and released to sea to supplement wild populations (Knapp et al., 2007). Hatcheries may have negative impacts on wild populations by increasing competition for food, encouraging overharvest of pink salmon which depletes "pure" wild stocks, and decreasing the genetic diversity of the total population (Knapp et al., 2007). Furthermore, the heavy reliance on hatchery fish may compromise the "wild" image of Alaskan salmon, which is particularly controversial in Alaska where salmon farming is prohibited (Knapp et al., 2007).

Despite concerns regarding the negative impacts of hatchery salmon, wild pink salmon stocks are judged to be healthy (Knapp et al., 2007) and the fishery is MSC certified

(MSC, 2007). Fishing effort is managed by licenses distributed by species and gear type, where pink salmon are mainly caught by purse seine (71%), with much smaller volumes caught by drift gillnet, set gillnet and power troll gears (Knapp et al., 2007; ADFG, 2010b). This study will examine pink salmon caught by purse-seine gear. Purse seine gear allow fishermen to surround dense schools of pink salmon targeted using fish finding devices or simply spotted in relatively shallow waters as they migrate to their natal streams.

Currently, the pink salmon catch may be processed on shore in either Alaska or China. This study models both fish processed on shore in Alaska, as well as fish transported (frozen) by sea to China for processing, followed in each case by final transport by sea to Grimsby, UK. For each supply chain, we sought to describe the contributions to climate change and other related impact categories associated with the life cycle of one kilogram of fillet.

4.2 METHODS

The study followed a life cycle assessment methodology, comprised of the four steps shown in Figure 1: goal and scope definition, inventory analysis, impact assessment, and interpretation.

4.2.1 Goal and Scope

The goals of this project were to:

- quantify the life cycle greenhouse gas emissions associated with frozen salmon fillets delivered to Grimsby following processing in either Alaska or China;
- identify hot spots in their respective supply chains;
- identify opportunities for greenhouse gas emission reductions; and
- consider the extent to which other key resource use and emission impacts vary with greenhouse gas emissions.

The scope of analysis encompassed all major material and energy inputs to three subsystems (Figure 14): fishing, processing and packaging, and transportation. The functional unit of analysis is one kilogram of packaged frozen fillet delivered to Grimsby.

Certain assumptions were made in order to simplify the system under study in light of time constraints and the difficulty in collecting data. Items deemed unlikely to contribute significantly to contributions to climate change (particularly given the functional unit of 1 kg of fillet) were excluded from the study. For example, the material and energy inputs to the engine and fixtures of the fishing vessel as well as infrastructure related to the processing plant were excluded due to their small mass relative to the salmon caught or processed during their service.

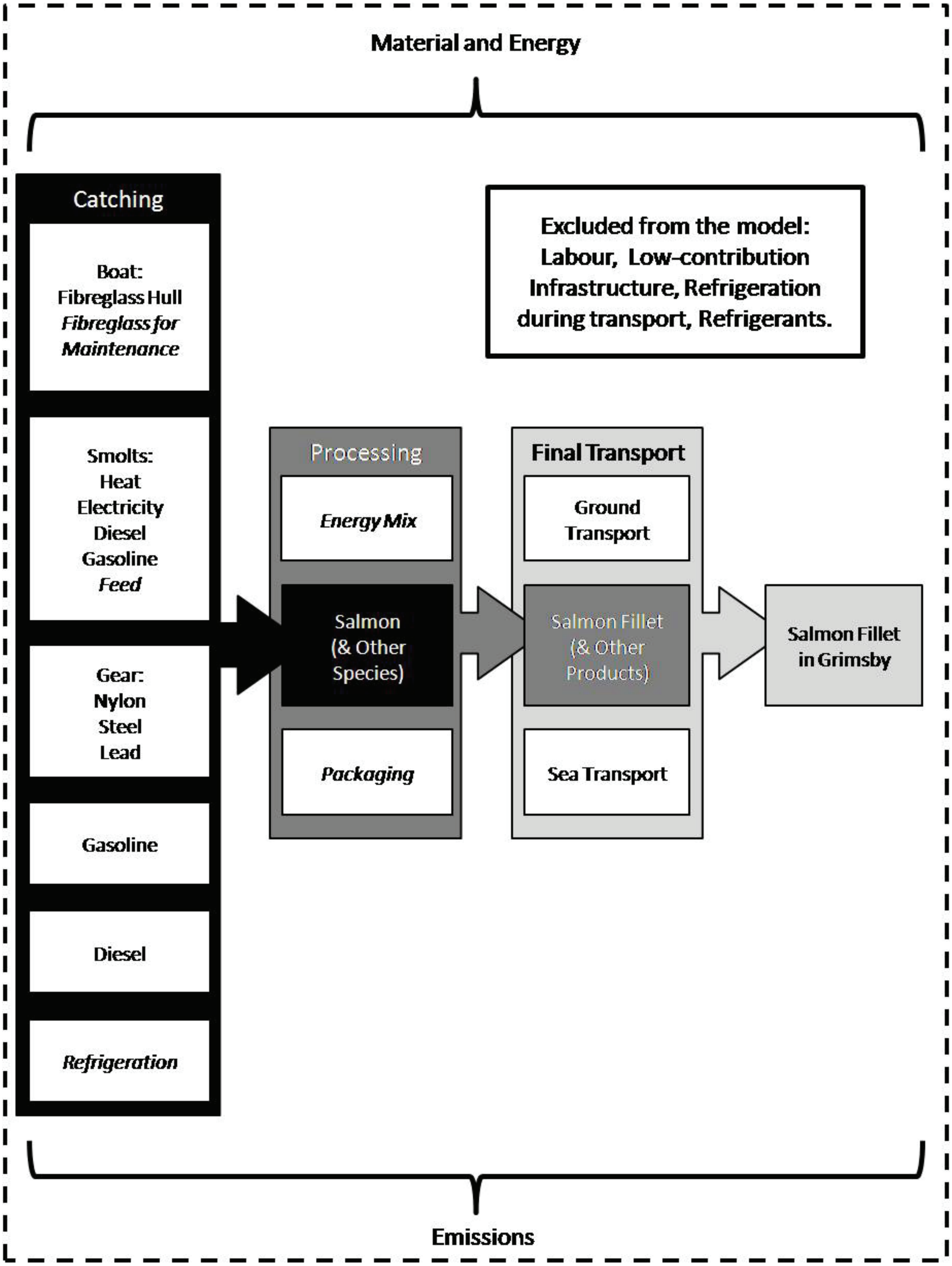

Figure 14. System boundaries for the LCA of one kilogram of frozen Alaskan salmon fillet from capture through to delivery in Grimsby, UK. Italicized font denotes background data as indicated in Tables 11-13.

4.2.2 Inventory Analysis

Data regarding inputs to a pink salmon hatchery were collected via a survey issued to all of the five hatcheries that primarily rear pink salmon in Alaska. The survey included questions regarding energy and feed consumption as well as smolt releases and returns. The responses were confirmed in part by email and phone communication with other salmon hatchery managers in Alaska. Based on government estimates of the number of hatchery-born salmon that support the average tonne of “wild”-caught salmon, data from this survey were used to estimate average hatchery inputs per tonne of salmon catch.

Data regarding direct fuel inputs to Alaskan purse seine fishing for pink salmon were based on data collected as part of another study of the broader Alaskan salmon fishing industry as of 2005 (Tyedmers et al., in prep).

Data regarding processing in China were collected via an English language survey issued to a large whitefish processor. Survey questions focused on energy inputs, packaging, and type of refrigerant used (see Appendix B). Salmon fillet yield from manual processing was obtained from a contact at Findus. A survey issued to a major Alaskan shore-based processor was not returned, and so an approximation for this product stream was made using the typical energy inputs for processing farmed salmon by machine in Norway and Scotland (F. Ziegler, pers. comm. October 1st, 2009) and packaging data from the returned Chinese survey.

Inputs to vessel construction and maintenance were estimated from secondary sources. Energy inputs to refrigeration, where this was not clearly accounted for in general fuel inputs to a vessel or processing facility, were drawn from previously published research. Final transportation was characterized through industry informants and online transport-mode specific mileage calculators.

All foreground inventory data were compiled in an Excel workbook where quantities of all inputs were organized on the basis of inputs to individual sub-processes. The LCA software package SimaPro 7.1, developed by PRé Consultants based in the Netherlands, was then used to calculate impact potentials for each sub-process and for the system as a whole. The calculation was based on the data regarding specific inputs to the system, a set of databases reflecting the provision and use of these inputs, and standardized impact assessment methodology.

4.2.3 Impact Assessment

Impact assessment methodology for the salmon system mirrored that used for the cod system. Mass allocation was used. Please refer to Chapter 2 for a detailed discussion. One modification was made in the case of the biotic resource use impact category. No data were available regarding the average rates of bycatch in purse seine fisheries targeting pink salmon, therefore biotic resource use for this fishery was calculated for pink salmon alone. The salmon fishery is thought to have very low rates of bycatch (mainly other species of salmon, see Alverson, 1994), so it is likely that this is still closely representative of the biotic resource use of the fishery.

4.2.4 Sensitivity and Scenario Analysis

In this study we tested the effect of decreased fuel efficiency in the catching phase, waste of processing byproducts, as well as an increased proportion of the “wild” catch originating in hatcheries.

4.3 RESULTS

4.3.1 Inventory Data

The combination of survey results, communication with industry experts and data drawn from previously published research all contributed to the inventory data presented in regards to catching (Table 11), processing and packaging (Table 12), and transporting (Table 13) pink salmon fillets.

Table 11. Inventory data for the catching phase of salmon fillet system per tonne whole landed pink salmon.

	Quantity	Source	Background Database
Hatchery[a]	5500 smolts	White (2009)	
Feed (tonne/tonne)	0.02	Survey	Pelletier & Tyedmers (2007)[b]
Diesel (l/tonne)	0.53	Survey	Franklin: Diesel equipment (gal)
Gasoline (l/tonne)	0.97	Survey	Franklin: Gasoline equipment (gal)
Fuel Oil (l/tonne)	8.3	Survey	EcoInvent: Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER S
Boat			
Fibreglass (kg/tonne)	0.42	Tyedmers (2000)	EcoInvent: Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S
Maintenance Fibreglass[c] (kg/tonne)	Included above.	Tyedmers (2000)	EcoInvent: Glass fibre reinforced plastic, polyester resin, hand lay-up, at plant/RER S
Gear			
Steel (kg/tonne)	2.8	Tyedmers (2000)	IDEMAT: X12Cr13(416) I &X10Cr13(mart 410)I
Lead (kg/tonne)	0.2	Tyedmers (2000)	IDEMAT: Lead I
Nylon (kg/tonne)	6.2	Tyedmers (2000)	EcoInvent: Nylon 6, at plant/RER S & Nylon 66, at plant/RER S
Direct Fuel (for fishing)			
Diesel[d] (l/tonne)	55.44	Tyedmers et al. (in prep)	Franklin: Diesel equipment (gal)
Gasoline[d] (l/tonne)	0.56	Tyedmers et al. (in prep)	Franklin: Gasoline equipment (gal)

[a] 5.5 individual smolts are estimated to be required per kg salmon catch. This was used to estimate the contributions of the hatchery to salmon catch, based on the inputs to one hatchery producing 220 million smolts.

[b] Inputs to feed were modelled using a generic salmon feed reported by Pelletier & Tyedmers (2007).

[c] A maintenance factor was added based on Tyedmers (2000), which assumed 25% of the original material and energy inputs would be used over the lifetime of that vessel for maintenance.

[d] Tyedmers et al. (in prep) found a potentially wide range of fuel efficiencies associated with purse seiners fishing for salmon in 2005, so a weighted mean based on catch volumes was employed in this case. Engine emissions were modified using the Lloyd’s Register set of emission factors for marine diesel engines

(Lloyd's Register, 1995). Lloyd's Register provides a set of emission factors more representative of the likely emissions of fishing vessel engines, and has previously been used in LCAs of seafood (Hospido & Tyedmers, 2005; Boyd, 2008).

Table 12. Inventory data for the processing phase of salmon fillet system per tonne frozen salmon fillet.

	Quantity	Source	Database
Alaska[a]			
Whole salmon (tonnes/tonne)	2.174	F. Ziegler (pers. comm. October 1st 2009)	N/A
Energy (MJ/tonne)[b]	2521	F. Ziegler (pers. comm. October 1st 2009)	
Coal	9%	Energy Information Administration (EIA) (2008)	EcoInvent: Electricity, hard coal, at power plant/US S
Natural Gas	51%	EIA (2008)	EcoInvent: Natural gas, burned in power plant/US S
Diesel	17%	EIA (2008)	EcoInvent: Diesel, burned in diesel-electric generating set/GLO S
Hydro[c]	22%	EIA (2008)	EcoInvent: Electricity, hydropower, at power plant/JP; CS; DK S
Unmarketed byproducts/ waste (tonnes/tonne)	1.174	F. Ziegler (pers. comm. October 1st 2009)	N/A
Marketed byproducts (tonnes/tonne)	0	F. Ziegler (pers. comm. October 1st 2009)	N/A
Storage (MJ/tonne)[d]	108	Magnussen (1993)	
Coal	9%	EIA (2008)	EcoInvent: Electricity, hard coal, at power plant/US S
Natural Gas	51%	EIA (2008)	EcoInvent: Natural gas, burned in power plant/US S
Diesel	17%	EIA (2008)	EcoInvent: Diesel, burned in diesel-electric generating set/GLO S
Hydro[c]	22%	EIA (2008)	EcoInvent: Electricity, hydropower, at power plant/JP; CS; DK S
China			

	Quantity	Source	Database
Transport[e]	6511	Dataloy AS, 2010	EcoInvent: Operation, transoceanic freight ship/OCE S
Whole salmon[f] (tonne/tonne)	1.923	D. Roe (pers. comm. February 15th, 2010)	N/A
Electricity (kWh/tonne)	391	Survey	
Coal	81%	International Energy Agency (IEA), 2007	EcoInvent: Hard coal, burned in power plant/CN S
Hydro	15%	IEA, 2007	EcoInvent: Electricity, hydropower, at power plant/JP; CS; DK S
Nuclear	2%	IEA, 2007	EcoInvent: Electricity, nuclear, at power plant/US; UCTE S
Gas	2%	IEA, 2007	EcoInvent: Natural gas, burned in power plant/US; UCTE S
Diesel (l/tonne)	6.87	Survey	Franklin: Diesel equipment (gal)
Gasoline (l/tonne)	1.38	Survey	Franklin: Gasoline equipment (gal)
Byproducts (tonne/tonne)	0.28	Survey	N/A
Storage[d] (MJ/tonne)	108 total	Magnussen (1993)	
Coal	81%	IEA, 2007	EcoInvent: Hard coal, burned in power plant/CN S
Hydro	15%	IEA, 2007	EcoInvent: Electricity, hydropower, at power plant/JP; CS; DK S
Nuclear	2%	IEA, 2007	EcoInvent: Electricity, nuclear, at power plant/US; UCTE S
Gas	2%	IEA, 2007	EcoInvent: Natural gas, burned in power plant/US; UCTE S
Alaska and China			
Packaging (kg/tonne)			
Carton (cardboard)	15.66	Survey	EcoInvent: Packaging, corrugated board, mixed fibre, single wall, at plant/RER S
Plastic bag	0.18	Survey	EcoInvent: Packaging film, LDPE, at plant/RER S
Liner (83% cardboard, 17% wax)	10.3	Survey	EcoInvent: Kraft paper, unbleached, at plant/RER S; Paraffin, at plant/RER S

[a] Inputs for processing were based on data collected from Norwegian and Scottish salmon processors and modified for an Alaskan energy mix. Yield of salmon fillets from live-weight was set at 46% for machine processing based on this data. Although these surveys indicated that byproducts of processing are disposed of in Norway and Scotland, we assumed that they were utilized in this model.

[b] Source specific inputs were calculated using the Alaskan energy mix underpinning electricity generation state-wide.

[c] A model for Alaskan hydropower was not available and so an average of life cycle inputs and impacts associated with European hydroelectric power generation was used.

[d] Due to the short fishing season, salmon may be stored for a large portion of the year. We modelled 6 months of storage in Alaska.

[e] Marine transport distances from Akutan, Cordova, and Sitka Alaska to Qingdao, China were averaged.

[f] Energy inputs to fillet processing in China were collected for a facility processing cod and haddock. It was assumed inputs to salmon processing would be similar. Salmon fillet yield (52%) was obtained from representatives at Findus and confirmed by previous research (Crapo, Paust & Babbit, 1993). Byproducts were assumed not to be wasted, based on the Chinese processing data.

Table 13. Inventory data for the final transportation phase of salmon system in terms of one tonne of salmon fillet delivered.

	Quantity	Source	Database
Alaska			
Ground[a] (tkm)	100	N/A	EcoInvent: Transport, lorry 16-32t, EURO4/RER S
Sea[b] (tkm)	15,240	Dataloy AS, 2010	EcoInvent: Transport, transoceanic freight ship/OCE S
China			
Ground[c] (tkm)	600	Survey (Cod)[a]	EcoInvent: Transport, lorry 16-32t, EURO4/RER S
Sea[d] (tkm)	17,648	Dataloy AS, 2010	EcoInvent: Transport, transoceanic freight ship/OCE S

[a] Estimate was made based on the assumption that processing facilities are unlikely to be located far from the dock where product may be shipped.

[b] Average of shipping from Akutan, Cordova or Sitka, Alaska to Grimsby, UK.

[c] Average distance based on the cod system, representing a 400 km trip with half of these trucks returning empty.

[d] Assume shipping from Qindao, China to Grimsby, UK.

4.3.2 Impact Assessment

Complete details regarding life cycle impacts associated with the fishing, processing, and transportation phases of frozen salmon fillets may be found in Appendix C.

In the case of fillets processed in Alaska and delivered to the UK, there was no clear pattern in the results: no single phase made the largest contribution to all the impact categories studied, although processing was never the largest contributor to any of the categories (Figure 15). This is in part due to the relative fuel efficiency of the purse seine pink salmon fishery: direct fuel inputs to fishing are relatively low compared to the values reported in other seafood research (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006). Inputs to processing however are not thought to be low relative to the average, and indeed contributions to climate change resulting from processing in Alaska were greater than that for comparable processing activity reported in Chapter 2. This is despite identical impacts in terms of cumulative energy demand, and therefore likely stems from the emissions intensity of electricity generation in Alaska compared to Iceland. Overall, the Alaskan-processed salmon system was found to contribute 0.48 kg CO_2 eq per kg of fillet in Grimsby.

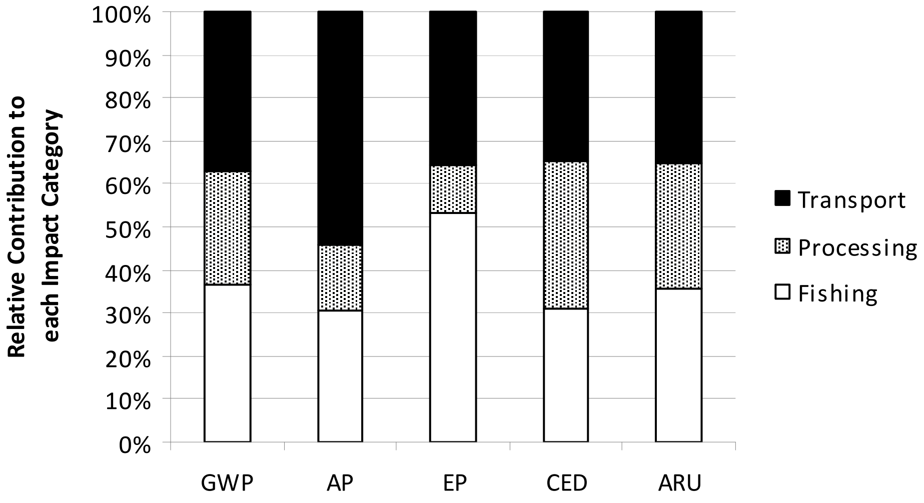

Figure 15. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) impact categories made by fishing, processing, and final transportation in the life cycle of a frozen pink salmon fillet processed in Alaska and delivered to Grimsby, UK.

In the case of fillets processed in China, processing is more important (Figure 16). Manual processing in China doubles the potential climate change impact compared to fillets processed by machine in Alaska. Greater electricity inputs required for processing in China (2.0 MJ eq compared to 1.6 MJ eq for processing in Alaska) and the greater greenhouse gas emissions associated with producing electricity from coal in China as opposed to natural gas in Alaska explain this difference. The importance of the method of electricity generation can be seen particularly when examining the data for impacts from storage: storage in China results in a 40% increase in contributions to climate change compared to an identical period of storage in Alaska.

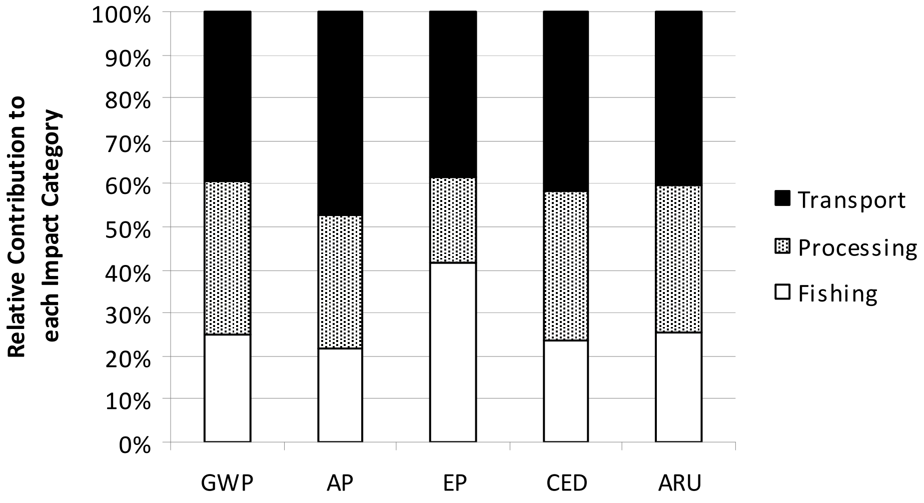

Figure 16. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) impact categories made by fishing, processing, and final transportation in the life cycle of a frozen pink salmon fillet processed in China and delivered to Grimsby, UK.

With reference to the food miles concept, it is interesting that less than one third of the difference in emissions between the Alaskan and the Chinese system resulted from additional transportation in this supply chain. Furthermore, the greatest proportion of this increase is associated with the increase in ground transportation from 100 to 600 km, rather than the much longer distance travelled by sea. Overall, the system in which salmon are processed in China was found to contribute 0.72 kg CO_2 eq per kg fillet delivered in Grimsby, 50% more than the alternative.

Returning to the fishing phase of both systems, the hatchery was not found to contribute a great deal to any of the impact categories (Figure 17), and contributed only 0.0059 kg CO_2 eq/ kg live-weight salmon produced (representing only 3% of total emissions up to the dock). Direct fuel inputs dominated the fishing phase, contributing 0.17 kg CO_2 eq / kg live-weight salmon (fully 94% of the total GHG emissions up to the dock).

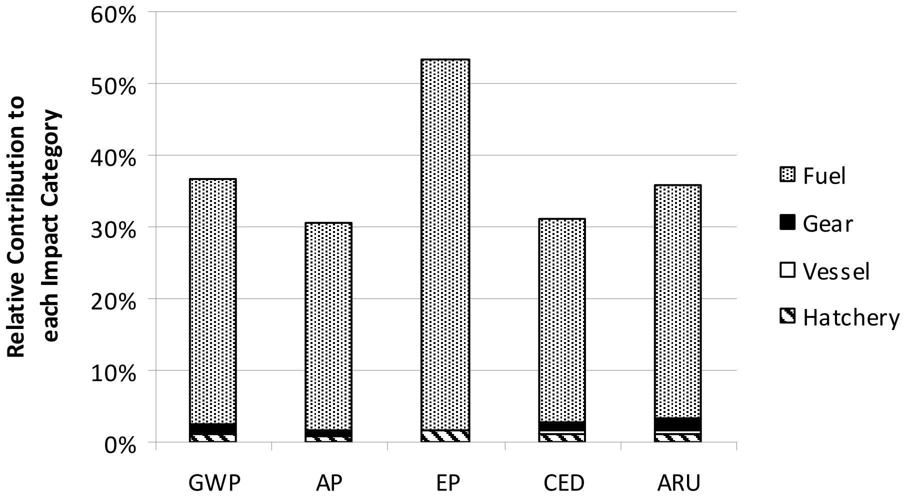

Figure 17. Relative contributions to global warming (GWP), acidification (AP), and eutrophication potential (EP) as well as cumulative energy demand (CED) and abiotic resource use (ARU) impact categories made by inputs to the fishing phase for pink salmon.

Unlike the other impact categories, biotic resource use is relevant only for the fishing effort. This fishery was found to require a NPP of just over 27 tonnes C per tonne of pink salmon. Biotic resource use was calculated using the trophic level for pink salmon of 3.39 ± 0.52.

4.3.3 Data Limitations

Fuel input data representing 33 Alaskan based purse seiners were collected by Tyedmers et al. (in prep) in their analysis of the broader salmon industry. Considerable variability exists within this data, and as such the weighted mean based on catch volume used in this study may not be representative of many individual boats within the fleet.

In addition, no data were available for Chinese-based salmon processing. Instead, estimates had to be made of major inputs based on an understanding of inputs to a single Chinese-based whitefish processing plant. Moreover, given the lack of specific insight into Chinese salmon processing, data regarding ground transportation in China should best be regarded as a "best guess." As such results should be treated as a broad stroke estimates of the impact potentials and differences between the systems, however further data are required to confirm and refine overall results.

4.3.4 Sensitivity and Scenario Analysis

Impact of Increasing Fuel Inputs

As discussed, to cope with the wide range of fuel intensities found by Tyedmers et al. (in prep), a weighted mean based on catch volume was used (56 l/tonne). Although this is relatively fuel efficient on the scale of fisheries globally (see for example Watanabe & Okubo, 1989, Tyedmers, 2004, Schau et al., 2009), direct fuel inputs were still an important driver of overall impacts (accounting for 35% of contributions to climate change in the case of Alaskan-processed fillets, and 24% in the case of Chinese-processed fillets). To test the sensitivity of our results to the fuel intensity of the fishery, we conducted an analysis in which the arithmetic mean of the data collected by Tyedmers et al. (in prep) was used (76 l/tonne). When fuel inputs were increased almost 36%, life cycle greenhouse gas emissions increase by 12% per kg of Alaskan-processed fillet delivered to the UK, and 8% per kg of Chinese-processed fillet.

Impact of Directing All Co-Products to Waste

In the base case model, impacts were allocated by mass regardless of the fate or value of co-products, provided these products were not true waste (i.e. disposed of at sea or landfilled). However, it was a subjective choice to allocate impacts to all products regardless of whether they were marketed for human consumption or not, and allocation can have an important impact on LCA results (Ayer et al., 2007; Boyd, 2008). For this reason a sensitivity analysis was conducted where impacts were allocated only to fillets (the only marketed product of processing).

When co-products of fillet processing are treated as waste, contributions to climate change nearly double in the case of Alaskan-processed fillets to just over 0.8 kg CO_2 eq/ kg fillet delivered to the UK. Impacts associated with Chinese-processed fillets increase by 50% to 1.1 kg CO_2 eq/ kg fillet delivered to the UK. The Chinese system is less sensitive to the change in allocation in part because fillet yield in China is greater (52%) compared to fillet yield in Alaska (46%).

Impact of Increasing Hatchery-Origin Fish in the Catch.

Currently, a substantial fraction (approximately 44%) of wild pink salmon caught in Alaska originates in hatcheries, and it is thought that these hatcheries may negatively impact wild stocks (Knapp et al., 2007). Just as importantly, the relative importance of hatchery-origin pink salmon has increased steadily in recent decades (Knapp et al., 2007). In this scenario analysis, I test what the effect might be of increasing the role that hatchery production might play on life cycle impacts of the resulting products by increasing all hatchery-related feed and energy inputs by 25% per tonne of all pink salmon landed in the commercial fishery. This increase does increase the impacts associated with the hatchery phase of production, but only by 0.0015 kg CO_2 eq / kg salmon fillet, or less than 1% of the total contributions to climate change of either system.

4.4 DISCUSSION

Previous studies have found that the capture of wild pink salmon is among the least energy intense method of salmon provision compared to either farmed Atlantic salmon or the capture of other wild Pacific salmon species (Tyedmers et al., 2007). This may be because of the abundance of pink salmon (Knapp et al., 2007) and the apparent responsible management of this fishery (Knapp et al., 2007, Driscoll & Tyedmers, 2009). The fuel efficiency we observed (56 l/tonne) may also owe to the gear employed (purse-seine). Purse-seine gear have been found to be relatively fuel efficient compared to the other gears used in the pink salmon fishery, gillnet and troll (Tyedmers, 2004). Indeed, the lowest fuel intensities reported for capture fisheries worldwide have all used purse seine gear (Tyedmers, 2004).

The relatively low importance of the fishing phase, in contrast to previous seafood studies (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006) is due in part to this fuel efficiency. The observed pattern is particularly remarkable though as in this study the fishing phase included inputs from hatcheries. Although 44% of “wild”- caught pink salmon originate in hatcheries (Knapp et al., 2007), inputs to smolts are apparently sufficiently low that this does not result in a large increase in the contributions to climate change associated with the final product. This is perhaps not surprising when it is understood that the 5500 smolts reportedly needed to support each tonne of wild catch amount to only 3.3 kg of smolts per tonne of caught fish. The sensitivity analysis we conducted confirms that even if the "wild" fishery were to increase their dependence on hatchery-raised fish, the implications for contributions to climate change would be low. These results may be applicable to other hatchery-supported fisheries (e.g. chum salmon) as inputs to hatcheries for other species of salmon may be similar (Anonymous, pers. comm. October 30th, 2009), however it is likely that pink salmon smolts receive some of the lowest hatchery feed inputs of all commercial salmon species (Tyedmers, 2000).

The low impact of the fishing phase means that the processing and transportation of fillets can have a relatively large impact on the total potential environmental impact of the system. It may therefore be important for future research not to overlook these phases, particularly in fuel efficient fisheries where few gains in environmental performance can be made through improving the efficiency of the fishing fleet. The comparison of the processing stream in China to the processing stream in Alaska offers an interesting insight into potential gains in this area: reducing energy inputs and ensuring energy inputs come from a source that minimizes emissions are the most important areas of focus to minimize contributions to climate change from the processing phase. Energy efficiency can be improved through a number of measures from modernizing and optimizing processing equipment to reducing lighting hours and installing programmable thermostats (Kelleher et al., 2001). As an additional benefit, Kelleher et al. (2001) have found that significant financial savings in terms of both energy and labour can be made by improving efficiency and productivity in seafood processing plants.

The observed impacts associated with storage (i.e. 6 months of freezing) also provide an interesting contrast with previous research. Ziegler (2001) and Winther et al. (2009) have each suggested that long period of frozen storage can be responsible for a commensurately large potential contribution to climate change and other impact categories. Our study did not confirm this, with storage accounting for less than 2% of the total impact in each system (2009). This is important to consider in light of the fact that salmon farming has been successful in part due to the ability to provide fresh fish on demand year round, unlike the seasonal fishery (Pelletier et al., 2009). The evidence provided in this study indicates that frozen fillets could be provided from the wild fishery year round without resulting in large storage-related contributions to climate change. Of course, fresh product is often valued over frozen (Fiskerifond, 2004), but there is evidence that taste and other qualities can be maintained with advanced freezing techniques (Boknaes et al., 2007) and as such consumer education may reduce the demand for fresh seafood. This transition from fresh to frozen products could potentially have a large positive impact on the climate change impact of the seafood industry, if freezing makes relatively low contributions to climate change (in terms of both energy and refrigerants, as shown here and in Chapter 2), while the air freight of fresh products makes large contributions (as seen in Chapter 2).

Overall, the provision of pink salmon was found to potentially offer the lowest impact fillet supply chain of the six studied in terms of contributions to climate change. The positive performance of this supply chain may be secured by ongoing conservative management and energy efficiency improvements during processing.

CHAPTER 5 DISCUSSION

Minimizing impacts associated with the provision of food can make a potentially important contribution to minimizing anthropogenic contributions to climate change and other environmental impacts. This study found a range of possible impacts associated with various seafood products, demonstrating that not all fish fillets are created equal. The study also led to some conclusions regarding LCA practice, and promising directions for new research.

5.1 COMPARING SYSTEMS

The contributions to climate change of all but one of the fillets studied fell in the range of approximately 0.5 to 1 kg CO_2 eq per kg of fillet. The exception was fresh cod fillets which were found to have a global warming potential of 2.6 kg CO_2 eq per kg fillet delivered to the UK (Figure 18). Air transport is the culprit in this case: the potential impact resulting from air transport from Iceland to the UK was greater than the potential impact associated with the complete supply chain of each of the other products studied.

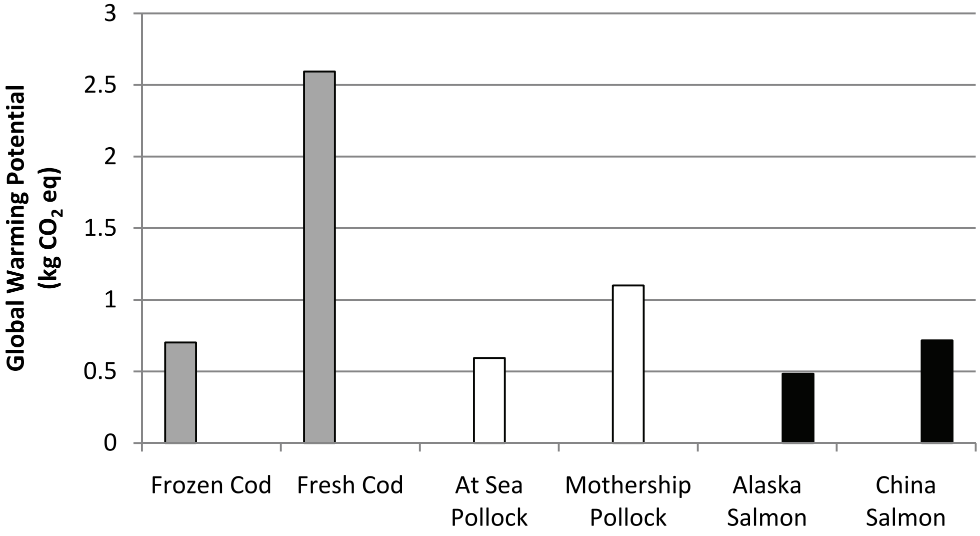

Figure 18. Life cycle greenhouse gas emissions associated with the six seafood product chains modeled.

Some of the remaining variation among products can be traced to differences in the fuel efficiency of the fisheries, ranging from 36 l/tonne of catch (pollock) to 125 l/tonne (cod). All the fisheries studied fall well below the average of over 500 l/tonne reported for twenty nine North Atlantic fisheries targeting demersal species by Tyedmers (2004). This discrepancy as well as the variation observed within the pollock fishing fleet over time suggest that ongoing study and re-evaluation may be required to better reflect the current fuel efficiency of global fisheries.

Overall, both energy efficiency and energy source (i.e. fossil fuel vs. less carbon intense forms of energy such as geothermal power) were important factors in determining the greenhouse gas intensity of each system. For example, where electricity for processing came from an emissions-intense form of generation (such as coal power), contributions to climate change were relatively high, while low emissions forms of generations such as geothermal or hydropower performed much better.

The following sections describe possible opportunities for improvement applicable to all six systems under study. However it is important to note that while all six products may have different potential environmental impacts, they may not all be considered interchangeable. Variations in taste, texture, appearance and so on may affect the value each product provides its consumer, and as such these results do not completely reflect the tradeoffs inherent in any consumer choice. Fresh cod may make larger contributions to climate change than it's frozen counterpart, however it is possible that a decision maker may deem these impacts "worth" the incremental value of having fresh fish rather than frozen. An examination of these factors is beyond the scope of this study, however such factors are likely to influence how these results are used, and are therefore worth noting.

5.1.1 Fuel for Fishing

Although not as important as had been reported in previous studies (Eyjólfsdóttir et al., 2003; Ziegler et al., 2003; Hospido & Tyedmers, 2005; Thrane, 2006) emissions resulting from fuel use by fishing boats made some of the greatest impacts in all three seafood systems studied. Unfortunately, the data collected were not sufficiently detailed to allow for us to describe what portion of the fuel is used for steaming to and from fishing grounds, for active fishing effort, and so on. It would be interesting to collect these data so that we might be more specific about where impacts occur and how they could be avoided. Schau et al. (2008) for example found that 20% reductions in fuel consumption are possible by reducing the distance travelled to capture fish.

There are a variety of ways that the fuel efficiency of fishing boats can be improved. Maintaining the engine can be important for emissions in the long run (Ziegler & Hansson, 2003), while retrofitting with new engines can achieve 10% reductions in emissions due to improved fuel efficiency (Wilson, 1999; Ziegler & Hansson, 2003; Corbett, 2004; Eyjólfsdóttir et al., 2004; Thrane, 2004). Optimizing propeller size and efficiency can also make significant improvements (Corbett, 2004; Eyjólfsdóttir et al., 2004; Thrane, 2004; Schau et al., 2008). The speed at which the boat is operated (Ziegler & Hansson, 2003) is also a factor, as is the skill of the skipper (Ruttan & Tyedmers, 2007). Hull shape is another obvious factor in fuel efficiency (Hayman et al., 2000; Corbett, 2004; Eyjólfsdóttir et al., 2004; Schau et al., 2009), as is the condition of the hull (Wilson, 1999; Ziegler, 2003), and hull size (Tyedmers, 2001; Thrane, 2004). Smaller, more stream-lined boats, free of debris tend to be more fuel efficient. Some of these factors are interlinked; for example, modifications to hull shape may affect the ability of the boat to operate at an optimal speed even in rough weather (Friis et al., 2010).

The choice of gear has an unclear impact on fuel efficiency: One gear is not clearly likely to be less fuel intensive than another. However certain gear types may be more efficient under certain circumstances (see for example Driscoll & Tyedmers, 2009), and the size, type, and material resistance of gear are all possible considerations when examining fuel efficiency (Ziegler and Hansson, 2003; Eyjólfsdóttir et al., 2004). This study did not compare different forms of gear within any single fishery and as such it is difficult to comment on the relative fuel efficiency of each of the three gears studied. However the performance of each gear examined may benefit from the many efforts being made to design “low carbon” fishing gear. Lee et al., (2010) and Ivanovic & Nielsen (2010), for example, have examined designs for trawl nets that reduce drag while maintaining catch performance.

It is possible that future research may contribute to reducing the emissions from fuel used in fishing by making alternate fuels more feasible. Natural gas, hydrogen fuel cells, biodiesel and even wind have all been suggested (Arnason et al., 2001; Eyjólfsdóttir et al., 2004; Schau et al., 2008; Brabeck, 2010). For the time being at least, switching to low sulphur fuels can reduce sulphur emissions by up to 98% (Ziegler, 2003)

The health and management of fish stocks also plays a role in fuel efficiency (Tyedmers et al., 2005, Driscoll & Tyedmers, 2009). In each of Chapters 2 through 4 the point was made that ongoing conservative management of these fisheries may help to maintain their low fuel intensity by maintaining stocks at levels that can be efficiently fished and reducing the “race to fish.” While having healthy, well managed stocks can obviously help increase the fuel efficiency of the fishery (Ziegler & Hansson, 2003), fuel subsidies are an example of a fishery management strategy that can have the opposite effect by removing disincentives to fuel-intensive fishing practices (Sumaila et al., 2008). Thrane (2006) also argues that while a quota may be designed to limit over fishing, it can limit consumers ability to “vote with their feet” by favouring more environmentally friendly seafood choices.

While improving the fuel efficiency of the fleet seems like an obvious improvement for the industry, one must be cautious of avoiding a rebound effect wherein fishing intensity increases and stocks are depleted. Efficiency improvements must therefore, and as always, be matched by effective effort management. The possibility of positive tradeoffs must also be examined. Thrane (2004), for example, hypothesized that the most fuel intensive fisheries are those using active gear to target ground or shellfish (i.e. using beam or bottom trawl gear). As such, addressing fuel consumption may indirectly address other concerns such as seafloor impact, which are associated with the same kinds of gear.

5.1.2 Refrigeration

While Winther et al. (2009) found that refrigerants may be a large contributor to potential climate change impacts, little is known regarding the leakage rates of various refrigerants necessary to conduct this assessment. We found collecting these data difficult in our own study. As knowledge of this area increases, possible tradeoffs should be kept in mind.

Ciantar (2001), for example, suggested that switching to a refrigerant with a lower global warming potential may lead to increases in the energy consumption of the refrigeration system, which might offset this intended improvement. Further research regarding the impact of refrigerants in the seafood supply chain may reveal important opportunities for emission reductions.

The link between refrigeration and transportation is also a potentially interesting one. Increased availability of data that would allow the modeling of refrigeration during transportation would increase the ease with which this element of the supply chain may be included in future models. Furthermore, new technologies that extend the shelf life of fresh products (such a super cooling) may provide an opportunity to transport "fresh" products to market by sea, thus avoiding the large GHG emissions associated with air transport.

5.1.3 Transportation (Food Miles)

This study reveals that mode of transport is potentially more revealing than the distance travelled by a product: fillets shipped by sea from Alaska to the UK were found to have fewer potential impacts than products flown from Iceland, a relative neighbor. Vanek and Campbell (1999) have suggested that beyond consideration of the mode and distance, both the technical and operational efficiency of the transportation networks that service the seafood industry are important in determining its energy efficiency. Greater energy intensity may be due to a greater number of transitions between modes, more kilometres travelled, or both.

5.1.4 Processing and Packaging

Reducing energy intensity and sourcing energy from "environmentally friendly" sources such as hydro are both key steps to limit contributions to climate change. This principle can be applied to the selection of packaging materials (Thrane, 2006), as well as efficiency improvements throughout processing activity (Kelleher et al., 2001; IFC, 2007).

5.2 COMPARISONS WITH OTHER STUDIES

One challenge facing practitioners of LCA is that there remains much variability in how the method is applied. Two studies examining the impacts associated with the provision of cod fillets, for example, may select a different functional unit, a different impact assessment method, set different boundaries for data collection, and apply different allocation methods. As such, it can be difficult to compare the results of two studies and draw meaningful conclusions. Discussion that leads to greater consistency in the approach used (at least by researchers using LCA to examine seafood products) would greatly increase our understanding of how different products compare relative to one another. In the absence of this consistent approach sensitivity and scenario analysis are important components of LCA practice, offering a way to test the results found in a particular study and, if confirmed, allow some comparison with other research.

5.3 IMPACT CATEGORIES

While this study is focused on contributions to climate change, we also evaluated a set of other environmental impact categories in our analysis: acidification and eutrophication potential, cumulative energy demand, abiotic resource use and biotic resource use. Our results in each of these categories may prove interesting for other researchers interested in the broader range of impacts of the seafood supply chain. For our purposes, however, it is interesting to note that in most cases the pattern of impacts in each of these other impact categories tracked the pattern found for global warming potential. In other words, it would appear that direct energy inputs are driving a majority of these impacts, not only global warming potential. Notable exceptions include where energy is derived from a renewable source, such as hydropower or geothermal. In this case cumulative energy demand remains high, but contributions to all other impact categories are reduced. Another exception are contributions to the biotic resource use impact category, which necessarily occur exclusively during the fishing phase and relate entirely to the living resource inputs to the systems under study.

5.3.1 Biotic Resource Use

Although biotic resources are “renewable,” concern regarding limits to growth includes whether we have exceeded the natural systems’ ability to regenerate biotic resources to keep pace with our ability to consume them. The seafood supply chain relies directly on the provision of biotic resources, so it is perhaps particularly important to evaluate this potential impact as part of any discussion of the environmental impact of this industry.

Cod was found to require a far higher net primary productivity than either pollock or salmon. The relatively large proportion of bycatch, combined with the input of bait, can account for this. However trophic levels are bracketed by a high degree of uncertainty, and as a result the average biotic resource use reported in our study falls within a wide possible range. When this range is considered, it is more difficult to conclude which fishery requires the greatest net primary productivity. However in general the method suggests that seafood products that rely on species of a higher trophic level, which result in large proportions of unmarketed bycatch, and/or use bait are likely to require greater inputs of biotic resources than species that do not share these characteristics.

Biotic resource use was the only impact category assessed that does not rely on industrial energy inputs, and so gives us a novel approach to examining the sustainability of seafood. However, it is also the impact category with the least developed impact assessment methodology: only one method of assessment is available, and this method results in a potentially wide range of values. More work on developing impact assessment methods for this category would provide a useful insight into the sustainability of the industry.

5.4 LABELING OF SEAFOOD

This study was commissioned in part because of growing consumer interest in understanding the environmental impact of seafood and their desire to be able to select more “sustainable” product options. This research demonstrates that many of the life cycle environmental impacts of seafood products rely heavily on the energy intensity of the fishing effort, but also on the energy inputs to processing, and the mode of final transportation. Labels which rely on "food miles" oversimplify the issue. Furthermore, few species of fish follow only one possible supply chain to market. For this reason, selecting seafood products purely on the basis of species or source locale similarly overlooks a variety of important contributors to the impact of that product. Unfortunately, there is no "one size fits all" solution to distinguishing among seafood products, however this study suggests there are a few key areas that can be optimized to avoid a large portion of the potential environmental impacts. This information is valuable for producers of seafood who would like to brand themselves as providing more sustainable seafood choices.

5.5 LIMITATIONS OF THE STUDY

The challenges in collecting data have been reviewed for each of the systems under study in Chapters 2-4. It is possible that data collection may have been easier had I been able to travel to the locations where these industries operate. However in the author's opinion it was in fact limitations on the available time of my prospective respondents and apparent concerns regarding compromising competitive advantage that were the greatest challenges facing my attempts to collect data. This is unfortunate since in many cases the data were readily available to those in industry that were contacted, but my lack of access prevented this study from providing more representative results. Nonetheless, I hope these results present at least an initial look at the extent and source of impacts associated with six comparable fillet products. Greater access to data would, in my opinion, provide the industry with valuable insights into their operations as an industry, and identify key opportunities for improvement.

Finally, it is important to note that the analysis did not capture all the environmental, social, or economic impacts associated with these supply chains. Indeed, it would have been impossible to do so given the time, data, and methods available. However this fact does not lessen the importance of results that are captured, and I am optimistic these findings will contribute to further research on these systems and other seafood products.

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APPENDIX A Sample Questionaire: Catching

Material and Energy Input Survey for Alaskan Pollock

If you would prefer to use units other than those specified (for example, litres rather than gallons), please note this in your responses.

Fishing

Please answer whichever one (A or B) of the following sets of questions is most applicable to you:

A. What was your total catch of pollock in 2008?

A. What proportion and weight of other species do you catch?

Species:_______ Mass: _____lbs
Species:_______ Mass: _____lbs
Species:_______ Mass: _____lbs
Species:_______ Mass: _____lbs
Species:_______ Mass: _____lbs

A. How much fuel did you burn in 2008?

Diesel: __________ Gallons
Gasoline: __________ Gallons
Other __________: __________ Gallons

OR

B. How many days do you usually spend at sea per year?

______ days OR _____ days/trip ______ trips/year

B. How much fuel do you burn, per trip or per day?

Diesel:

__________ Gallons per trip OR __________ Gallons per day

Gasoline:

__________ Gallons per trip OR __________ Gallons per day

Other __________:

__________ Gallons per trip OR __________ Gallons per day

B. What is your average catch per trip, or per day?

___________ tones per trip OR ___________ tones per day

What is the size of your boat?

Length: _______ ft Beam: ________ ft Gross tonnage: ________

What is the primary hull material?

Fiberglass Steel Aluminum Wood

Combination (please specify proportions):

From what company did you purchase your boat?

How old is your boat, and when do you expect to replace it?

Age (years): ________ Anticipated Year of Replacement: __________

What is the horsepower of the main propulsive engine? ______ HP

Who is your catch delivered to?

How far and by what mode does your catch travel from your boat to the processing facility?

a. ______ miles Truck
b. ______ miles Barge/ship
c. ______ miles Ferry
d. ______ miles Helicopter

e. ______ miles Well-boat

f. ______ miles Air-freight

How is your catch stored before delivery to the processing facility?

Packaging: (please state proportion e.g. tones/tone whole fish)

Refrigerant: (please state proportion e.g. tones/tone whole fish)

Duration of storage:

In what form do you deliver your Alaskan Pollock to the mothership?

a. whole
b. bled
c. bled, gutted, head-on
d. bled, gutted, head-off
e. Other (please specify):

What is the how often do you replace your active fishing gear?

___________ years

What is the fate of fishing gear no longer useful for fishing?

a. Disposed of
b. Recycled (please describe)

In the following Table please provide an indication of the amount of major material inputs used in the construction of a typical pollock trawl net:

Type of material	Pounds
Steel	
Lead	
Line (please indicate type)	
Other (please indicate type)	

Do you use anti-fouling paint on your boat?

If so, how much anti-fouling paint do you apply yearly?

_________ Gallons yearly

Thank you for your assistance with this survey. If there is any material or energy input to the catching, processing, storage, packaging or transport of pollock fillet that you think we may have overlooked, please indicate it here along with your name and contact details so that we may follow up with you directly to better understand what we've overlooked.

APPENDIX B   Sample Questionaire: Processing

Material and Energy Input Survey for Line-Caught Icelandic Cod: Processing Only

If you would prefer to use units other than those specified (for example, gallons rather than litres), please note this in your responses.

Where are you located?

Does your plant use a generator to produce electricity? If so, please specify the type, and the quantity of electricity produced by this generator annually:

How much energy does your facility use annually (in 2008)?

a. diesel? __________________litres
b. gasoline? ________________litres
c. electricity (from the grid) ___________________kWh
d. fuel oil____________m^3
e. natural gas___________kg or_____________m^3

What proportion of your energy use would you estimate is used directly for processing cod fillets? (i.e. excluding processing other species, or general electricity use for lights, computers, etc.)

What is the approximate mass and composition of the large infrastructure used in your facility? (e.g. building, processing machinery, storage materials, etc.)

How often is the above infrastructure replaced?

How much freshwater does your facility use annually (in 2008)?

What other detergents or chemicals are used during processing?

Name: ___________ Quantity: ___________
Name: ___________ Quantity: ___________
Name: ___________ Quantity: ___________
Name: ___________ Quantity: ___________

How many tonnes of live weight cod were processed in 2008?

___________ tonnes

How does product enter your facility?

Unprocessed Bled Gutted head on Gutted head off

What is the average product yield (dress-out %) from live weight?

Bled_______ gutted head on_________ gutted head off_________

What is the average yield of fillet from this form of fish?

Regarding by-products (i.e. marketed fractions) from processing

a. What is the mass of marketed by-products?

b. What is the ratio by weight of fillets to marketed by-products?

c. What is the ratio by value of fillets to marketed by-products?

d. Please indicated the uses of by-products generated and their relative proportions:

__________ %
__________%
__________%

What is the fate of wastes from processing? If more than one fate, please provide proportions and details:

___________%
___________%
___________%
___________%

How are solid processing wastes transported and how far?

___________ km Large Truck
___________ km Small Truck
___________ km Other: _________

Is liquid waste treated on site, disposed of, or sent for municipal treatment?

Packaging & Storage

In what form are fillets frozen? (e.g. 50 pound blocks, etc.)

How are fillets packaged?

Material: ________ Amount: _________ kg
Material: ________ Amount: _________ kg
Material: ________ Amount: _________ kg
Material: ________ Amount: _________ kg

Where is this material sourced from?

How are processed products stored?

Cooling agent (e.g. ice, R22, R404a, NH3): ________
Quantity: _______ (please specify units)

How long are processed products stored for before transport to Grimsby?

What proportion of the products stored are cod fillets?

Final Transport

Where are the cod fillets transported to after processing?

a. Direct to Grimsby, UK
b. Other: __________ (please describe the route to the best of your knowledge)

How far are they transported?

Mode:
Distance:
Mode:
Distance:
Mode:
Distance:

Are other products (seafood or other) transported with the cod fillets? If so, please specify the relative proportions if known.

Thank you for your assistance with this survey. If there is any material or energy input to the catching, processing, storage, packaging or transport of cod fillet that you think we may have overlooked, please indicate it here along with your name and contact details so that we may follow up with you directly to better understand what we’ve overlooked.

APPENDIX C   Detailed Impact Assessment Results

Table 1. Impact assessment results for cod system in terms of 1 kg of fillet.

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
Fishing	Vessel	0.0078	negligible	negligible	0.17	negligible	N/A
	Gear	0.016	negligible	negligible	0.25	0.00011	N/A
	Bait (Mackerel)	0.016	0.00018	negligible	0.29	0.00010	N/A
	Bait (Squid)	0.046	0.00054	0.00011	0.67	0.00030	N/A
	Fuel (Fishing)	0.45	0.0053	0.0012	6.3	0.0030	N/A
	Refrigeration	0.032	0.00033	negligible	0.47	0.00030	N/A
Processing	Energy	negligible	negligible	negligible	1.6	negligible	N/A
	Packaging	0.027	0.00012	negligible	1.1	0.00023	N/A
Transport	Ground	0.092	0.00035	negligible	1.6	0.00066	N/A
	Sea[a]	0.018	0.00039	0.000033	0.28	0.00012	N/A
	Air[a]	1.9	0.0073	0.0013	30	0.013	N/A
	TOTAL Frozen[a]	0.70	0.0072	0.0013	13	0.0048	131,157
	TOTAL Fresh[a]	2.6	0.014	0.0026	42	0.017	131,157

[a] The only distance between the fresh and frozen fillet systems (in this model) are that frozen fillets are transported by sea, while fresh fillets are transported by air.

Table 2. Impact assessment results for pollock trawler/mothership system in terms of 1 kg of fillet.

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
Fishing	Vessel	negligible	negligible	negligible	negligible	negligible	N/A
	Gear	negligible	negligible	negligible	negligible	negligible	N/A
	Fuel	0.11	0.0013	0.00028	1.5	0.000707	N/A
Mothership	Vessel	0.00086	negligible	negligible	0.14	0.000075	N/A
	Diesel	0.11	0.0013	0.00030	1.6	0.00075	N/A
	Heavy fuel	0.29	0.0031	negligible	4.4	0.0019	N/A
Transport	Sea	0.088	0.0019	0.00017	1.3	0.00059	N/A
Processing	Energy	0.18	0.0019	0.000070	2.0	0.0011	N/A
	Packaging	0.027	0.00012	negligible	1.1	0.00023	N/A
Transport	Ground	0.092	0.00035	0.000070	1.6	0.00066	N/A
	Sea	0.18	0.0039	0.00033	2.5	0.0012	N/A
TOTAL		1.1	0.014	0.0014	16.5	0.0072	23,283

Table 3. Impact assessment results for pollock catcher/processor system in terms of 1 kg of fillet.

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
Fishing	Vessel	0.0097	negligible	0.0000072	0.16	0.000011	N/A
	Gear	negligible	negligible	negligible	negligible	negligible	N/A
	Fuel	0.30	0.0036	0.00081	4.2	0.0020	N/A
	Packaging	0.027	0.00012	0.000033	1.1	0.00023	N/A
Transport	Ground	0.092	0.00035	0.000068	1.6	0.00066	N/A
	Sea	0.16	0.0036	0.00031	2.6	0.0011	N/A
TOTAL		0.59	0.0077	0.0012	9.6	0.0040	23,283

Table 4. Impact assessment results for salmon processed in Alaska in terms of 1 kg of fillet.

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
Fishing	Hatchery	0.0059	0.000059	0.000014	0.083	0.000036	N/A
	Vessel	negligible	negligible	negligible	0.051	0.000022	N/A
	Gear	0.0057	0.000046	negligible	0.10	0.000056	N/A
	Fuel	0.17	0.0020	0.00044	2.3	0.0011	N/A
Processing	Energy	0.092	0.00083	0.000054	1.6	0.00070	N/A
	Storage	0.0086	0.000077	0.0000051	0.15	0.000065	N/A
	Packaging	0.027	0.00012	0.000033	1.1	0.00023	N/A
Transport	Ground	0.015	0.000058	negligible	0.26	0.00011	N/A
	Sea	0.16	0.0036	0.00031	2.6	0.0011	N/A
TOTAL		0.48	0.0068	0.00085	8.2	0.0034	27,275

Table 5. Impact assessment results for salmon processed in China in terms of 1 kg of fillet.

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
Fishing	Hatchery	0.0059	0.000059	0.000014	0.083	0.000036	N/A
	Vessel	negligible	negligible	negligible	0.051	0.000022	N/A
	Gear	0.0057	0.000046	negligible	0.10	0.000056	N/A
	Fuel	0.17	0.0020	0.00044	2.3	0.0011	N/A
Processing	Energy	0.18	0.0019	0.00012	2.0	0.0011	N/A
	Storage	0.012	0.00013	negligible	0.13	0.000074	N/A
	Packaging	0.027	0.00012	0.000033	1.1	0.00023	N/A

Phase		GWP (kg CO_2 eq)	AP (kg SO_2 eq)	EP (kg PO_4 eq)	CED (MJ)	ARU (kg Sb eq)	BRU (kg C)
	Transport to China	0.036	0.00080	0.000068	0.58	0.00024	N/A
Transport	Ground	0.092	0.00035	0.000068	1.6	0.00066	N/A
	Sea	0.19	0.0042	0.00035	3	0.0013	N/A
TOTAL		0.72	0.0095	0.0011	11	0.0048	27,275