Review of life cycle assessment research on products derived from fisheries and aquaculture:

A report for Seafish as part of the collective action to address greenhouse gas emissions in seafood.

Final Report

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Introduction

Measuring, understanding and improving the greenhouse gas (GHG) emissions, or carbon footprint, of fishery- and aquaculture-derived products is an important part of the seafood industry's efforts to alleviate environmental burden, label and market products to consumers, meet government regulations, and improve long-term environmental and economic sustainability. To this end, life cycle assessment (LCA) has been increasingly applied in recent years to analyze the emissions of GHGs, as well as other substances of environmental concern, associated with seafood supply chains (Ziegler, 2006b; Pelletier & Tyedmers, 2008; Thrane *et al.*, 2009).

To help expand the use of LCA to measure and improve seafood systems, Seafish, Dalhousie University, the Food and Agriculture Organization of the United Nations (FAO), and UK seafood processors have partnered to explore LCA and carbon footprint methodologies, develop a methodological standard, and apply this standard to a number of key UK seafood supply chains. To support this effort, a review of existing literature was carried out to gather, synthesize and summarize the range of available reports and studies regarding GHG emissions from seafood supply chains. This review is intended to:

- Provide an understanding of the range of LCA application to fisheries and culture systems, and the types of systems that have received the most attention
- Identify patterns in the literature based on study parameters, methodological choices, *etc.*
- Summarize results from existing studies and identify major patterns in GHG intensity and contributions to GHG emissions from different life cycle stages of products
- Identify gaps in the literature, including insufficient understanding related to certain species, production systems, life cycle stages, *etc.*

This review is not intended to judge the quality, rigour or confidence in individual studies. Nor does it argue in favour or against certain methodological choices; for instance, the choice of allocation procedure, or the use of mid-point or end-point indicators of impact. Rather, it is intended to be a detailed summary of LCA literature examining fishery- and aquaculture-derived products.

This report describes the scope of the review and the methods of analysis, briefly discusses major patterns and findings, and presents a number of gaps in the literature where additional work is required. Appendix A provides a full list of LCA case studies included in the review, appendix B provides a descriptive list of the points of interest used for the review, and appendix C contains detailed results of the review, broken down by system type: seafood products from fisheries; seafood products from aquaculture; aquaculture feeds; and other products from fisheries and aquaculture. Appendix D provides a breakdown of fuel use intensity (litres per tonne of landings) for a number of species-, gear- and location-specific fisheries, as extracted from a database of fisheries fuel use studies.

Scope of review and methods of synthesis

Reports and studies included in the review were identified and collected via:

- Internet search engines (*e.g.* Google Scholar)
- Journal databases (Scopus and ScienceDirect)
- Thesis databases
- Bibliographic searches
- Conference proceedings

Searches identified studies relating to 'fisheries', 'aquaculture' and 'seafood', and internet and database searches used keywords such as 'life cycle assessment', 'LCA', 'carbon footprint', 'fuel use', 'fuel consumption', 'energy use' and 'greenhouse gases'.

The review included only those studies which were published, completed or undertaken since 2000[1], and focused on LCA case studies or carbon footprint studies that applied a life cycle approach. Supply chains with final products derived from aquaculture or fishing activities were included, while supply chains with resulting products related to the seafood industry but not actually derived from fisheries or aquaculture were not; for example, LCAs of seafood packaging

[1] Some studies published since 2000 report data collected earlier, and those studies are still included here (*e.g.* Ziegler *et al.*, 2003). As well, it is important to note that many secondary sources of data, including life cycle inventory databases, include data from prior to 2000.

materials (*e.g.* Williams, 2011) and seafood transportation methods (*e.g.* Emanuelsson *et al.*, 2010) were excluded. While these studies are relevant and can help guide decision-making processes regarding additional activities (e.g. packaging choices), their inclusion would demand the consideration of numerous additional relevant studies of packaging materials, transportation modes and other activities beyond the scope of this study. Case studies of aquaculture feeds were included, in part because they typically include inputs from fisheries, and also because they contribute substantially to the life cycle GHG emissions of many cultured species. Qualitative assessments of seafood products were not included (*e.g.* Mungkung & Clift, 2003), nor were social or economic life cycle studies (*e.g.* Kruse *et al.*, 2009).

In addition to life cycle assessments and carbon footprint studies, fishery fuel use studies were included (*e.g.* fuel use intensity in litres per tonne of landings by species and gear) due to the relevance of fuel consumption to fisheries supply chains. The primary source of these studies was a 'Fisheries and Energy Use Database' created and managed by Dr. Peter Tyedmers at Dalhousie University in Halifax, Nova Scotia (pers. comm., Peter Tyedmers, 2011). This database includes publicly available fuel consumption studies as well as numerous unpublished analyses and was most recently updated in 2011. Similarly to the LCA studies, only energy use studies completed, undertaken and/or published since 2000 are included in this review.

After literature collection was completed, a list of case studies was produced. In some cases, a single study yielded several case studies; these were considered to be unique if they assessed a different species or production method based on primary data. Scenario analyses (*i.e.* assessing the effect of a hypothetical change in the system, such as the transport mode) were not considered to be unique case studies. In cases where multiple articles or reports addressed the same case study, it was treated as a single case study and the source materials were noted. If, in these cases, data conflicted between articles or reports, preference was given to information and values from peer-reviewed journal articles.

Case studies were categorized by general type of product or system (fishery, aquaculture, *etc.*), class of species (shellfish, whitefish, *etc.*), and species. For fish feed studies, cases were categorized as either conventional feeds (using typical feed inputs from fishery and agricultural sources), non-conventional feeds (*e.g.* organic, low-fish input), or individual fishery-derived inputs, and by functional unit (*e.g.* one tonne feed, one tonne fish produced from feed).

After case studies were listed and categorized, Microsoft Excel was used to construct a number of review tables (Appendix C):

- General information pertaining to each case study (species, fishing gear or culture system, functional unit, system description, location, date, sample size)
- Life cycle impact categories
- Life cycle stages and processes included in analysis (and feed ingredient mixes in the case of feed studies)
- Methodologies (LCA type, allocation procedure, software used, characterization models used, databases used for inventory construction, analysis and interpretation methods)
- Quantified impact potentials of both global warming potential (CO_2-equivalent GHGs) and other emissions and resource use impact categories
- Breakdown of GHG emissions by life cycle stage

Results of literature collection

A total of 62 sources were collected, including academic journal articles, theses, conference presentations, and industry reports. Journal articles made up the majority of studies, accounting for 32 of the sources (Appendix A). Together, these sources yielded 113 case studies, including 47 fishery cases, 46 culture cases, 17 feed cases, and three other product cases (Table 1).

TABLE 1. Number of studies and unique case studies included in the review of fishery- and aquaculture-derived product LCAs. Note: Number of studies refers to the number of research projects, rather than the number of published articles or reports; e.g. if a research project yielded both a thesis and a journal article, it would be recorded here as one study.

SPECIES GROUP	**FISHERIES**		**AQUACULTURE**		**FEED**		**OTHER PRODUCTS**	
	# studies	# cases	# studies	# cases	# studies	# cases	# studies	# cases
Shellfish: crustaceans	5	8	4	5	0	0	0	0
Shellfish: molluscs	0	0	1	4	0	0	1	2
Small pelagics	6	12	0	0	1	1[a]	0	0
Whitefish: cod	9	14	0	0	0	0	0	0
Whitefish: other	4	6	7	12	1	2[b]	0	0
Salmonids: Atlantic salmon	0	0	5	11	3	10	0	0
Salmonids: Rainbow trout	0	0	6	11	2	7	0	0
Salmonids: other	1	2	3	3	0	0	0	0
Tunas	3	4	0	0	0	0	0	0
Other	1	1	0	0	1	2[a]	1	1
TOTAL	**22**	**47**	**20**	**46**	**7**	**22**	**2**	**3**

a. Case studies of individually sources fishery inputs to feed, classified by the source fishery (two case from Antarctic krill fisheries, one case from Peruvian anchovy fisheries)
b. Case studies of feeds intended for multiple species, classified here as whitefish but not necessarily limited to whitefish species (see Appendix C for more details).

Focus of LCA case studies

While a large and growing number of case studies have been completed assessing fisheries and aquaculture-derived products, the focus of many of these studies has been a small number of key species, particularly Atlantic cod (*Gadus morhua*), Atlantic salmon (*Salmo salar*), and Rainbow trout (*Onchorhynchus mykiss*) (Table 1). Moreover, most products assessed have been located in European waters (or on land in European countries in the case of some farms), fished by European fishermen, or destined for European markets.

Within fisheries, the most studied systems were trawl and longline fisheries for Atlantic cod, with 10 case studies assessing cod fillets, one assessing gutted cod, and three assessing value-added products; all of these cases examined cod derived from fisheries in the northeast Atlantic and/or Scandinavian waters. While a number of species other than cod have been assessed, most have only been the focus of a single study.

A similar pattern of focus was found in aquaculture LCA studies, with the most common species studied being salmonids, particularly Atlantic salmon and Rainbow trout. Together, case studies of these two species account for half of all aquaculture LCA case studies. Most other species were the focus of only one or two studies.

Geographically, the majority of LCA work on seafood systems has been carried out by European researchers. By first author institution, the most prominent sources of LCA research on fisheries and aquaculture have been the Institut National de la Recherche Agronomique (INRA) in France, the Swedish Institute for Food and Biotechnology (SIK) in Sweden, Dalhousie University in Canada, and the University of Santiago de Compostela, Spain (Appendix A).

Patterns in objectives, parameters and methodologies

Objectives

Overwhelmingly, publicly available studies have been executed in an academic context and communicated in academic venues (*e.g.* journal publications). Many studies have focused mainly on the GHG emissions associated with products, while fewer have included a broader suite of impact categories as suggested by the ISO standards (ISO, 2006).

In addition to quantifying impacts and identifying hot spots of environmental burden, the majority of studies have included the objective of comparing multiple species, products, and/or production methods (In Appendix C, compared products or systems are differentiated in the reference columns with letters). These analyses include comparisons of:

- multiple species from a single fishery or culture (1 study)
- multiple fishing gears or farming methods for a single species (11 studies)
- multiple species from multiple fishing or farming methods (8 studies)
- multiple products derived from a single species (6 studies)
- fish grown using different fish feeds (3 studies)
- products sources from multiple fishing, farming or processing locations (3 studies)

Functional unit

The functional unit is the basis of analysis in LCA studies, or the quantity of product against which environmental impacts are measured. The type of functional unit used may affect the usefulness of studies to different readers and practitioners; for example, fisheries managers may be more interested in impacts per live tonne fish landed, while seafood retailers may be more interested in the impacts of packaged sale-ready fillets. The choice of functional unit can also be an important methodological choice when comparing seafood products, because certain products may perform better when assessed in terms of per-mass impacts, while others may perform better when assessed, for example, in per-protein or per-energy terms (Parker & Tyedmers, 2012).

The most common functional unit for fisheries case studies in this review was a given mass of fillets (20 cases), while most aquaculture studies reported the environmental impacts per live weight tonne at farm gate (34 cases). Relatively few studies have measured the impacts of value-added products.

Life cycle stages

The number of life cycle stages included in a study influences both the effectiveness of the study to identify impacts and environmental trade-offs resulting from system changes, and the comparability of different studies. The inclusion and exclusion of certain life cycle stages and/or processes is determined by the objectives of a study, the availability of data, and the established importance of processes in contributing to impacts (*e.g.* some fishery studies have deliberately excluded gear and/or vessel construction due to the anticipated triviality of their contributions).

Most fishery LCA case studies have followed products (typically fillets) to the point of arrival at a destination (*e.g.* imported into a country or shipped to a market), taking into consideration impact from fishing, processing, packaging, storage and transport. Only seven studies (10 case studies out of 47) followed fishery products through the sale, consumption and waste management stages of the life cycle. Aquaculture LCAs have typically included even fewer life cycle stages than fishery studies, with 30 case studies out of 46 reporting impacts associated only with feed provision and production of fish at the farm – this relatively short life cycle is related to the functional unit of live weight fish at the farm gate. Only three studies (six case studies) have followed the life cycle of aquaculture products through sale, consumption and waste management.

Impact categories

While the specific focus of this review, and indeed of many LCAs, is the measurement of GHG emissions, LCAs typically report quantifications of numerous environmental impacts. The inclusion of multiple impacts not only provides a broader understanding of the environmental performance of products, but also helps to identify trade-offs between different impacts (*e.g.* certain products may have a lower carbon footprint but a greater dependence on biotic resources), but also identifies patterns and common impact drivers (such is the case with fuel use by fishing vessels contributing substantially to a number of emissions-based impacts as well as cumulative energy demand of fishery products).

Global warming potential (carbon footprint) was the only environmental impact measured by all completed LCA studies of seafood products to date. A number of other impact categories have also been applied by numerous studies, with particular attention being paid to acidification potential, eutrophication potential, energy use, and biotic resource use (Table 2).

Importantly, some studies reported impact in some categories in non-typical units (*e.g.* eutrophication potential in NO_3-equivalent emissions rather than PO_4-equivalent emissions)[2]. To avoid confusion, those particular impacts are excluded from the impact potentials tables in Appendix C. They are, however, still included in the impact categories tables.

TABLE 2. The ten most commonly included impact categories in seafood LCAs, and their occurrence in case studies included in this review.

Impact Category	Typical Reference Species[a]	# of case studies				
		Fisheries	Aquaculture	Feed	Other	**Total**
Global warming potential	CO_2-e	43	45	16	3	**107**
Acidification potential	SO_2-e	31	40	16	3	**90**
Eutrophication potential	PO_4-e	29	42	16	3	**90**
Cumulative energy demand	CFC-11-e	15	31	14	1	**61**
Biotic resource use	C NPP[b]	7	23	14	1	**45**
Abiotic resource use	Sb-e	20	14	2	2	**38**
Ozone depletion potential	CFC-11-e	21	8	4	3	**36**
Marine toxicity	1,4-DB-e	12	10	6	2	**30**
Photochem. oxidation potential	H_2C_4-e	17	8	2	2	**29**
Human toxicity	1,4-DB-e	12	13	2	2	**29**

a. 'e' represents 'equivalent' units; *e.g.* global warming potential is typically communicated in terms of kg carbon dioxide-equivalent (CO_2-e) emissions.
b. Net primary productivity, expressed in kg carbon

[2] The choice of reference species to communicate impact potential is sometimes relevant to the system being studied. For example, in the case of eutrophication, nitrate (NO_3) is the main limiting nutrient in marine environments while phosphate (PO_4) is the main limiting nutrient in freshwater environments; therefore, studies interested in eutrophication impacts on marine environments may choose to communicate impact in terms of NO_3-equivalent emissions.

Most LCA studies of fisheries and aquaculture systems have used mid-point indicators of impact.[3] Only three studies (seven case studies) included in this review applied an end-point method of expressing environmental impacts, in which all emissions and uses of resources contribute to an environmental impact score. These studies also reported an independent measure of GHG emissions to accompany the points-based impact values.

A more detailed discussion of impact selection in seafood LCAs has been carried out by Pelletier and colleagues (2007).

Methodologies

Almost all LCA studies of seafood systems have applied an attributional LCA approach, where environmental burden of processes in the system are measured and attributed to one or more products.[4] One study (Thrane, 2004b) applied a consequential LCA approach, where changes in regional or global production of goods as a result of a product or service are anticipated and the environmental impacts of such changes are measures. One additional study (Myrvang, 2006) used a hybrid input-output approach whereby already established national impact values for classes of materials and energy sources were used to estimate the impact of a product requiring a given quantity of those materials and energy sources (as opposed to using product-specific measurements or secondary databases).

The use of software, characterization models, and databases of life cycle inventory data, is a typical part of LCAs due to the immense amount of additional time and effort that would otherwise be required for data collection and analysis. The most common software package used by practitioners of seafood LCAs is SimaPro (multiple versions) from PRé Consultants in the

[3] Impact categories can be categorized as either midpoint or endpoint indicators of environmental impact. Midpoint indicators are quantified measures of emissions or resource consumption, while endpoint indicators are quantifications of actual environmental changes in terms of impact to ecosystems and/or humans (ISO, 2006). For example, a midpoint indicator might communicate the amount of emissions being released into an environment while an endpoint indicator would communicate the extent of biodiversity loss or human health impact as a result of those emissions. While endpoint indicators may more directly address the issues of concern to environmental scientists and governments, they are also subject to far greater degrees of uncertainty.

[4] ISO-compliant LCAs can be broadly categorized as either attributional or consequential studies. Attributional studies measure the impacts of products strictly as a result of the material and energy flows throughout their supply chains. Consequential LCAs, meanwhile, address the potential impact of products on other production systems and supply chains as well, seeking to understand economy-wide changes in production and related impacts as a result of a certain product being produced and used. For example, in the case of fish meal as a feed input, an attributional LCA would measure the material and energy inputs and outputs associated with producing the fish meal, while a consequential study may examine how the use of that fish meal would affect demand for other feed inputs such as soy meal.

Netherlands. The most commonly applied characterization model suite was CML (multiple versions) from Leiden University, while the most common database used to construct life cycle inventories was EcoInvent from the Swiss Centre for Life Cycle Inventories – both of which are included in the SimaPro package. Importantly, different life cycle inventory databases include data sourced from different countries and/or different years of production. EcoInvent, for example includes data specific to European and Swiss materials and processes, and therefore may be more relevant to European supply chains than to supply chains situated in other parts of the world. In some cases, European data can be altered to better represent activities in non-European countries, *e.g.* by applying country-specific electricity mixes.

One of the most commonly discussed methodological choices in LCA is the method of allocation between by-products (for example, between multiple species being landed by a fishing vessel). The allocation procedure used can heavily influence results. Of those studies which applied some method of allocation, and which addressed its use in the resulting reports/articles, most applied either mass- or economic-based allocation (Table 3)[5]. Interestingly, fisheries case studies more commonly included mass-based allocation methods, while aquaculture and feed case studies more commonly applied economic- or energy-based allocation. In some cases, multiple allocation methods were applied for different processes, to reflect the process (*e.g.* a study using energy-based allocation may employ mass- or volume-based allocation for transportation processes because they are limiting factors for those processes) As well, some studies present results of both mass-based and economic-based analyses to[6], and many have presented sensitivity analyses, to demonstrate the effect of this often-critical methodological choice (Ayer & Tyedmers, 2009; Boissy *et al.*, 2011; Driscoll, 2008; Pelletier & Tyedmers,

[5] Proponents of economic allocation argue that environmental burden of co-products should be allocated on the basis of the contribution of those co-products to the revenue streams of the producer. This is because those products which are more economically valuable to producers drive industrial activities while less valuable products may simply be by-products or 'wastes' of an otherwise already active system. Proponents of biophysical allocation methods (*e.g.* energy- or mass-based allocation), meanwhile, argue that allocating based on economic contributions to revenue streams: does not reflect the actual biophysical relationships between products and their supply chains; inadvertently suggests that the production systems from which less valuable products are derived have little environmental impact; and results in the illusion that the environmental performance has changed when product value increases or decreases, when in reality the actual supply chain has not changed (Pelletier & Tyedmers, 2011).

[6] In cases where multiple sets of results were presented using different allocation methods, they were treated as single case studies with methodological scenario analyses and only the mass-based impact values are recorded in the impact potential and GHG contribution analysis tables.

2007; Svanes *et al.*, 2011; Vázquez-Rowe *et al.*, 2010; Ziegler & Valentinsson, 2008; Ziegler *et al.*, 2011).

A more detailed discussion of the use of allocation procedures in seafood LCAs has been carried out by Ayer and colleagues (2007).

TABLE 3. Descriptions of allocation methods used in seafood LCAs, and occurrence of allocation methods in this review (when overtly stated).

Allocation Method	Description	# of case studies
Mass	Relative mass of output (kg)	38
Economic	Relative importance to producer revenue streams, in dollar values	30
Gross energy content	Relative energy content of output (MJ)	18
System expansion	Use of already known impacts of an identical or subtitutable product for one or more outputs	9
Volume	Relative volume of outputs (m3)	2
Temporal	Relative time dedicated to output	1

Patterns in impact assessment results

Wild capture fisheries

While LCA case studies of wild capture fisheries have assessed products from fishery to post-consumer disposal, most have focused on impacts from fishing, processing (primarily into fillets) and transportation. Typically, the fishing stage has been identified as the key life cycle stage in terms of contributions to GHGs.

Fuel consumption during fishing made up the largest single contributor to GHG emissions of fishery-derived products in 25 of the 39 case studies for which GHG contribution analysis results were provided. An additional three case studies had the general fishing stage or fishing and processing together as making up the largest contributor. Of the 11 case studies for which another life cycle stage was reported as the most influential in overall GHGs, four reported transportation of products by air, two were canned ingredients with added oil (Buchspies *et al.*, 2011), and one did not include the fishing stage in the life cycle. When products are not being transported by air, and when no emissions-intensive ingredients are added, fuel use by the fishing vessel may be a useful proxy for the overall carbon footprint of most fishery products up to the point of arrival at the product destination.

Because of the importance of fuel use intensity to the overall GHG emissions of fishery-derived products, a number of studies have included sensitivity or scenario analyses regarding fuel consumption by fishing boats (Hospido & Tyedmers, 2005; Boyd, 2008; Driscoll, 2008; Fulton, 2010; Parker, 2011; Thrane, 2004; Ziegler & Valentinsson, 2008). These analyses have typically found fuel use intensity variation to have marked effects on the overall performance of fisheries, with changes in GHG emissions in some cases nearly identical to changes in fuel use; this effect is, of course, less prominent when products are transported by air.

A number of studies have been completed in recent years reporting fuel consumption by species, fishing gear and location (*e.g.* Tyedmers, 2001; Thrane, 2004; Schau *et al.*, 2009; Tyedmers & Parker, 2011). These studies have demonstrated that, generally, fisheries targeting small pelagic species demand markedly less fuel per tonne of landings than those targeting larger, higher trophic level species and shellfish (Appendix D). Additionally, fisheries employing purse seine gear typically require less fuel per tonne of landings than those targeting the same species but using other gears (e.g. longline, trawl) (Appendix D). These patterns provide a good basis of assumption for comparing fisheries on the basis of energy use or carbon footprint when actual fuel use values are not available.

Aquaculture production systems

Case studies of aquaculture production systems have typically included feed production and farm activities, often broken down by sub-processes (*e.g.* electricity use, chemical inputs, *etc.*). Less commonly, some case studies have followed aquaculture supply chains through to processing, transportation, consumption and post-consumer activities. Feed production and on-farm electricity are commonly found to be the major drivers of GHGs in aquaculture systems.

Production of feed makes up the single most important contributor to the GHG emissions for 28 of 45 aquaculture studies, with an additional two cases reporting feed and farming together to contribute most heavily. For Atlantic salmon and Rainbow trout production, feed accounts for, on average, 87% of total GHG emissions.

In those cases where feed production was not the most influential source of GHGs in aquaculture, on-farm energy use typically was. This is particularly the case for land-based systems (*e.g.* recirculating systems) which require energy to run aeration systems, regulate temperatures and circulate water – processes which, in a marine net-pen system, are provided by the ecosystem. Because of the relative importance of energy use, a number of studies have conducted sensitivity and scenario analyses regarding the electricity mixes (Ayer & Tyedmers, 2009; Cao *et al.*, 2011; Ellingsen & Aanondsen, 2006; Schmidt & Thrane, 2007; Ziegler *et al.*, 2011; Samuel-Fitwi *et al.*, 2011). As a result of the importance of the electricity mix, farm location can drastically influence GHG emissions of aquaculture products; Ayer and Tyedmers (2009), for example, compared Arctic char cultured in coal-dependent Nova Scotia with Atlantic salmon cultured in British Columbia where electricity in mostly hydroelectric[7]. In this regard, studies of systems in France, where most energy is sourced from nuclear power, may not be directly applicable to studies in countries with greater reliance on fossil fuels for their electricity mix.

Fish feed production studies

Two feed-related variables are consistently reported to be major determinants of overall GHG emissions of cultured fish products, and are commonly recommended as areas of potential improvement in aquaculture: feed conversion ratio (FCR) and feed ingredient mix. Several studies have measured the sensitivity of GHGs to FCR (Cao *et al.*, 2011; d'Orbcastel *et al.*, 2009; Grönroos *et al.*, 2006; Pelletier & Tyedmers, 2007), and have generally demonstrated that improving FCR to optimal levels would improve overall aquaculture GHG emissions by upwards of 20%. A number of additional studies have explored the potential change in impacts, both positive and negative, of different feed ingredient mixes (Boissy *et al.*, 2011; Bosma *et al.*, 2011; Cao *et al.*, 2011; Ellingsen & Aanondsen, 2006; Grönroos *et al.*, 2006; Papatryphon *et al.*, 2004; Pelletier & Tyedmers, 2007; Samuel-Fitwi *et al.*, 2011). Results of these analyses vary, with some studies showing substantial improvement by using non-conventional feeds while others show little improvement or even increases in emissions. It is clear that a major driver of the performance of fish feeds is the fisheries from which meal and oil are sourced, and so selection of meal and oil species based on environmental performance may be a method to improve GHG emissions of many aquaculture-derived products; it would follow that the relative fuel use intensity of small pelagic fisheries would be an important indicator of the environmental performance of feeds which include them.

[7] In this case, while the difference between GHG emissions of the two systems is vast, much of the difference is due to the high energy-dependence of the land-based Arctic char system.

Major gaps in our understanding of the GHG emissions of seafood products

1. **Fisheries targeting non-cod species.** Most species other than Atlantic cod have received attention by only one study, offering little opportunity to gauge the relative performance of those fisheries and the range of emission intensities within them. While some inferences can be drawn from fuel use intensity studies, these studies cannot replace LCA as a tool for measuring and characterizing the carbon footprint of fisheries. In particular, more work needs to be completed on globally important species (e.g. Peruvian anchovy, Alaska pollock, Atlantic herring, Skipjack tuna). As well, little work has been completed on inland fisheries and fisheries beyond the north Atlantic and Scandinavia.
2. **Aquaculture of non-salmonids**. Outside of Atlantic salmon and Rainbow trout studies, most cultured species that have been assessed have only been the focus of one to two studies, and in some cases these studies have reported markedly different results. Additionally, those studies that have focused on non-salmonid species have generally only presented results for one type of farm system, leaving a great amount of uncertainty as to other potentially less emission-intensive methods of culturing fish. Systems that require additional attention include farms for carp, tilapia and other globally significant species. Having a broader range of species studied would allow for more comparison between substitutable products, as well as a better understanding of the relative performance of salmonid products when compared to other major fish protein sources.
3. **Reduction fisheries for meal and oil**. When considering the critical role that feed plays in the overall GHG performance of aquaculture, and the importance of the source fishery in the GHG emissions of different feeds, it is surprising that relatively little work has been done on the major world fisheries targeting small pelagic species for reduction into meal and oil. Those studies which have assessed small pelagic species have typically focused on fisheries for direct human consumption. There has been no completed work on fisheries for Peruvian anchovy, the largest fishery in the world by landings and a major source of meal and oil for aquafeeds, although there is one study currently underway by Freon and colleagues (2011). It is also common for aquaculture LCAs to assume the source fishery of meal and oil and not run scenario analyses to gauge the influence of the source fishery; doing so may reveal that substantial improvements to

aquafeeds and cultured fish may result from selecting low-impact fisheries as the source for meal and oil.

4. **Value-added products**. Most LCAs have reported the environmental impacts relative to a given mass of live weight fish or fillet. Very few have extended the life cycle to incorporating processing activities and additional ingredients for value-added products. In some cases, analysis of these additional processes have identified non-fishery ingredients as important drivers of GHG emissions; such is the case for canned mackerel with added oil (Buchspies *et al.*, 2006) and fish burgers (Svanes *et al.*, 2011).
5. **Post-landing or post-farm-gate life cycle stages**. Processing, packaging, transport, sale, consumption and waste management are not commonly included life cycle stages in seafood LCAs. This is particularly the case in aquaculture studies, while fisheries studies have often followed products through the transport stage. While product-specific studies are not necessary to estimate the impact of these stages (the emissions intensity of packaging materials or transportation modes, for example, can be assumed to be similar across most seafood products), these additional stages would be useful in placing earlier stages in context. This may be particularly important for products that are a) transported fresh by air; b) processed into value-added ingredients; or c) cooked for consumption.
6. **Common basis of comparison**. Unfortunately, comparison of products between studies is difficult because of different functional unit, life cycle stages, or methodologies. An important step in improving the comparability of different studies is the reporting of impact assessment results for a common basis of comparison (*e.g.* one kg fillet transported to market). While this would not remove the barriers caused by the use of different methodological choices, it would provide greater ease of access to industry practitioners interested in the relative performance of different products. It may be useful for studies to report results both in terms of this comparison-ready functional unit and a functional unit that extends into other life cycle stages which differ between systems, thus providing complete results for the system at hand and also providing a basis of comparison with other studies
7. **Availability of non-academic sources.** While most of the publicly available studies identified and included in this review have been completed by academics and communicated in academic venues, there is likely a substantial amount of data that has

been produced by industry but which has not been made publicly available (*i.e.* 'grey literature'). This represents a substantial barrier to understanding which could be overcome through data-sharing initiatives and cooperative research engagements.

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