



Aquaculture and the Environment

Life Cycle Assessment on Icelandic Arctic char fed with three
different feed types

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**Faculty of Life and Environmental
Sciences
University of Iceland
2013**

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Environmental and Natural Resources

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Reykjavik, May 2013

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Bibliographic information:

Birgir Örn Smárason, 2013, Aquaculture and the Environment. Life Cycle Assessment on Icelandic Arctic char fed with three different feed types, master's thesis, Faculty of Life and Environmental Sciences, University of Iceland, pp. 111.

Printing: Háskólaprent.
Reykjavik, Iceland, May 2013

Abstract

With ever growing consumption the world tries to supply food for a population exceeding 7 billion. Aquaculture has been heralded for its potential to meet this huge increase in food demand and is therefore a large contributor to feed the world. It continues to be the fastest growing animal food production sector, accounting for 45.6% of the world's fish consumption in 2011. However, according to WWF one-third of global wild-caught fish is processed into fishmeal and fish oil used in large quantities for fish feed. This puts the sustainability of wild fisheries under threat while the environmental impacts of aquaculture are increasingly criticized and analyzed.

This study utilized Life Cycle Assessment (LCA) to quantify the environmental impacts of 1 kg of live-weight Arctic char, cultivated in an Icelandic land-based aquaculture farm. The functional unit included assessments of three different feed types; Conventional feed, ECO feed and the Black soldier fly feed. Results of the study indicate that the feed production causes the greatest environmental impacts from all feed types considered. The Black soldier fly feed demonstrated the best environmental performance of the three feed types. Furthermore, it can be concluded that by increasing agriculture based ingredients at the cost of marine based ingredients, a better environmental performance can be reached. This study also confirmed that the transportation of materials needed for the aquaculture process, including the feed materials, has very low environmental impacts. Transporting by air causes immense environmental impacts compared to sea transport. This study demonstrated the importance of feed production for aquaculture in terms of environmental impacts and showed that by decreasing the amount of feed consumed, reducing the amount of fishmeal and fish oil and even creating new types of feed from other forms of biotic ingredients can greatly reduce the overall impacts of aquaculture.

Útdráttur

Með vaxandi neyslu reynir heimurinn að sjá fyrir 7 milljörðum jarðabúa. Fiskeldi hefur verið hampað fyrir þann möguleika að mæta þeirri gríðarlegu aukningu sem hefur verið í neyslu sjávarfangs og hefur átt stóran þátt í því að fæða heiminn á undanförunum árum. Það heldur áfram að vaxa hraðast af öllum matvælaframleiðslugreinum og stendur fyrir 45,6% af allri fiskneyslu í heiminum árið 2011. Samkvæmt WWF er 1/3 hluti af öllum veiddum fiski unninn í fiskmjöl og lýsi sem notað er í stórum stíl við gerð fódurs. Þetta setur sjálfbærni villtra fiskistofna í hættu um leið og gagnrýni á umhverfisáhrif af fiskeldi fer vaxandi.

Þessi rannsókn notaðist við Vistferilsgreiningu (Life Cycle Assessment, LCA) til að mæla umhverfisáhrif af 1 kg af lifandi bleikju, sem ræktuð er í íslenskri landeldisstöð. Aðgerðareiningin innihélt mat á þremur mismunandi gerðum af fódri; Conventional fódur, ECO fódur og Black soldier fly fódur. Niðurstöður rannsóknarinnar benda til þess að fódurframleiðslan veldur mestum umhverfisáhrifum með öllum fódurgerðum, en Black soldier fly fódrið olli minnstum áhrifum. Með því að auka innihaldsefni í fódri úr plönturíkinu á kostnað sjávarafurða má lækka umhverfisáhrif töluvert. Þessi rannsókn leiddi einnig í ljós að flutningur á hráefni sem notaður er í fiskeldisferlinu, þar með talið hráefni í fódur, hefur mjög lítil umhverfisáhrif miðað við aðra ferla. Flutningur með flugi veldur gríðarlegum umhverfisáhrifum miðað við sjóflutning. Þessi rannsókn sýndi að framleiðsla á fódri er gríðarlega mikilvægt ferli þegar talað er um umhverfisáhrif af fiskeldi. Hún sýndi jafnframt að með því að minnka það fódur sem fiskar borða, minnka hlutfall fiskimjöls og lýsis og jafnvel að gera nýtt fódur úr annarskonar lífrænum innihaldsefnum getur minnkað verulega umhverfisáhrif af fiskeldi.

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Abbreviations

ABD	Abiotic depletion
ACD	Acidification potential
BSF	Black soldier fly
CED	Cumulative energy demand
CML	Centre for Environmental Studies
CO ₂	Carbon dioxide
CO ₂ eq.	Carbon dioxide equivalence
EIA	Environmental impact assessment
EROI	Energy return on investment
EU	European Union
EUT	Eutrophication potential
FAO	Food and Agriculture Organization
GWP	Global warming potential
HTP	Human toxicity potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MJ	Mega joule
MTP	Marine toxicity potential
NPP	Net primary production
PO ₄	Phosphate
WWF	World Wildlife Fund

Acknowledgements

This study was conducted from mid-2012 to the early months of 2013. It was a long and challenging process where hard thinking and good advises steered me towards the end. The study was funded by the food and biotech R&D company Matís ohf and written on one of their desks at Vínlandsleið 12.

The good advises I got during the project came from the many experts within Matís, especially from one of my supervisors Ólafur Ögmundarson, aquafeed experts Dr. Jón Árnason and Stefán Björnsson and processing expert Magnús V. Gíslason. Supervisors Dr. Brynhildur Davíðsdóttir from the University of Iceland and Halla Jónsdóttir from the Innovation Center of Iceland also deserve a big thank you for their massive contributions with their expert knowledge.

I would like to send Samherji ltd, Laxá hf and Silfurstjarnan aquaculture farm my appreciation for their contribution to this project as well as everyone mentioned above. Special thanks go to my fiancé, who stood by my side and cheered me, and last but not least to Elín Heiða Ólafsdóttir who graciously spent her time proofreading this study.

1 Introduction

Aquaculture remains a growing, ever evolving and important production sector for high protein food sources. In the year 2000, 32.4 million tons of aquaculture-grown species were produced. In the past decade this number has grown substantially, reaching 52.5 million tons in 2008. It continues to be the fastest growing animal food sector accounting for 45.6% of the world's fish consumption (FAO, 2011). As the production and consumption increases, with the ever growing human population, the world tries to supply food for a population exceeding 7 billion. Aquaculture has had a large part in feeding the world in recent years but has come under increased scrutiny and criticism. This is largely due to environmental impacts connected to the aquaculture process, and the impact it could have on wild species already under threat. (Tidwell and Allan, 2001).

Aquaculture, like most other food industries cause harm to the environment. Pollution, damage to sensitive coastal habitats and aquatic biodiversity must be reduced to assure sustainability and balance in ecosystems. There is a great potential for aquaculture for food production and alleviation of poverty for people living in coastal areas. For example, aquaculture in the Asia-Pacific region contributes to 62.3% of global aquaculture production (FAO, 2011). However, a balance between food security and environmental costs must be attained. Initially, the growth of aquaculture was driven by governments due to its economic success (Emerson, 1999), but more recently governments have started to implement strict environmental and social regulations to ensure sustainability of the industry. The growth of the aquaculture sector today is due to number of contributing developments that should achieve the sector's long-term economic, social and environmental goals. However, this depends primarily on the commitments by governments to support a good framework to ensure sustainability. This cannot be achieved without continuous research and development to address the relevant environmental and social concerns, backed with scientific data (Emerson, 1999).

1.1 Background

The original concept of this project came from Samherji Ltd., the biggest manufacturer of aquaculture farmed Arctic char in the world, with a production capacity of 3.000 tons per year. The company operates 3 large Arctic char aquaculture farms in Iceland. One of them is Silfurstjarnan, a land-based farm on the north-east coast. There they produce three species, Arctic char, turbot and salmon in 23.800 m³ farming space, with production capacity of 1.500 to 1.800 tons. While Arctic char is produced in larger scales on other farms owned by the company, the conditions at Silfurstjarnan are unique for the char. During one year period, about 70 tons of Arctic char were produced. This fish goes fresh straight to a wholesaler in the U.S. who focuses on buying products that are grown under environmentally friendly conditions. Therefore, the use of medicine, chemicals or other additives is prohibited in the production of the Arctic char at Silfurstjarnan. Furthermore, Icelandic conditions for aquaculture offer renewable energy, clean water and the feed used is special made, containing natural pigments.

Samherji seeks to measure the environmental impacts of the production of Arctic char at Silfurstjarnan to confirm and demonstrate their claimed environmental performance and further strengthen the position of Icelandic aquaculture. Wholesalers and consumers are thus given the opportunity to choose a product that is produced in greater harmony with the environment, if that is the case. It should be mentioned and made clear, that most of the data gathered for this study is proprietary data owned by the involving partners of this study, and can therefore not be presented.

This project provides an opportunity to identify pollution hot spots, and further investigate how to reduce them. For example, it is known that the feed production for aquaculture usually has the largest impact on the environment (e.g. Blancheton et al., 2009). Therefore it is important in a study of the environmental impacts of aquaculture, to explore different types of feed and new feed compositions at experimental stages, and assess how that impacts the outcome. One such feed type is being developed at food and biotech R&D Company Matís; the Black soldier fly feed. The goal of that new feed type is to reduce the environmental burdens associated with aquaculture feeds by reducing the use of marine based ingredients. Up to 5 kg of wild fish is needed to produce 1 kg of fish in aquaculture through fishmeal and fish oil. This puts even more pressure on the sensitive fish stocks and earth's eco-systems.

1.2 Objectives of the thesis

The objectives of this thesis is to analyze the environmental performance of the Arctic char aquaculture in Silfurstjarnan using Life Cycle Assessment, and compare the environmental impacts of currently used feed type with two new experimental feed types. Many factors regarding environmental impacts of aquaculture processes will be analyzed to gain a better understanding of their relation to the environment. The report will aim to answer the following research questions:

- **What are the cradle to gate environmental impacts associated with 1 kg of Arctic char farmed in Silfurstjarnan, a land based aquaculture in Iceland?**
- **Where are the hot spots within the system and how can we reduce them?**
- **Will the Black soldier fly feed and the ECO feed have a better environmental performance than the conventional feed?**
- **Will less marine based ingredients in feed improve environmental impacts?**

1.3 Brief description of the methods used

This study uses the Life Cycle Assessment (LCA) methodology to assess the environmental impacts of the processes considered in this project. LCA is an ISO standardized methodology used to measure the impacts that the life cycle of a product or a product chain has on the environment. This study is considered a cradle to gate assessment where the processes occurring after the production of the product are not taken into account, such as distribution to customers and consumption. The impact assessment method used was CML 2 Baseline 2000 and impact categories chosen were Global warming potential, Abiotic depletion, Acidification potential, Eutrophication potential, Human toxicity potential, Marine aquatic ecotoxicity and Cumulative energy demand.

1.4 Aquaculture farming in Iceland

Aquaculture in Iceland dates back to late 1800's, when Icelanders began to transfer live freshwater fish into fishless lakes or streams. In 1884, salmon and trout hatchery first came into action, but aquaculture mainly involved hatching of salmonids and restocking of rivers. It wasn't until 1950 that production of food-fish in aquaculture came into being in Iceland. In 1952, Reykjavík Power Company started a summer-hatchery of salmon in an

aquaculture in river Elliðaá and Laxeldisstöð ríkisins, government owned salmon aquaculture, started to farm salmon in 1961 (Gunnarsson, 2006).

In the mid 1980's, interest in salmon aquaculture grew rapidly and between 1984 and 1986 the number of aquaculture farms increased from 40 to 102. The production increased as well during that time, from 150 tons in 1985 to 3.000 tons in 1990. Production mainly featured salmon and rainbow trout. However, the aquaculture business was not thriving well in Iceland during that time and many farms went out of business. Stagnation occurred in production around the turn of the century, but trout farming was the only production growing, from 70 tons in 1990 to 900 tons in 1999. Interest in aquaculture grew again in the beginning of a new century when large seafood companies took the lead in research and development of aquaculture. In 2006, production in Iceland reached an all-time high, with 10.000 tons produced from aquaculture, of which 7.000 tons came from salmon farming. Production decreased in the following years due to companies leaving salmon farming, holding 5.000 tons in 2008, of which the majority came from trout farming (Landsamband Fiskeldisstöðva, 2009).

1.4.1 Arctic char aquaculture in Iceland

Arctic char (*Salvelinus alpinus*), or Iceland Arctic char, the name of farmed Arctic char in Iceland, is one of the most northern freshwater fish species around the Arctic. Known are both anadromous breeds, which migrate from salt water to spawn in fresh water, and breeds which stay in fresh water throughout their whole life cycle (Fisheries.is). Arctic char is well suited for life in the northern hemisphere, and it spreads more north than any other freshwater species (Gunnarsson, 2006).

The Arctic char, like most salmonids, has a fusiform body shape, but is distinguished by a small and delicate head, but body form and coloration varies greatly during its lifetime (Johnson, 1980). The fish is generally silvery with a dark back, but during the spawning season, the belly becomes red and the sides become brownish.

Arctic char is in many ways an appropriate species for aquaculture farming in the northern hemisphere. It thrives under low-temperature conditions and can be grown in high-density cages compared to other aquaculture-farmed species. That means more efficiency per square meter of farming space built compared to for example Atlantic salmon. The Arctic char is also more resilient than many other species, tolerating diseases and hard conditions

in farming. The Arctic char also has a very good feed utilization due to eating off bottom and in darkness (Thorarensen, 2011).



Figure 1. Arctic char (Menja)

However, the fish also has some downsides as a farmed fish. For example, it tends to enter the puberty phase too soon, or on its second year of existence, which makes it a non-selling product. By entering the puberty phase, the fish grows considerably slower. This tends to happen when it is raised too fast with excessive feeding. The fish size also tends to vary within groups, making it difficult to make plans for feeding and other operations (Thorarensen, 2011).

There have been many improvements in Arctic char farming through the years, and trial and error has educated farmers to stabilize the production. With technical methods such as genetic engineering (not genetic modification), it has been possible to reduce the frequency of early puberty within the second year and to increase the growth rate substantially.

In Iceland, Arctic char is mainly grown in inland tubs, with self-running freshwater. Coastal farms grow the fish in brackish waters. Production time varies between farms and conditions on each place. Generally, aquaculture farms grow their fish in 6-8 C water biggest part of the year (Thorarensen, 2011).

1.4.2 Production

Hatchery of Arctic char spawns started as early as 1910 near Lake Mývatn. Up until 1930, many hatcheries were operating, mostly to release spawns in lakes and streams. In 1961, Laxeldisstöð Ríkisins, a government owned aquaculture farm, started to produce Arctic char for food. The operation was small-scale and produced about 1.3 tons of fish in 1974.

It wasn't until 1987 that interest in farming Arctic char increased in Iceland, with the opening of Smári hf. aquaculture farm in Þorlákshöfn. Aquaculture farms grew in numbers and by the year 1992, 38 farms were operating throughout Iceland. However, in recent years, the number of farms producing Arctic char has decreased, but the remaining ones have grown considerably larger in size. In 2003, total production was 1.670 tons (Gunnarsson, 2006). Since Arctic char farming began in Iceland, the production has grown exponentially, excluding 2004 and 2005, when a kidney-disease infested several farms and distribution of spawns was prohibited. In 2009, production reached 3.000 tons and was expected to increase by 10% every year from 2011, with 10.000 tons in 2020. (Landsamband Fiskeldisstöðva, 2009).

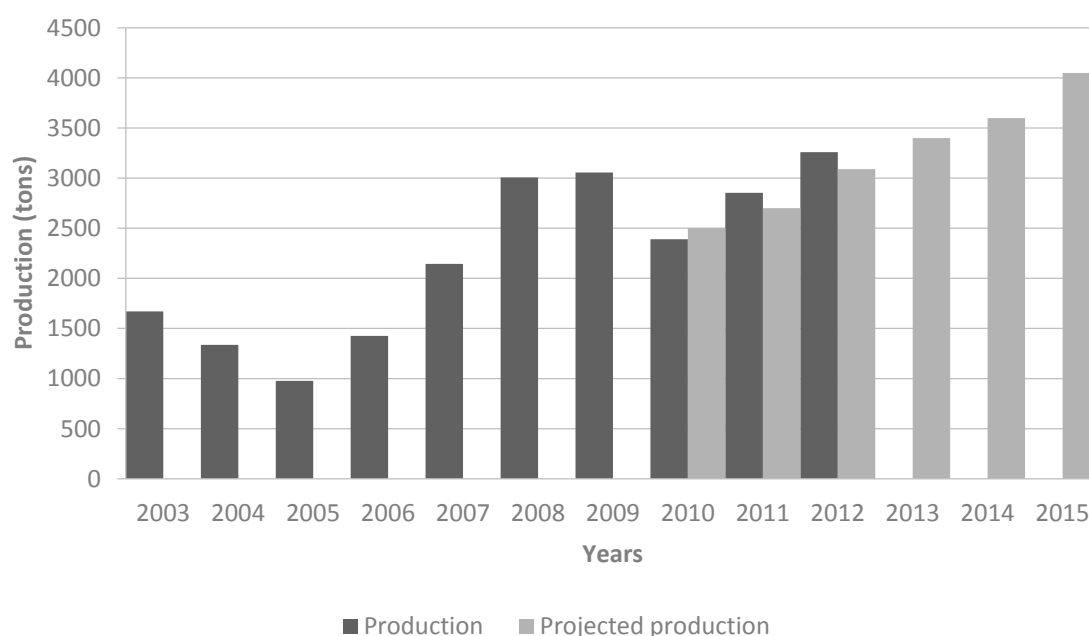


Figure 2. Arctic char production in Iceland from 2003-2012 with estimated production from 2010-2015 (Landssamband Fiskeldisstöðva).

In figure 2, the production of Arctic char in Iceland is presented from 2003-2012, with estimated production from 2010-2015. In 2010, actual production was lower than estimated production, but in the two following years actual production rose considerably higher than estimated production, or from 2700 estimated tons in 2011 to 2854 tons. There seems to be a build-up in the Icelandic Arctic char production and it will be interesting to see if the projection of 10.000 tons in 2020 will hold true.

1.5 Aquaculture and the environment

The culture of aquatic animals for the use of mankind involves all kinds of interaction between the cultured species and its physical and biological environment. Aquaculture can directly affect the environment through the output or consumption of materials, and indirectly through the biological environment or community. Currently there is no simple way to generalize the effects of aquaculture. The interaction between aquaculture production and its surroundings is different from each combination of production and the physical and biological setup of its geographical location (Iwama, 1991).

Aquaculture has been heralded for its potential to meet the huge increase in fish product consumption, decreasing the pressure on wild fisheries. But as has been said, aquaculture can have numerous effects on the environment including wastes from fish farms, which can pollute adjacent waters and harm fish and other wildlife. Chemicals, including antibiotics can be released into the environment. Escaped species can compete with wild species over food and habitat, diseases can be transferred and nonnative DNA can enter the wild gene pool. In addition, fish caught to make fish now represents a third of the global fish harvest. Instead of reducing the pressure on fisheries as the aquaculture industry grows, the pressure actually increases (WWF, 2006).

According to FAO (2013), much of the controversy surrounding aquaculture and environmental degradation is derived from inadequate management of development and irresponsible practices risks discrediting the aquaculture sector. Furthermore, FAO states that the main risks of environmental impacts from aquaculture are associated with high input and output systems where the impacts include discharge of suspended solids, nutrient and organic enrichment, changes in benthic communities, eutrophication of lakes and escapes or farmed individuals.

This is somewhat in line with what Huntington et al. (2003; 2006) determined to be the three key interactions of relevance for aquaculture and the environment:

- Sustainability of feed sources: Growth in aquaculture exerts an increasing demand for fishmeal and fish oil, which creates implications for the impact of industrial fisheries upon wild fish stocks.
- Eutrophication and harmful algal blooms: Interactions between aquaculture and harmful algal blooms are relevant to human and fish health with both social and

economic effects. Fish contributes to eutrophication through uneaten food, feces and metabolic by-products.

- Genetic integrity of wild stocks: Research shows that implications are significant of farmed fish on wild stock fitness. Genetic studies have shown that farmed fish are only 1-2% as fit as wild fish and lifetime success of escapees is only 27 to 89% if compared to their wild counterparts.

There are many other factors that can affect the environment from aquaculture processes. Impact categories such as land use, water use and other chemical compounds that can enter the air, water and soil have to be accounted for. With a tool like the LCA methodology the opportunity is given to document the whole life cycle of aquaculture processes and to further analyze processes that occur before and after the farm activities. The impacts that aquaculture has on the environment is bound to its geographical location, farm system technology, and further the combination of its ecological surroundings. As will be discussed in the next chapter, the feed production for aquaculture generally has the most direct environmental impacts. The feed production is a complex procedure which causes environmental impacts through the whole chain, or the whole life cycle, from raw material acquisition to the fish offal entering the water. Although the list presented by Huntington et al. (2003) shows where the main concerns in terms of environmental impacts of aquaculture lie, it is far from being complete.

1.5.1 Aquaculture feed

In aquaculture, feed is both the most important factor for fish growth and welfare, and in most cases, has the most environmental impacts. In a recent review by Parker (2012), the feed production accounted for 87% of greenhouse gas emissions from Atlantic salmon and Rainbow trout aquaculture production, when reviewing 45 aquaculture studies (Parker, 2012). The reason behind this is the magnitude of different marine and plant based ingredients, fished and grown in various parts of the world. In addition, the raw material ingredients have to be further processed. For example, fish has to be extracted into oil and meal, and many plant based ingredients have to be dried, milled and improved. This ensures even more environmental impact in addition to all the transporting of the raw materials to the feed mill. In 2008, 28.8 million tons of compound aquafeed was produced. The major consumers of aquafeed are herbivorous and omnivorous fish, which consume relatively less feed than carnivorous fish. However, carnivorous fish cannot survive

without marine proteins as a major component of their diet (FAO, 2011). Further, carnivorous species like tuna and salmon consume more fish protein than they produce which results in net loss of fisheries product. As it stands now, one-third of global wild-caught fish is used for fishmeal and fish oil and the demand keeps growing, with the sustainability of wild fisheries and connected ecosystems under threat (WWF, 2006). It has been argued that the continued demand for fishmeal and fish oil will drive the price upwards to a level where it may not be financially viable for use in feed production. The concerns about the use of fishmeal and fish oil and their rising prices has led to investments in research to find alternative sources of cheaper and high-quality ingredients of plant and animal sources. The main challenge lies with finding sources with high omega-3 fatty acids (De Silva and Hasan, 2007). It is important to continue the research and development of aquafeed and for producers to adopt policies for sustainability criteria and even the branding of aquafeeds produced using sustainable raw materials and responsible fisheries. Further, the development of plant and other substitutes for fishmeal and fish oil should continue. As Pelletier and Tydemers (2007) and Boissy et al. (2011) pointed out, increasing plant materials in aquafeed, and even substituting it for fishmeal and fish oil has a lower environmental impact and decreases the pressure on wild fish stocks. It has been seen that no adverse effects occur by changing the composition of diets for species like Arctic char. Feed expert Dr. Jón Árnason conducted an experiment involving the amount of protein and the effect on fish growth and feed cost. The results showed that a diet where only 23% of the protein came from fishmeal resulted in comparable growth as a diet where 90% of the protein was fishmeal protein. Calculation of feed raw material cost per kg growth showed that in all cases the cost is lower where the fish is fed on test diet with lower share of marine protein (Dr. Jón Árnason, personal communication, February 26, 2013)

1.5.2 Policies and regulations regarding Icelandic aquaculture and the environment

Despite substantial progress towards environmental protection, the struggle for more sustainable aquaculture production is nowhere near over as the industry keeps growing and evolving. The need for continuous improvements and investments are important to ensure environmental sustainability and economic viability as the pressure on natural resources and public awareness in environmental affairs continues to grow (Subasinghe, 2009). As a

result of commercial and public scrutiny on the environmental impacts of aquaculture over the past decades, significant progress has been made in addressing some of the key factors in its management. This has led governments to recognize that well governed aquaculture can result in economic and societal gains as well as minimizing the environmental degradation. Many countries have already implemented policies and regulations focusing on environmental sustainability and protection. The private sector has contributed to improvements and advances in the sector, improving environmental impacts as well as efficiency and profitability with social responsibility, self-regulations and environmental certifications, proving that their product does not harm the environment or is not ecologically threatening. In countries such as the United States of America and Canada, significant progress has been made by providing effective environmental stewardship. Water quality problems with excess nutrients and organic enrichment (eutrophication) have been reduced and producers are required to conduct environmental impact assessment (EIA) (FAO, 2011).

In Iceland, number of laws and regulations must be fulfilled before starting an aquaculture production. The aquaculture Act No. 70/2008 regulates all aquaculture activity in Iceland. The main purpose is to promote profitability and competitiveness within the framework of sustainable development. Environmental licenses are issued by the Ministry for the Environment and Natural Resources and Ministry of Industry and Innovation, and the Icelandic Environmental Agency governs the environmental licensing of aquaculture. The license contains criteria regarding harmful chemicals, pollution, distribution of suspended solids and other local environmental issues. If the annual production is 200 tons or more and waste water is returned into the ocean, or if annual production is 20 tons or more and waste water is returned into freshwater, the producer is obligated to notify the respected authority. An environmental impact assessment is required before a license is issued under those conditions if the Ministry of the Environment and Natural Resources fears there is a danger for the environment, based on a report from the Environmental agency (Ministry of Industry and Innovation, 2011).

Research on the environmental impact of Icelandic aquaculture has not been conducted according to the author's knowledge except Banze (2011), where the environmental impacts of Atlantic salmon farmed in sea-cages in north-west Iceland were assessed. The Icelandic aquaculture sector is therefore in need of more environmental research to assess

and confirm their position within the industry. Further, increased environmental stewardship and self-regulation is needed from the private sector, and governing bodies need to strengthen their policies and regulations with research to assure sustainability.

2 Previous LCA studies on aquaculture farming

LCA is becoming the most dominating and widespread method of environmental analysis (Ellingsen et al., 2008). The method is used to identify environmental impacts of a chosen product or product system over its full lifetime, or life cycle. All potential resource extraction from raw materials, transports, processing, consumption and waste treatment have to be considered if it falls under the system boundaries in any given study (Ellingsen et al., 2008). The European Commission has concluded that LCA provides the best framework for assessing environmental impacts of products (European Commission, 2012) and the method is currently required for various eco labels such as the EU-flower and the Nordic Swan.

Significant potential is indicated for the use of LCA when it is applied to fisheries and aquaculture production systems to assess the state of knowledge, for promoting environmental and social improvements in these industries. It focuses attention on sustainability issues and eco-efficiency that are often overlooked in fisheries and aquaculture production (Pelletier et al., 2007).

The original concept of LCA has been widely used for the past two or three decades, mainly for industrial products (e.g. Baumann, 1996). Recently, its use for food products has been increasing, and has been promising (Mungkung and Gheewala, 2007). For food products, the purpose of LCA is to assess and identify the sources of environmental pollution, and options for improvements to the system.

In recent years LCA has increasingly been applied to assess the environmental impacts of aquaculture systems (e.g. Papatryphon et al., 2003; Ayer & Tyedmers, 2008; Grönroos et al., 2006; d'Orbcastel et al., 2008; Pelletier, et al., 2009; Ytrestøyl et al., 2011; Banze, 2011). A pattern of species and geographical locations was found in aquaculture LCA studies with the most common species studied being those who are most common in culture such as salmonids, particularly Atlantic salmon (eg. Banze, 2011) and Rainbow trout (eg. Grönroos et al. 2006). Combined, half of all studies applied for aquaculture

focused on those two species. Majority of those projects were conducted by European researchers. Most products have been assessed in European seas and inland waters, or ended in European markets (Parker, 2012).

Research in aquaculture has followed several lines and has been used to perform comparative studies to evaluate different production systems, or styles of system management, to see which system has the best environmental performance. The feed industry has used the method to evaluate feed compositions to make strategic decisions (Pelletier et al. 2011), and several studies have assessed different aspects of the production, including production systems and feed composition (Ayer and Tydemers, 2008; d'Orbcastel et al., 2009; Pelletier and Tydemers, 2007). Comparisons have also been made with other animal products such as chicken (Ellingsen & Aanonsen, 2006) and cod fisheries (Buchspies et al., 2011).

It can prove difficult to compare different LCA studies with each other although the same impact categories are used within these projects. Different system boundaries and allocation methods as well as functional units make LCA's not directly comparable. Most aquaculture studies draw their boundaries around the farming process itself, excluding the infrastructure production, packaging, consumption and waste disposal and in some cases transportation of feed and products. This is because the biggest environmental emission contributors are within the farming system itself and the feed production, which can for example account for up to 87% of total greenhouse gas emissions (Parker, 2012).

Most aquaculture studies are cradle to gate oriented, thus the focus has been on production as mentioned above, leaving out processing, consumer use and end of life. This can cause problems as cradle to gate studies avoid allocation required for fish processing, and allocate 100% of life cycle burdens exclusively to the fish, instead of distributing the impacts between the fish and the co-products. Allocation methodology can have significant impact on the results of a study. See chapter 3.2.5 for further allocation discussion.

Although the use of LCA in the aquaculture industry has increased in general, few studies have been made on land-based Arctic char farming, and it is safe to say that no LCA study has been made on Icelandic Arctic char. Many important studies for the aquaculture sector have been made however, and are important to this study. The search criteria utilized to find relative studies included aquaculture LCA's on both salmon and trout. This was done because of how few studies have been conducted on Arctic char or trout specifically.

Furthermore, the criteria included studies on different kinds of feed and farming techniques.

Ayer and Tyedmers (2009) studied different salmonoid culture systems in Canada with LCA. They quantified and compared the potential impacts of culturing salmonoids in a conventional net-pen system with three alternatives; a marine floating bag system, a land-based saltwater flow-through system and a land-based freshwater recirculating system. As the system explored in this study is a land-based non-recirculating freshwater system, it could prove important and interesting to compare the environmental performance of non-recirculating and recirculating land systems. The general conclusions were that the marine floating bag system demonstrated the best environmental performance of all four systems modeled. Although the marine floating bag system was not equipped to collect and treat wastewater it released less eutrophying emissions than the others. Interestingly, the land-based recirculating system had the poorest environmental performance of the four systems. By collecting and treating wastewater, this system did worse than the others in terms of eutrophication potential. Other notable impacts were directly linked to energy use, abiotic depletion, global warming potential and acidification. The authors take an example of producing 1 ton of live-weight fish in the recirculating system resulted in release of 28 tons of CO₂ eq., compared to 2 tons of CO₂ eq. in the net-pen system. Those results indicate that a shift in production mode from conventional net-pen system to closed-containment systems will result in a significant increase in energy use and material inputs for every ton of live-weight fish produced due to increased inputs needed to maintain and build the infrastructure and the higher energy inputs needed to pump water and operate all the mechanical equipment needed (Ayer and Tydemers, 2009).

With similar results, d'Orbcastel et al. (2009) compared two trout farming systems using LCA. The two systems explored, located at the same site, utilized a flow-through system and an experimental pilot low head recirculating system. The difference of the two systems was mainly water use, eutrophication potential and energy use. After two years of experiments and research results showed that the trout recirculation system demonstrated limited environmental impacts in comparison with the flow-through system. They however underline that further research is needed to confirm those results. The recirculating system, which has a lower feed conversion ratio than the flow-through system, has more favorable environmental impacts in all categories except energy use. Water usage is 93% lower and

therefore waste release is considerably lower. It is however notable that the recirculating system is more energy intense but has a potential for energy reduction to the same level as the flow-through system (d'Orbcastel et al., 2009).

Grönroos et al. (2006) conducted an LCA of marine cultivated rainbow trout in Finland and analyzed the contribution of different production phases, impacts, emissions and the use of fossil fuels to the environmental impacts of typical rainbow production. The functional unit was one ton of ungutted rainbow trout after slaughtering. They however included the gutting process because the gutting process takes place at the same time as the slaughtering. This was done to avoid allocation of the gutted fish, roe and gutting waste, as guided in the ISO standards. The system boundaries included raw material extraction and production, hatcheries, the fish farm itself, slaughtering, gutting, transport of raw materials and final products and production of packages, fuels and electricity, and ended with the delivery of gutted fish to the retailers or further processing forms. The authors studied one typical product system and six alternative systems, three of which with different feed coefficients and other three methods which were closed floating cage, funnel and land-based marine farm. The results indicated that atmospheric emissions from raw material production, and transportation contributed to only a fraction of the total environmental impacts. Emissions to water caused the most significant impact from nitrogen and phosphorus released. They conclude with stating that with new environmentally friendly feed, it is possible to reduce emissions to water substantially (Grönroos et al., 2006).

Buchspies et al. (2011) studied environmental impacts of high-sea fish and salmon aquaculture. The aim of the study was to assess the impacts of fish products sold in Swiss supermarkets. The functional unit of the study was one kilogram of fish fillet sold in a Swiss supermarket. The fish products were produced in Denmark and Norway and transported to Swiss. They also compared the fish products with several meat products. System boundaries included the catch of the high-sea fish with trawl or gillnet vessels, transportation, processing, packaging and distribution and selling in supermarkets. The salmon production included hatchery, fish feed production, farming, processing, packaging, transportation and distribution and selling. The results indicate that the high-sea fish is at the lower end of range for all compared products, with fishing and packaging the main contributors to environmental impacts. For the salmon aquaculture, feed production and the nutrient emissions into the sea are the biggest contributors. Further, the results

show that fish offers an alternative to meat regarding the global warming potential, but it is concluded that fish cannot be regarded as a more environmentally friendly food product than meat in general because the impacts of different fish products varies and can exceed the impact of meat (Buchspies et al., 2011).

Increasing amount of studies assess the carbon footprint of products and systems. Carbon footprint can thus be a strong environmental indicator for aquaculture and other food products. Some studies tend to present only the carbon footprint while others show the carbon footprint and a whole range of environment impact categories.

Ellingsen et al. (2008) studied the present status of the Norwegian fishery and aquaculture industry, focusing on environmental methods and analyses. They included a recent study of the CO₂ emissions associated with the production of farmed salmon in Norway using LCA (Ellingsen and Aanonsen, 2006), and further updated the results. The calculations of the CO₂ emissions were carried out for the functional unit 1 kg of salmon fillet, following the life cycle from hatching to consumption, including smolt production, transportation, fish farming, slaughtering and consumption. Results showed that calculated CO₂ eq. for 1 kg of salmon fillet is 2.3 kg when leaving the slaughterhouse if the feed is processed with the use of heavy oil, and down to 2.2 kg CO₂ eq. with the use of natural gas. When the unit reaches the average consumer in East-Norway, 2.7 kg CO₂ eq. is found to be emitted. Again, the feed production and the fishing phase are found to be the dominating contributors to the emissions. The results vary significantly if the feed is dried with natural gas or heavy oil. CO₂ emissions can be reduced by 20% with the use of natural gas. It is interesting to see that the transportation phase has minimal impact on the overall environmental impact. The authors state that it seems to be more effective to optimize the production phase than to focus on transportation distances (Ellingsen et al., 2008).

In a very recent study by Ytrestøyl et al. (2011), resource utilization and eco-efficiency of Norwegian salmon farming was explored, using LCA as well as other methods to calculate food sustainability such as the ecological footprint and material and energy flow analysis to trace nutrient flows. The LCA was performed for production of salmon with the impact categories occupation of agricultural land, energy use, carbon footprint and ocean primary production. Swedish pig and chicken production was also assessed with the LCA method, and compared with the production of Norwegian salmon. The carbon footprint of the salmon production was 2.6 CO₂ eq./kg edible product and 3.4 for the production of chicken

in Sweden and 3.9 for production of pigs in Sweden. Production and transport of feed ingredients and feed held a total of 96% of the total carbon footprint. Similarly, Pelletier et al. (2009) studied global salmon farming systems using LCA, and found that the global average farm-gate greenhouse gas emissions stood at 2.15 CO₂ eq./kg. It has to be taken into account that the system boundaries studied in Ytrestøyl et al. (2011), included construction and maintenance of infrastructure, leaving higher CO₂ numbers in general, which Pelletier et al. (2009) left out of their study.

Five different feed compositions were assessed including blends with high content of marine ingredients, poultry by-products and high content of plant ingredients. Only marginal difference was between feed compositions assessed in respect to carbon footprints. Even changing the diet composition from 85% plant ingredients to 88% marine ingredients resulted in minor changes to the carbon footprint, or from 2.47 CO₂ eq./kg to 2.40 CO₂ eq./kg (Ytrestøyl et al., 2011).

The results from Ytrestøyl et al. are similar to other comparable studies. Boissy et al. (2011) studied the environmental impacts of plant-based salmonid diets and found that the use of plant-based ingredients does not decrease the environmental impacts by a large margin, but show that its use instead of fish oil and fishmeal could drastically decrease the pressure of aquaculture on marine biotic resources. Further, like most studies imply, they confirm that the feed is the major contributor to the environmental impacts of fish farming. They also conclude that the origins of ingredients influence the results of studies and fish species used to produce fish meal and oil affect the environmental impacts (Boissy et al., 2011).

The first LCA study on aquaculture farming in Iceland was made by Banze (2011). He analyzed the environmental impacts of Atlantic salmon farmed in sea cages with the functional unit 1 metric ton of the whole Atlantic salmon produced in sea cage system and delivered to a processing plant in Patreksfjörður. System boundaries included the feed production, hatchery, sea-cage farming, farming equipment and transportation at all stages. Once again the results indicated that feed production makes the most significant environmental impacts. A scenario analysis was made to identify the most impacting factors of the system studied and to recommend opportunities of improvement. There he found out that an electrical feeding system is better in terms of environmental performance, compared with the use of a boat for feeding. Fish species used is also an important factor

for the environmental performance of the production of fish meal and oil. Further, the analysis found that the transportation distance of feed ingredients makes considerable difference in terms of environmental impacts (Banze, 2011).

In 2010, Ingólfssdóttir carried out an LCA of the carbon footprint of the post landing activities of cold fish supply chains with two different transport modes. The results showed that the air freighted cold supply chain has 18 times larger carbon footprint than the sea freighted supply chain, with 4.7 kg CO₂ eq. and 0.3 kg CO₂ eq. respectively (Ingólfssdóttir, 2010).

2.1 General conclusions from aquaculture LCA's

Common conclusions from chosen aquaculture LCA studies show that the aquafeed production and use is generally the dominant factor for most environmental impacts considered. Some studies report that the feed contributes up to 90% of overall impacts. However it cannot be considered as an absolute result because those conclusions vary between studies with different boundaries and within different locations. Geographical location of the farming system under study affects the outcome and shows variety of different results partly because of different power and fuel sources. It is evident that no consensus can be found regarding whether transportation is considered a high impact factor or not. Some studies report that more focus should be put on balancing the farming stage for better environmental performance instead of minimizing the transportation distances because the impact is minimal. Others, like Banze (2011), report that transportation distances of feed ingredients makes considerable difference. This could partly be because of the geographical location of Iceland compared to other European countries, making the transportation distances longer for most materials.

Other interesting conclusions are the comparison of different feed types. Most studies that focus on aquafeed have included feeds with different amount of fishmeal and oil against feeds with increased amount of plant based ingredients. Ytrestøyl et al. (2011) and Boissy et al. (2011) both conclude that only marginal difference is found in carbon footprint and most other impact categories, but point out that increasing plant based ingredients can decrease the pressure on marine biotic resources greatly.

2.2 Possible additions to current literature

From the literature reviewed in this study, some general conclusions can be drawn as seen in last chapter. The feed production for example is without any doubt the most dominant factor when it comes to aquaculture. Other factors such as the transportation of feed ingredients, does not seem to have any consensus regarding its contribution, with e.g. Banze (2011) stating that the transportation is an important factor and Ellingsen et al. (2008) stating the opposite. This study thus has the opportunity to clarify this matter somewhat, since the materials have to be transported long distances to Iceland.

The use and production of different types of aquafeed is an ongoing debate, whether high-plant or high-marine based ingredients, or even organically grown (Pelletier and Tyedmers, 2007) ingredients have the best environmental performance. This study introduces a new feed type based on other type of organic ingredient, namely the Black soldier fly larvae, which replaces fishmeal completely. Comparing this new feed type to the other two considered in this study, and even others outside of this study, will show the difference between marine-based feed against the BSF feed in terms of environmental impacts and energy use.

3 Methodology

One aspect of achieving sustainability is to measure and compare the environmental impacts of production and supply of goods and services in order to minimize impacts. The life of every product starts with the design/product development, and from that point adoption of resources and raw materials, production, use and end of life activities. Life cycle assessment (LCA) is a methodology used to estimate and evaluate the environmental impacts of a product's life cycle. Traditional life cycle assessment is measured from cradle to grave. That means that the life cycle is registered from the extraction of raw materials to the usage and disposal of the product. From cradle to gate means that the life cycle is registered from the extraction of raw materials to a so called gate or farm-gate, which is usually some sort of product process, before it is sent for use.

Life cycle assessment is based on four steps, as standardized by the ISO standard 14040 series (ISO 14040:2006(E)) and presented in figure 3. Those steps are: Goal and scope, inventory analysis, impacts assessment and interpretation. In addition to these steps it is necessary to determine the functional unit. Definition of the functional unit is the foundation of life cycle assessment because the functional unit sets the standard in order to compare two or more products and for improvement analysis. All data collected during the project will be put in context with the functional unit. When comparing different products that fulfill the same function, the definition of the functional unit is very important. One primary purpose of the functional unit is to provide a reference to which input- and output data can comply with.

System boundaries define process/activity (e.g. manufacturing, transport and waste), and the input and output materials that shall be included in the analysis. Definition of system boundaries vary between research projects as they define what is included in the assessment. As the choice of system boundaries can certainly affect the results, it is important to encourage a transparent working process, and report every assumption made.

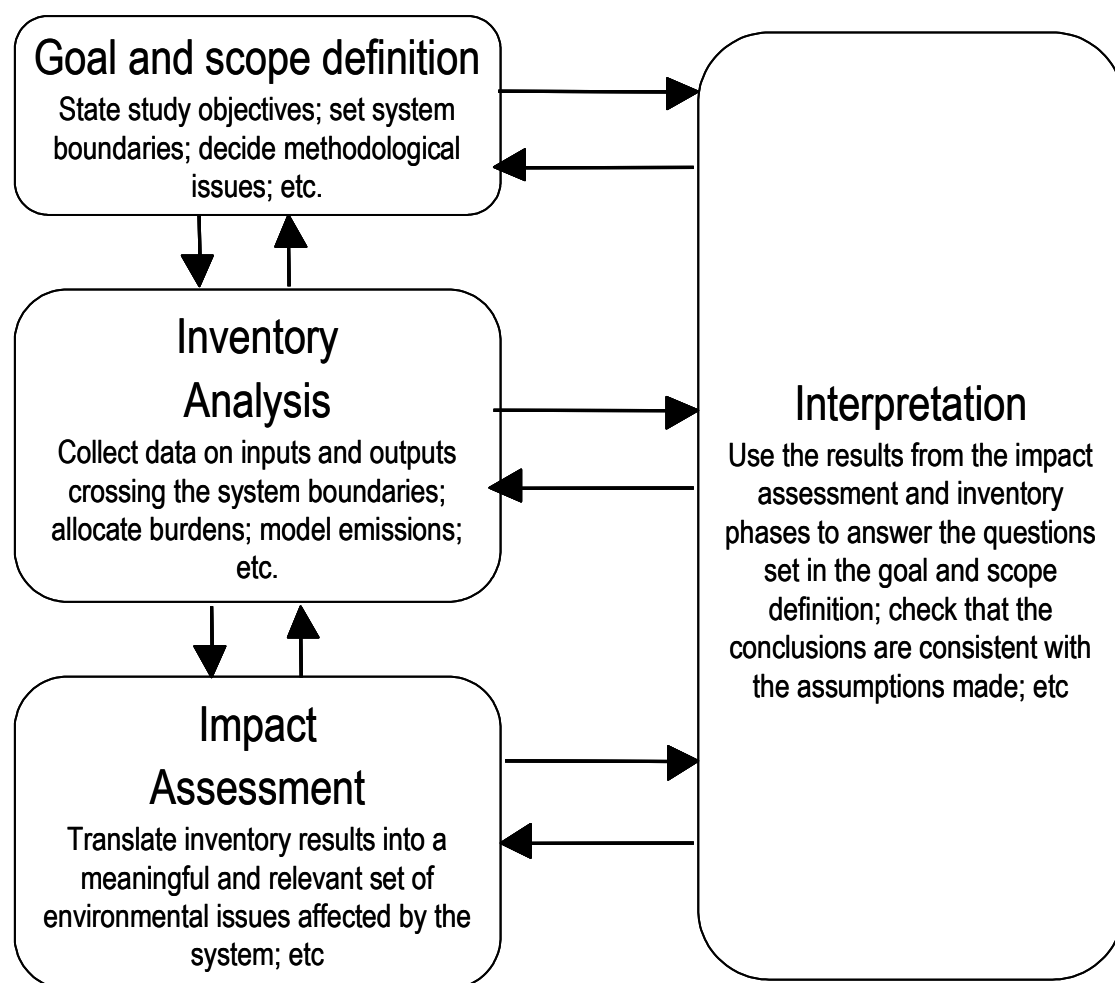


Figure 3. The 4 steps in conducting Life Cycle Assessment as standardized in ISO 14040 and 14044 (ISO 14040:2006(E)).

3.1 Feed types considered

Before introducing the methodological core of this LCA study, a review of the 3 feed types considered is important to understand better the methodological descriptions in following chapters.

3.1.1 Conventional feed

The feed used for the char production in Silfurstjarnan is a conventional (Conv.) aquafeed with high values of fishmeal and fish oil (see table 1). However, the ingredients are chosen specifically to reduce environmental impacts with for example natural pigments according to the producer. This feed type has become some sort of industry standard according to aquafeed expert Dr. Jón Árnason (personal communication, December 13, 2012), but is

becoming obsolete due to rapid changes in feed composition. Table 1 shows the ingredients of the Conv. feed with shares for each type and their country of origin.

Table 1. Ingredients of the Conv. feed with shares and origin.

Ingredients	Conv. %	Origin
Fishmeal	35.50%	Iceland
Fish oil	21%	Iceland
Wheat	10%	UK
Hipro soy meal	18%	Brazil
Corn gluten meal	7%	China
Rapeseed meal	7%	Denmark
Vitamins/minerals	1%	Germany
Aquasta natural colorant	0.50%	USA

3.1.2 ECO feed

The second feed type considered is a new model called the *ECO* feed (ECO) which is still at the research and development stage and has not been tested in the industry. In the ECO feed, the share of fishmeal has been reduced down to 15.7% with increased shares of rapeseed meal and oil. The share of fish oil is 17%. Thus the share of agricultural products has increased at the cost of marine ingredients as can be seen in table 2.

Table 2. Ingredients of the ECO feed with shares and origin.

Ingredients	ECO %	Origin
Fishmeal	15.70%	Iceland
Fish oil	17%	Iceland
Wheat	10%	UK
Soya	12%	Brazil
Corn gluten meal	10%	China
Wheat gluten meal	10%	UK
Rapeseed oil	6.50%	Denmark
Rapeseed meal	17%	Denmark
Vitamins/minerals	1%	Germany

3.1.3 The Black Soldier fly feed

The prototype Black soldier fly feed (BSF) contains much lower values of marine ingredients. The Black soldier fly larva replaces fishmeal completely and lowers the contribution of fish oil from 21% in the Conv. feed to 17% (see table 3).

The research and development of aquafeed from invertebrate species has been ongoing since the 1950's. It has been confirmed as valuable feedstuff for livestock and aquaculture, although it is not commercially widespread throughout the world. The Black Soldier Fly larva (*Hermitia illuscens*) has been studied for the last decades but BSF composting is a relatively new practice in the western world. Available studies indicate that complete or partial replacement of fishmeal and fish oil with Black soldier fly pre-pupae will take place in the coming years, especially in the light of decreasing fishmeal supplies (Sheppard et al., 2008).

The Black soldier fly is found throughout the Western Hemisphere and is a wasp like the fly of the genus *Stratiomyidae*, which thrives in warm places. The fly is completely harmless, does not have a stinger or any mouth functional parts. It does not consume or regurgitate on human food in its adult stage and is therefore not associated with transmission of diseases (Björnsson, 2012). The larva mainly consumes decaying organic matter such as rotting fruits and vegetables, animal manure and spoiled feed (Newton and Sheppard, 2004).

Table 3. Ingredients of the BSF feed with shares and origin.

Ingredients	BSF %	Origin
Fish oil	17%	Iceland
Black Soldier fly larvae	41.60%	Iceland
Wheat	8%	UK
Soya	14.80%	Brazil
Corn gluten meal	10.60%	China
Wheat gluten meal	7.30%	UK
Vitamins/minerals	1%	Germany

3.1.4 BSF production

Since the BSF feed considered in this study has not yet been produced or industry tested, assumptions regarding the BSF production had to be made. Formulations of BSF feed ingredients have been made at Matís and will be used in accordance with Björnsson (2012) and Dr. Jón Árnason. The current formula assumes 41.2% of BSF meal, which is 416 g of BSF larvae dry matter for 1 kg of aquafeed.

The bioconversion rate of the BSF larvae is a highly important factor. It varies depending on diet and ambient conditions. The larva has a potential daily feeding capacity of 3-5 kg/m² and 6.5 kg/m² when fed with market waste and human feces (Diener et al., 2009). Assuming 4 kg/m² of daily feeding capacity and bioconversion rate of 15% yields 0.6 kg per day or 219 kg/m² per year of pre-pupae (Björnsson, 2012). For this study, tomato and potato leftovers (by-product) were considered as raw material inputs for BSF larvae feed because it resemblances the plans that Mátís has for the BSF production. Using leftovers (by-products) from the company kitchen both reduces production costs and the environmental impacts of the production itself. Domestic production of tomatoes and potatoes was modeled for human consumption and it was assumed that 10% goes to waste and used as larvae feed, with allocation calculated accordingly. Further allocation discussions and how this feed input was defined can be found in chapter 3.2.5.

Using the kitchen leftovers, it was decided to use a bioconversion rate of 13% for this study. Björnsson (2012) states that according to reports from various websites and blogs, a bioconversion rate of 15-20% using mixed household waste can be reached. There is however no consensus so far because commercial scale production using household waste has not yet been tested. For comparison, Diener et al. (2011) conclude that 6.1% bioconversion rate can be reached using similar waste. The gap here is fairly large, but Björnsson (2012) also points out that home composting using BSF larvae has been increasing rapidly for the last years, resulting in more knowledge.

To get 1 kg of BSF dry matter with the conversion ratio of 13%, a total of 18.4 kg of tomatoes and potatoes has to be used as feed raw material for the larvae. It was assumed that tomatoes consist of 5.5% dry matter and boiled potatoes of 16% dry matter. This results in 1.978 kg of dry matter with $(0.16+0.055)/2$ and 16.422 kg of water as raw material in for the BSF pupae. Calculated biomass out is then 2.39 kg, which of 1 kg is dry matter and the rest water. For better understanding of the above calculations, see figure 4.

[illegible]

Figure 4. This figure shows how bioconversion rate was calculated considering conversion rate of 13%. Dry weight of potatoes and tomatoes was 5.5% and 16% respectively.

The pupation process itself requires no power, chemicals or water. When the larva is ready to hatch, it climbs up a ramp with 30-40° slope out of the container and falls down to a collecting bin. The larvae is then ready for drying, milling and eventually for BSF meal production (Björnsson, 2012).

3.2 Goal and scope of the study

3.2.1 Goal and scope

In this study, the goal is to conduct an LCA on an Icelandic aquaculture farm and assess the environmental impacts associated with the production of 1 kg of Arctic char from cradle to farm-gate. Further, the goal is to compare existing feed type used in the aquaculture with new feed types under development at Icelandic food & biotech company Matís. As the general conclusion from majority of aquaculture LCA studies show, the feed production is by far the most contributing process in terms of environmental impacts (e.g. Buchspies et al., 2011). Therefore it is extremely important to continue the research of new feed types, as it is the most important factor of the aquaculture process both in terms of environmental impacts and fish wellbeing. By assessing the environmental impacts using LCA, the hot spots within the life cycle will be identified. That information can be used to further improve the aquaculture process and reduce the environmental impacts.

Only one LCA study on aquaculture in Iceland has been conducted so far (Banze, 2011). It is therefore important to further analyze how the environmental impacts of the Icelandic aquaculture scene compares with others around Europe, and even the world. It will give the

Icelandic farms, especially Silfurstjarnan, an opportunity to see where they stand and improve their processes or market their products in line with the results. A better corporate- or product image can be gained by favoring a cleaner product and consequently a cleaner environment. Consumers will benefit as well, having the opportunity to choose environmentally friendly products.

3.2.2 Functional units

The functional unit of this study was chosen to be 1 kg of live-weight Arctic char, cultivated in the Icelandic aquaculture farm Silfurstjarnan, fed with a) conventional feed, b) Black soldier fly feed, c) ECO feed.

3.2.3 System boundaries

The system boundaries for this study were carefully chosen to be in line with similar studies in this field. This is important to be able to compare the outcome of this study to other studies with similar functional units. This study is therefore a cradle to gate assessment as it does not include the processes occurring after the farm-gate. The product stops at the farm-gate, leaving out slaughtering, packaging, transport to consumers, the consumer end-use i.e. buying of the product, cooking, consumption and disposal. If all those processes were taken into account, this study would be a full cradle to grave assessment. It is however evident that the majority of aquaculture LCA's only include the cradle to farm-gate processes (Parker, 2012).

The life cycle of the functional unit is divided into four main phases; fish farming, hatchery, transportation and feed production. System boundaries include background processes such as raw material extraction, energy production, and production of agricultural inputs. In the feed production phase, crop production for ingredients and the fishing for fishmeal and fish oil are within the boundaries as well as feed milling, production and packaging. The transport phase includes transport of all raw materials for feed between countries, all domestic transport between feed production plant and trout farm.

The number of life cycle phases in a study can be subjective but are usually determined by the objectives of any given study. The exclusion or inclusion of phases and processes are determined by the availability of data and the established importance of processes in contributing to impacts (Parker, 2012). For this study, farming equipment was deliberately

excluded for two reasons; a) the objectives of this study are mainly focusing on the comparison of different feed types and b), the anticipated triviality of its contribution, which is expected to be minimal (e.g. Banze, 2011; Ayer & Tyedmers 2009). The manufacturing of transportation vehicles and the fishing vessel are excluded in this study.

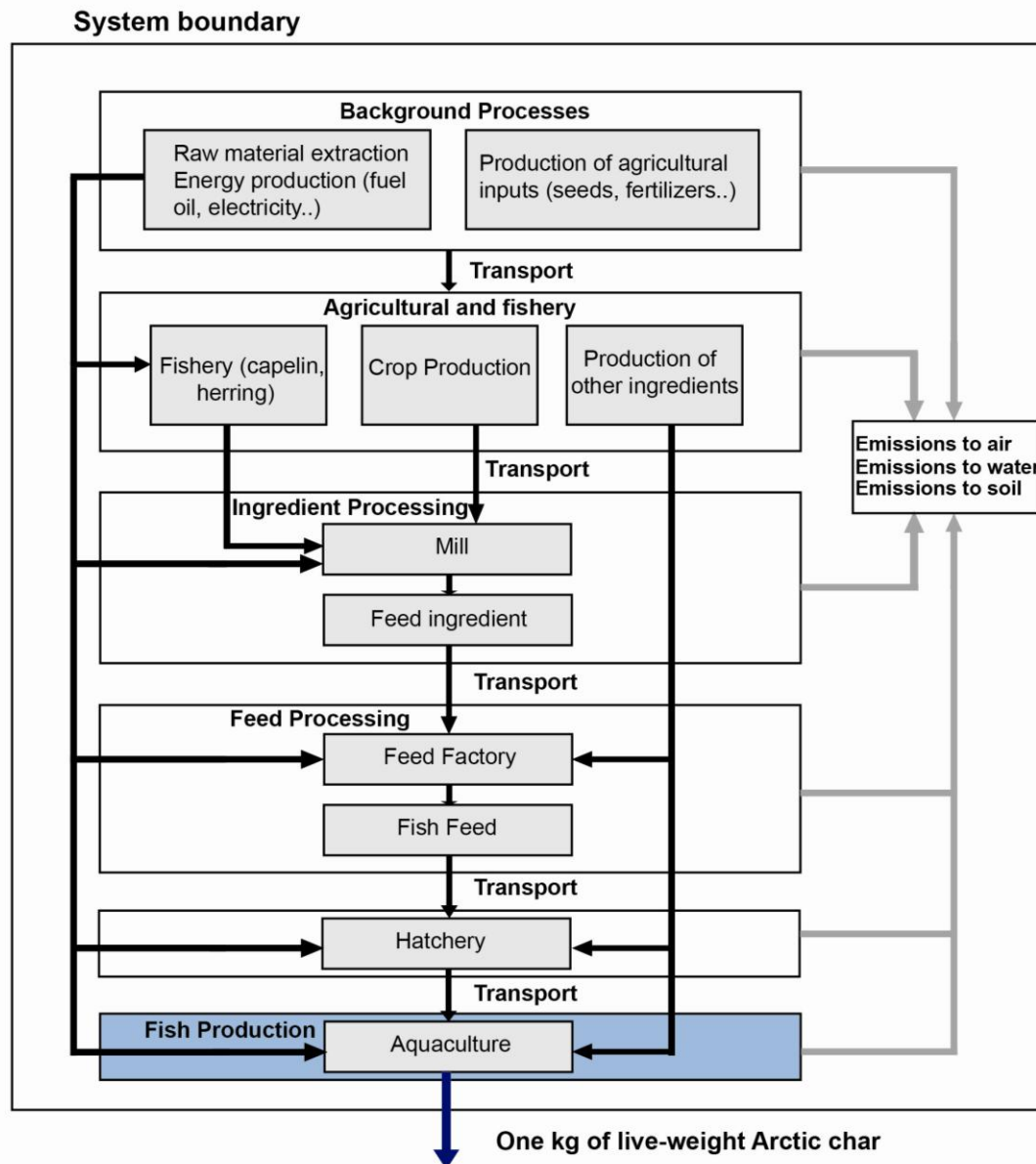


Figure 5. System boundaries of the functional unit.

3.2.4 System description

The trout farming system at Silfurstjarnan is a conventional land-based system. The trout is farmed in large circular outdoor tanks. New water is continuously pumped into the tanks

from on-site wells consisting of fresh and brackish groundwater of different temperature and salinities, seawater pumped up from the shore and geothermal water, which are mixed together to reach the best possible temperature for trout farming. In addition, the warm groundwater compensates for the lack of minerals in the well-water making it a perfect mixture of mineral water (Heiðdís Smáradóttir, project manager in fish farming, personal communication, 23 August 2012). The trout feeding system is fully automated, powered by electricity from the Icelandic national power grid, as well as the water pumps.

3.2.5 Allocation

Allocation in LCA studies is an ongoing problem and issue of debate (Weidema, 2000). Although international methodological standards have addressed this matter, considerable inconsistency is however evident. This can be the cause of the major methodological differences between LCA studies. In LCA, some product systems are multi-functional and deliver more than one product out of the system. For example, fishmeal production produces two co-products; the fishmeal itself and fish-oil. It would not give the right image of the environmental impacts by allocating the burden 100% to the fishmeal. Instead, it is necessary to allocate appropriate shares of the fishery and processing to the co-products. According to ISO 14044 (2006), the study shall identify all co-products and deal with them according to the standard's procedure which is as follows:

- Avoid allocation wherever possible. This includes two steps; a) dividing the unit process in order to allocate them into two more sub-processes or b) by system expansion where one has to include the additional functions related to the co-products.
- If allocation cannot be avoided, the inputs and outputs should be partitioned by some underlying physical relationship. This can be done with mass allocation, energy content or relative economic value.
- If physical relationship cannot be used for allocation, other relationships have to be found between products and functions such as the use of input and output data being allocated in proportion to the economic value of the product (ISO 14044:2006(E)).

For the purpose of this study, mass allocation was used to partition the environmental impacts in all systems yielding co-product ingredients, i.e. allocating co-products based on their mass. Other allocation methods were considered such as system expansion, economic

value and gross nutritional energy content. The use of mass allocation is however in line with many aquaculture and seafood studies done in recent times, although Henriksson et.al. (2011) explain that economic value and gross nutritional energy content have been more commonly used in later publications. The use of mass allocation provides stability and encourages the food industry to make use of by-products because high environmental burden is allocated to them. It is also less time consuming compared to other methods. Economic allocation for example, is affected by high variability in both fish and feed input prices in recent years, making this method reasonably unstable over time (Winther, 2009). System expansion was not thought to be possible in this study because of problems connecting products to the by-product being examined.

Allocation problems arose in several instances throughout this study, mainly when dealing with by-catch at the fishery stage and by-product ingredients in the feed production stage. In the fishery stage where by-catch is landed, the environmental burden needs to be allocated between the target species and the by-catch. The information on by-catch and allocation numbers cannot be revealed in order to protect the marketing competition of Samherji Ltd. the owner of Silfurstjarnan, who provided the data. The many different feed types used in modern aquaculture setting generally contain many ingredients, which are by-products of other processes. The burdens associated with these co-products must be determined by allocating the impacts of the upstream production system between the main product and the by-products (Ayer et al., 2007). This is very time consuming because data has to be gathered on upstream processes where needed. For the same reasons as the fishery phase, the data on feed production allocation cannot be revealed.

In the BSF production phase, allocation problems arose when considering the feed for the larvae. As explained in chapter 3.1.4, tomatoes and potatoes were used as leftovers from human consumption for larva feed. A total of 10% was assumed to go to waste and thus the environmental burdens were allocated accordingly. The real issue however was to determine whether to define this as waste or leftovers. Currently the issue of what is waste and what is not is being debated, and whether to burden it in the current product system or in the previous/next one. According to the EU definitions waste used as raw material is free of burdens (European Commission, 2012). In this case, the burdens are 100% allocated to the previous systems, which would be the tomato and potato productions. However, if it is not a waste, therefore a non-waste/by-product, then the burdens should be

allocated to the study's main product system. The question however is whether the kitchen leftovers are waste or secondary materials. In the case of this study, it was assumed that the leftovers are not waste, but a by-product. Given there is no way to know which part of the vegetable ends up in the waste (nutritional or energetic value could suit this example better if that was the case) the 90/10 allocation based on mass is adequate. This will however be tested to some extent in a sensitivity analysis in chapter 5.2.

3.2.6 Impact assessment method

The environmental impacts associated with the studied system were calculated using the CML 2 Baseline 2000 midpoint approach, originally developed by the Centre for Environmental Studies (CML) of the University of Leiden in the Netherlands (Buonocore et al., 2009). In a midpoint approach, the life cycle inventory results are characterized into relevant environmental impact categories. They are then shown in reference units to indicate their potential contribution to specific environmental impacts. If global warming is taken as an example, all emissions that contribute to that particular impact category are interpreted in CO₂ eq. This value shows the potential contribution to environmental impacts, not the actual extent of resulting damage of the environmental impact (Ayer & Tyedmers, 2008).

The CML method is the most widely used impact assessment method in LCA aquaculture studies, with very few utilizing endpoint methods (Henriksson et al., 2011). The method is one of the most up-to-date of currently available methods and includes a balanced set of impact categories (Buonocore et al., 2009). While endpoint methods provide a more direct approach on issues of concern, they also have far greater degree of uncertainty. Midpoint methods express the actual amount of emissions being released into an environment, while endpoint methods express the biodiversity loss or human health impact as a result of those emissions (Parker, 2012).

In addition to using the CML 2 Baseline 2000 impact assessment method, the Cumulative Energy Demand (CED) v1.08 was used to quantify the actual energy use of the system studied.

3.2.7 Impact categories

The impact categories chosen for this study reflect the most common and important categories used in aquaculture LCA studies. However, there have been debates in recent

times within the LCA sector on which impact categories are relevant and whether current categories used reflect the actual environmental impacts associated with the aquaculture industry (Pelletier et al., 2007). Several practitioners have led an innovation of new impact categories that account for several of the unique interactions characteristics of aquaculture that will improve the usefulness of LCA, such as socio-economic impact categories (Dreyer et al., 2006) and Net Primary Production (NPP) as a proxy for biotic resource use impacts (Papatriphon et al., 2004). While the development of new impact categories is interesting and needed, especially for specialized systems like aquaculture, this study does not introduce new ways of assessing impacts because of time limitations and the investment needed for further research.

The environmental impact categories quantified in this analysis were global warming potential (GWP), abiotic depletion (ABD), acidification potential (ACD), eutrophication potential (EUT), human toxicity potential (HTP), marine toxicity potential (MTP) and cumulative energy demand (CED). By including multiple impact categories, the results provide a broader understanding of the environmental impacts and helps identifying trade-offs between impacts.

The four most commonly used impact categories in seafood LCA are global warming potential, acidification potential, eutrophication potential and cumulative energy demand (Parker, 2012). These impact categories were all chosen for this study as well as human and marine toxin potentials in order to address human and ecological health.

3.2.8 Classification and characterization

In order to calculate characterization factors, classification must be done to organize and combine Life Cycle Inventory (LCI) results into impact categories. For items that only contribute to a single impact category, such as carbon dioxide can be classified into the global warming category, the job is relatively easy. For items that contribute to more than one category, steps have to be taken to assign them to relevant categories by partitioning a representative portion to the impact categories they contribute to, or assign all LCI results to all impact categories to which they contribute. When this has been done, characterization factors have to be found to convert and combine LCI results into indicators of impacts to human health and ecological health by using science based conversion factors. These factors are commonly called equivalence factors. Characterization factors therefore translate different inputs into directly comparable impact

indicators (SAIC, 2006). For characterizing different impact indicators, the following equation is typically used:

$$\text{Inventory Data} * \text{Characterization Factor} = \text{Impact Indicator}$$

If the calculation of methane global warming impacts is taken for example, using the IPCC characterization factors (IPCC, 2007) where methane has the value 25, and we assume the weight of 100 kg from the LCI results, we get:

$$\text{Methane GWP Impact} = 100 * 25 = 2500$$

If we compare the methane with 10 kg of nitrous oxide which has the value 298:

$$\text{Nitrous Oxide GWP Impact} = 10 * 298 = 2980$$

The calculations show that 10 kg of nitrous oxide has a larger impact in global warming than 100 kg of methane.

3.2.9 Normalization and weighting

Normalization and weighting are both optional steps under ISO 14044:2006. Normalization is used to express impact indicator data so it can be compared among impact categories (SAIC, 2006). It is obtained by multiplying the characterization factors by their respective emissions. The sum of these products in every impact category gives the normalization factor. To get normalized results from characterized the characterization factors must be divided with the normalization factors (Frischknecht & Jungbluth, 2007).

Weighting assigns weights or relative values to impact categories based on their importance (SAIC, 2006). If in accordance with the goal and the scope of the study, weighting of the normalized indicator results may be performed (European Commission, 2010).

The CML 2 Baseline 2000 impact assessment method includes the option of normalization, and is thus used in this study to gain a better understanding on the magnitude of environmental impacts.

3.2.10 Description of environmental impact categories

Global warming potential (GWP)

Climate change is related to greenhouse gases released into the air and can have negative effects on human and ecosystem health. Factors are expressed as Global Warming

Potential for time horizon of 100 years (GWP100), in kg carbon dioxide/kg emission. The characterization model is taken from the Intergovernmental Panel on Climate Change (IPCC) (Pré, 2008). GWP is expressed as kg CO₂ eq.

Abiotic depletion (ADP)

The depletion of abiotic resources indicator is related to the extraction of minerals and fossil fuels. The ADP factor is determined for each extraction of minerals and fossil fuels based on concentration reserves and rate of depletion. Further, ADP is concerned with the protection of human health and welfare and ecosystem health (Pré, 2008).

Acidification potential (ACD)

Substances that cause acidification can inflict a wide range of serious impacts on soil, surface- and groundwater, organisms and ecosystems. Acidification is expressed as kg SO₂ equivalents/kg emission (Pré, 2008).

Eutrophication potential (EUT)

Eutrophication is caused by excessive levels of macro-nutrients in the environment from emissions of nutrients to air, soil and water. Eutrophication is expressed as kg PO₄ equivalents/kg emission (Pré, 2008).

Human toxicity potential (HTP)

The Human Toxicity Potential is derived from effects of toxic substances on human environment. For each toxic substance HTP is expressed as 1,4-dichlorobenzene equivalents/kg emission (Pré, 2008).

Marine toxicity potential (MTP)

Marine toxicity potential is derived from toxic substances entering the marine ecosystem. It is expressed as 1,4-dichlorobenzene equivalents/kg emission (Pré, 2008).

Cumulative energy demand (CED)

Cumulative energy demand method is used to provide gross industrial energy use through the life cycle of a product, with environmental performance identified in view of direct and indirect energy inputs used. Direct energy inputs refer to the primary energy required for manufacture, use and end of life. Indirect energy inputs refer to indirect consumption of energy due to the use of for example construction material or raw materials (Frischknecht & Jungbluth, 2007).

3.3 Life cycle inventory analysis

The life cycle inventory analysis is the fundamental basis of every LCA study. It involves the collection and compilation of all the data required to quantify the relevant input and output data associated with the functional unit. This data is used to create a model that contains all inputs and outputs of the product and their amount.

In life cycle assessment methodology, a product system implies a collection of unit processes that are materially and energetically connected and perform one or more defined functions. The unit process is the smallest unit of a product system for which data is collected. The system boundaries define which unit processes belong to the LCA study, but the aim is to include all relevant unit processes, from raw material production to the transportation between all stages (Silvenius & Grönroos, 2003). Data collection and quality

Data availability and data quality are a well know problem in LCA studies. Most studies rely on both background data from databases and real foreground data (site samples). It is highly important to extensively report where the origin of the data comes from, and which processes, data and data sources have been included (Henriksson, 2011).

In this study, collection of data is as accurate and up-to-date as possible. All of the data collected was gathered by the author of this study with interviews with facility managers, questionnaires and on-site measurements. Official data was always used wherever possible. If information was not available, estimations had to be used or secondary data from the Ecoinvent or ELCD databases included in the SimaPro software package. It is important to note that many of the data gathered and used is considered proprietary and sensitive marketing data and is therefore not shown to a full extent in this study, to protect the marketing competition of the companies involved.

The life cycle of the functional unit was divided into four main phases: hatchery, fish farming, feed production and transportation. Each phase included:

Feed production – Raw material extraction, crop cultivation and production, fertilizer and chemical inputs, capture fisheries for fishmeal and fish oil with its production, packaging material, electricity and oil consumption and transportation between all stages.

Hatchery – Hatching of roe and growth of spawns, feed use, electricity consumption, chemical inputs and transportation between all stages.

Fish farming – Trout grow-out, feed use and power use.

Transportation – Transportation between all stages, fuel use and distance.

3.3.1 Feed production

The feed production stage was the most data intensive stage, including agricultural crops from many sources, capture fishery processes and feed milling and manufacturing. Data gathered for this stage was derived from Laxá hf., the manufacturer of the feed used in Silfurstjarnan, Samherji ltd. for the capture fisheries, fishmeal and fish oil production and Icelandic transport companies for more accurate data on transport and average fuel consumption. Data for the Black soldier fly feed was derived from Björnsson (2012), and Dr. Jón Árnason (personal communications, 2012).

The majority of feed raw materials are imported from abroad and all transported via sea to either Reykjavík or Akureyri where the feed production plant is located. Materials stopping in Reykjavík were transported to Akureyri with a lorry. Other ingredients such as natural pigments and vitamins and minerals were also transported via sea to either Reykjavík or Akureyri. The Black soldier fly eggs are imported from Germany and hatched in a special hatching room owned by Matís in Iceland. The larvae is grown until it reaches optimum size, dried and transported to Laxá for feed production. All feed types are transported 173 km to Silfurstjarnan by a lorry after production. Country specific electricity mixes were used in the inventories and proportion of electric energy sources were adapted to national contexts.

Feed conversion ratio (FCR) for the char in Silfurstjarnan is 1:1 with the Conv. feed. That means that 1 kg of feed is needed for 1 kg of live-weight char. Since the BSF and ECO feeds has not yet been tested, the FCR of 1 was assumed since the currently used feed has the FCR of 1. In chapter 5.1, the FCR is further tested in a sensitivity analysis.

Fishery products inventories were based on numbers from Samherji ltd, the owner of the fishing vessel used. Fishing of capelin and herring was used for fishmeal and fish oil and mass allocation was utilized as allocation method for by-catches. Construction and maintenance of fishing vessel was not taken into account.

Most feed production inventories were extracted from the Ecoinvent database and were adapted to the study's methodology and to local contexts due to data limitations on actual crop production in every country considered.

3.3.2 Hatchery

Inventory data for the hatchery was derived from Samherji ltd. Included in this stage is the hatching of roe and growth of spawns, electricity consumption, chemical inputs, feed use and transportation between all stages. Excluded was the selection of brood fishes and their growth, and construction and maintenance of equipment. The hatchery takes place in Núpár in south Iceland, in a facility owned by Samherji. When spawns reach 0.1 g, they are transported to Öxnalækur, another facility nearby owned by Samherji. The char is grown to 70-100 g before it is transported to Silfurstjarnan in a specialized transport truck. The standard ECO feed is used, but adjusted to the growth of spawns. The spawns (0,1-100g) utilize the feed even better than the grow-out char, reaching a FCR of 0.9. Nutrient and solid emissions associated with fish rearing that entered water were assessed by using nutrient-balance numbers from the fish farms in question (Heiðdís Smáradóttir, personal communication, December 6, 2012).

3.3.3 Fish farming

Data on the fish farming stage were taken from one-year reports from Silfurstjarnan aquaculture. This stage includes char farming, feed use, electricity consumption and production. The slaughtering, processing, consumption and end of life were not included. Nutrient and solid emissions associated with fish offal were assessed in the same way as in the hatchery stage. Actual data were taken from reports from Silfurstjarnan. The FCR for the char is as mentioned in chapter 3.3.2, is 1:1.

4 Results

The results of this study presented in this chapter, include findings from the gathering, analysis, calculations and assumptions of data coming from various sources connected to this work. This study was carried out fulfilling the ISO 14040 series standards on LCA and was modeled in the SimaPro software.

The life cycle of 1 kg of Arctic char farmed in Silfurstjarnan aquaculture was divided into four phases; hatchery, fish farming, feed production and transportation. As outlined in previous chapters, this study is strictly a cradle to gate assessment, and therefore excludes processes that occur after the fish is full-grown, such as slaughtering, transport to consumers and cooking. Using this approach, more focus can be put on the aquaculture phase itself and the feed production, which is the main input of this study.

4.1 Overall environmental impacts

The results from the overall environmental impacts are obtained with the Conv. feed in mind because that is the feed type currently in use. Feed comparison will be conducted in chapter 4.3

The characterized results of the functional unit, 1 kg of live-weight Arctic char, cultivated in the Icelandic aquaculture farm Silfurstjarnan, fed with a) conventional feed (Conv.) are presented in table 4.

*Table 4. Total environmental impacts of the functional unit fed with Conv. feed.
ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.*

Impact category	Hatchery	Feed Production	Fish farming	Transport	Total
ADP (kg Sb eq)	1.09E-04	8.69E-03	9.89E-05	1.16E-03	1.01E-02
ACD (kg SO ₂ eq)	6.23E-05	1.37E-02	5.67E-05	2.08E-03	1.59E-02
EUT (kg PO ₄ eq)	2.53E-03	4.35E-03	1.59E-02	2.77E-04	2.30E-02
GWP (kg CO ₂ eq)	1.48E-01	1.76E+00	1.35E-01	1.74E-01	2.22E+00
HTP (kg 1,4-DB eq)	2.27E-03	4.32E-01	2.06E-03	6.49E-03	4.43E-01
MAE (kg 1,4-DB eq)	2.93E-01	2.67E+02	2.67E-01	2.04E+00	2.69E+02
CED (MJ)	43.8	33.7	39.8	2.38	120

It can be seen in table 4 and figure 6, that the feed production generated the highest environmental impact by far, through all categories except eutrophication potential and cumulative energy demand. This is in line with other aquaculture LCA studies, as discussed in chapter 2, that the feed production is the dominant source of environmental impact. Included in the feed production phase are the acquisition and the production of raw materials for the feed itself and the feed milling process.

The fish farming phase contributes mainly to eutrophication potential and cumulative energy demand. Eutrophication in this phase is caused by nitrogen and phosphorus release to water from feed and fish, and cumulative energy demand mainly comes from on-site electricity usage from gridlines to power water pumps, lights, automatic feeders and other on-site equipment. The electricity mix used is 100% renewable, 73.8% hydro and 26.2% geothermal (Orkustofnun, 2010).

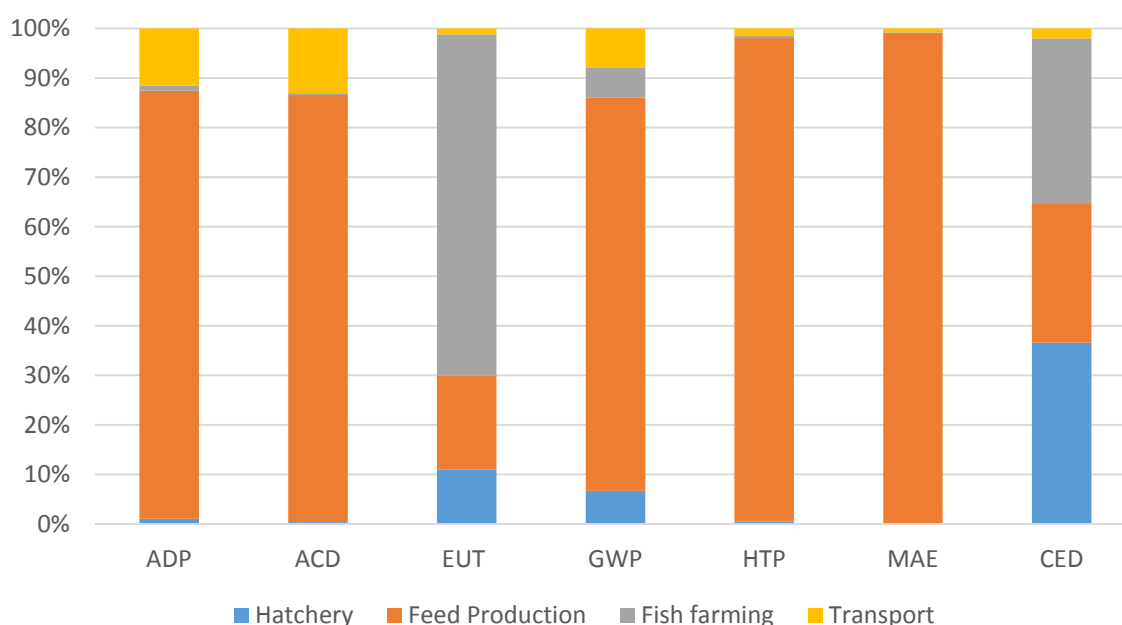


Figure 6. Relative contribution of the functional unit fed with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

The hatchery phase has only minimal contribution on the overall impacts of the life cycle. Emissions from the hatchery come from juvenile production, feed use, fish offal and power consumption. The hatchery's power consumption is greater than for the fish farming or

43.8 MJ versus 39.8 MJ respectively. The difference is related to the usage of heating and lighting.

Normalization was used to better understand the magnitude of the environmental impacts from each phase of the life cycle. As explained in chapter 3.2.9, normalization is an optional step in LCA and is used to express impact indicator data so it can be compared among impact categories.

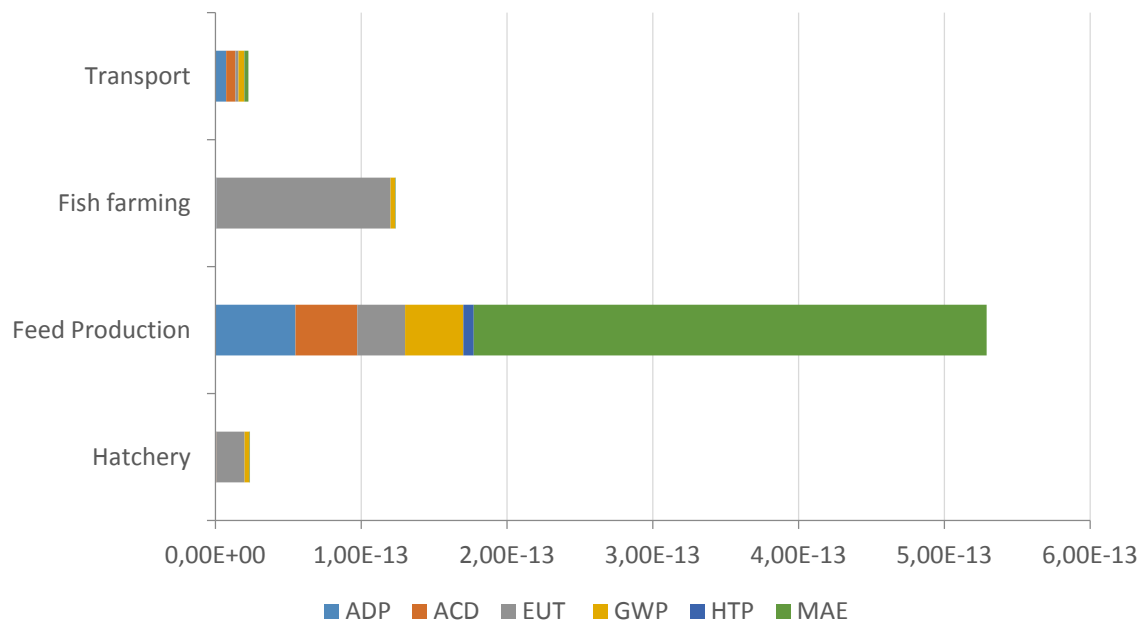


Figure 7. Normalized results of the functional unit fed with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

In figure 7, the dominance of feed production can be seen more clearly, with the fish farming stage coming in second. Feed production contributes significantly to marine aquatic ecotoxicity due to the amount of marine ingredients, and all other categories except eutrophication potential, which is derived mostly from the fish farming stage. Again, it is interesting to see the transport phase so low compared to other phases, despite the magnitude of raw materials imported.

4.2 Transportation

Though the transportation phase is not prominent in the overall environmental impacts, it is important to further add to the discussion whether transportation is a large factor in the process or not. The most interesting result in the transport phase was that domestic transportation in Iceland contributes significantly more to the overall environmental impacts of the transport phase compared to the oceanic carrier, which transports all foreign raw materials to Iceland. As seen in figure 9, the transportation of fish from the hatchery dominates every impact category except acidification potential and eutrophication potential, where the oceanic carrier dominates.

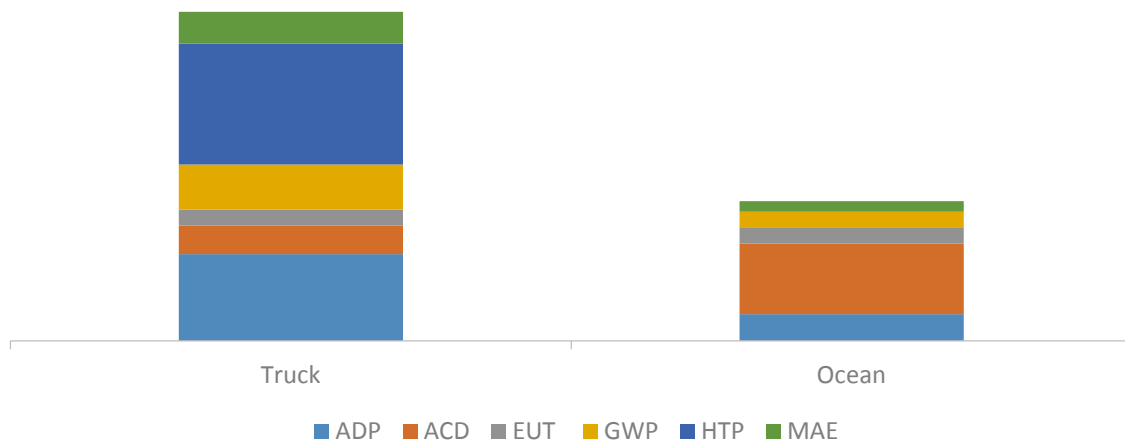


Figure 8. Normalized values of truck transport versus ocean transport, with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

The transportation of feed from the feed production to the aquaculture and the fishmeal and oil from the processing plant to the aquaculture which are all domestic, contribute minimally compared to the oceanic carrier and the hatchery transport, or 6.7% and 7.4% respectively compared to 23.7% and 62% respectively. One of the reasons for high impacts from the hatchery transport and relatively low from the ocean carrier despite long travel distances is the oil consumption/weight carried ratio between a transport ship and a transport truck. To transport fish from the juvenile production a special tank truck is needed which transports large amounts of water and fish. The distance between the hatchery and the aquaculture is relatively long and the fuel consumption is high. In figure 10, normalized results from the transportation phase show the magnitude of impacts.

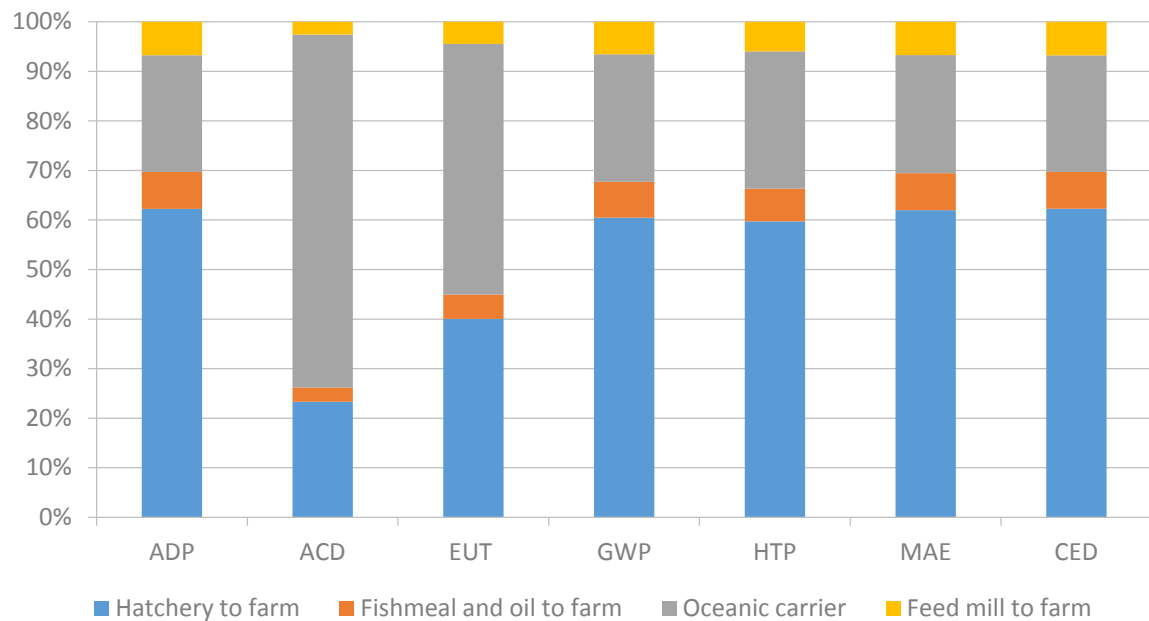


Figure 9. Relative contribution of all stages in the transport phase, with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

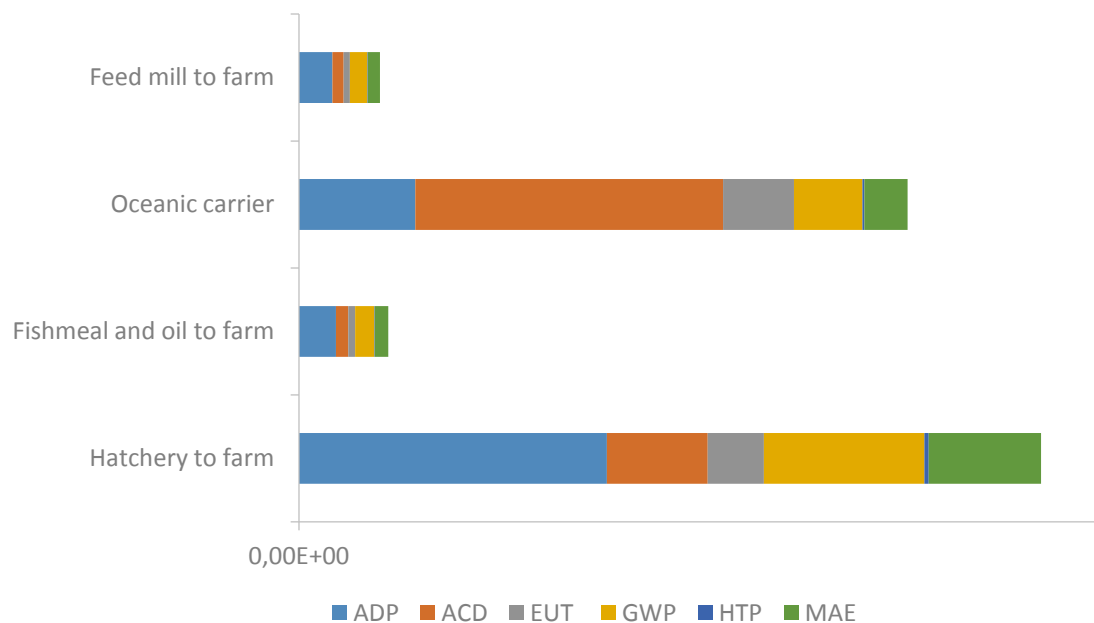


Figure 10. Normalized results of stages in the transport phase, with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

4.3 Comparison of feed types

One of the main inputs in this study was the assessing of the aquaculture with different feed types. Already mentioned feed types all have different features and ingredients which can dramatically alter the environmental impacts of feed production. It has already been demonstrated that the feed has the most environmental impacts overall (Conv.). In this chapter, the other two feed types, namely the ECO feed and the BSF feed will be assessed and compared with the Conv. feed.

4.3.1 Conventional feed

Included in the feed production phase, as explained in chapter 3.3.2, was the production of both marine based and plant based raw materials and feed manufacturing. Transportation between all stages was taken into account, but included in the transport phase of the LCA. This was done to separate the two stages to better understand the impacts from each phase.

In figure 11 the relative contribution of the feed production ingredients and processes can be seen. The production of fishmeal and oil dominates all impact categories except cumulative energy demand. This does not come as a surprise and has been reported by many studies (e.g. Banze, 2011). The marine aquatic ecotoxicity is a dominant impact category in those two processes and is mostly derived from fuel oil burning during fishing stages. As for agricultural ingredients, marine aquatic ecotoxicity is visible but not to the same extent marine ingredients. This is derived through agricultural operations that require use of fuel oil and fertilizer.

The two marine ingredients dominate the cumulative energy demand category with 9.28 MJ for the fishmeal process and 7.84 MJ for the fish oil. The feed milling and production and the soy meal processes are also prominent with 7.62 MJ and 5.71 MJ respectively.

The soy meal production process is visible in eutrophication potential and global warming potential, and as for all agricultural ingredients, comes from crop fertilizers and other agricultural inputs, while global warming potential is derived from CO₂ emissions from agricultural operations.

The magnitude of environmental impacts from the feed production processes can be seen in figure 12 with normalized results, where the fishmeal and fish oil dominate every impact category (cumulative energy demand not included with normalized results).

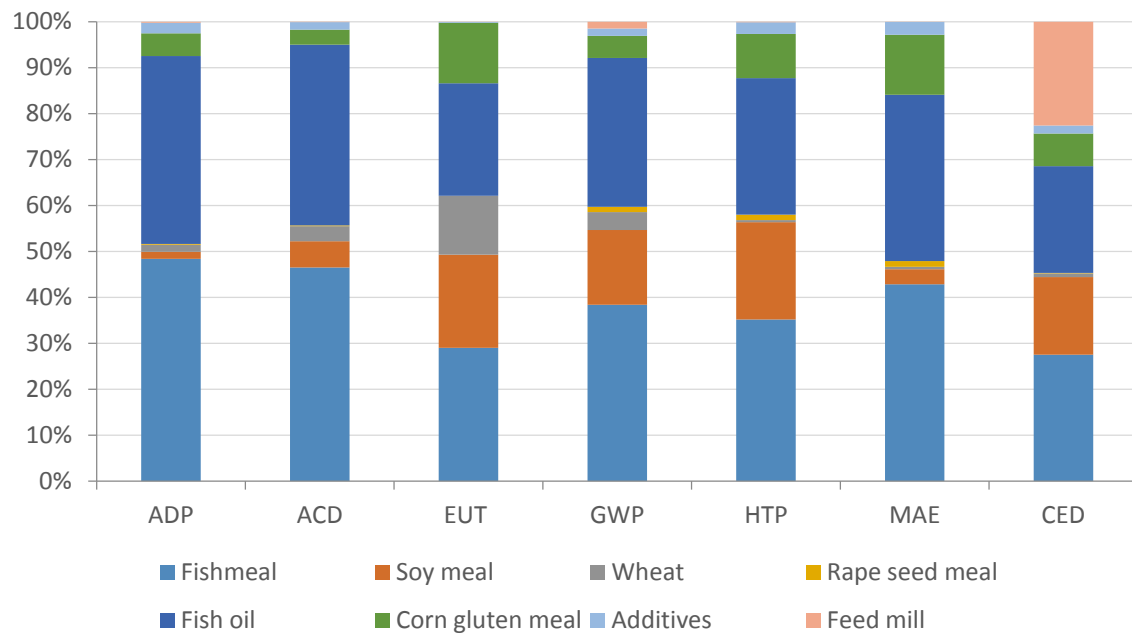


Figure 11. Relative contribution of the all processes in the Conv. feed production phase.
 ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

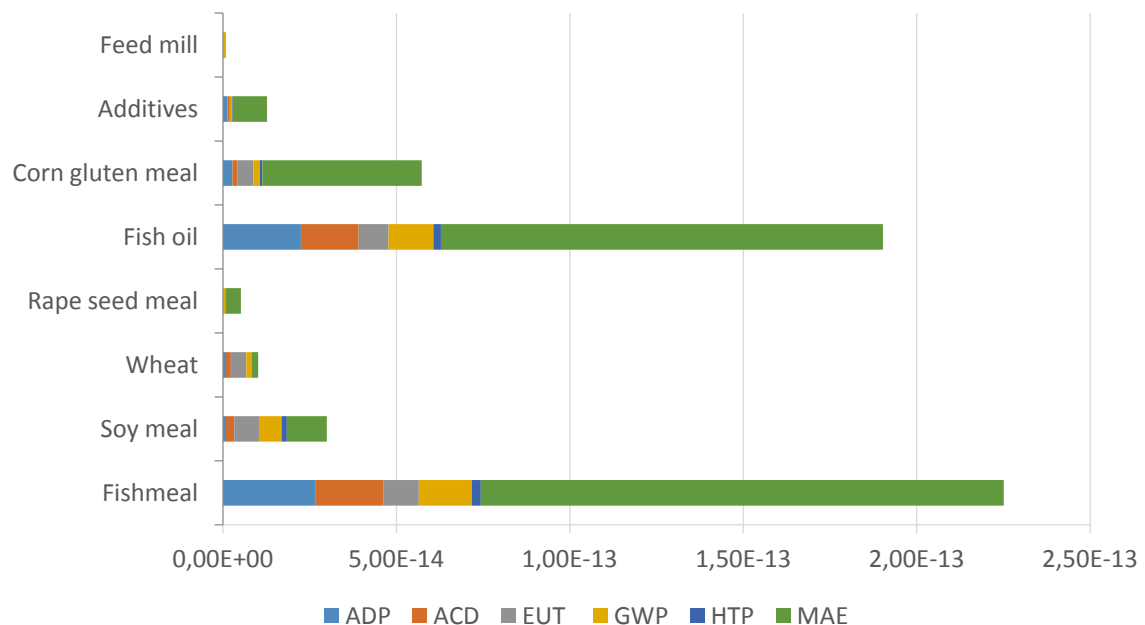


Figure 12. Normalized results of all processes in the Conv. feed production phase.
 ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

4.3.2 ECO feed

The ECO feed is a new formula for the Conv. feed currently used in the aquaculture which is somewhat an industry standard (Dr. Jón Árnason, personal communication, 15 November 2012). The new formula has lowered marine ingredients significantly by increasing the share of plant based ingredients such as rape seed oil. Though marine ingredients have proven to increase environmental impacts, traditional big scale crop production cannot be called environmentally friendly either, with its fertilizer use and heavy machinery.

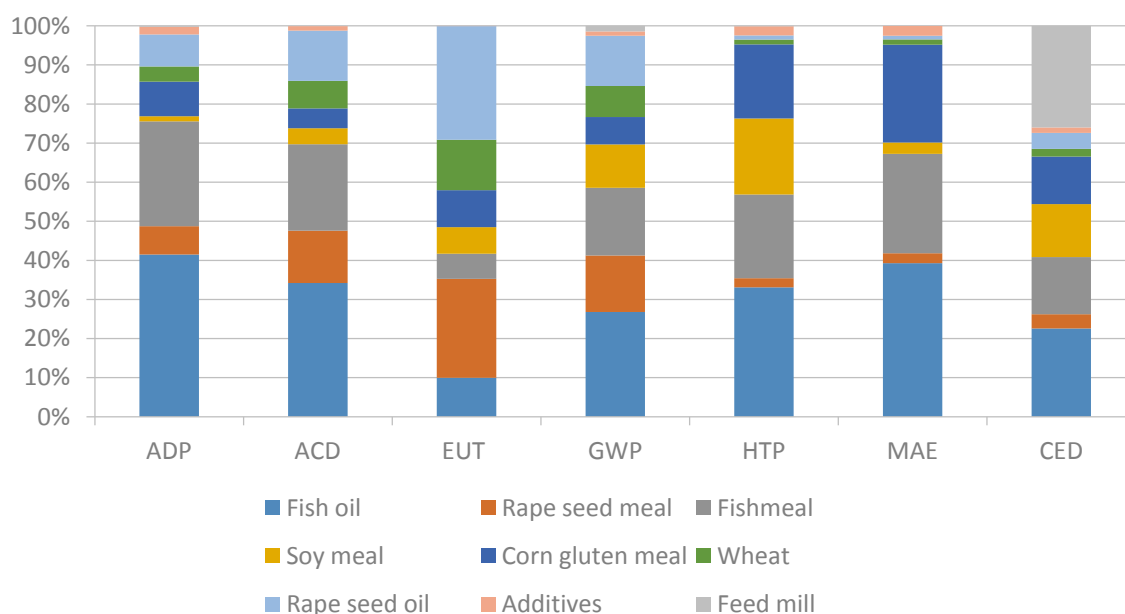


Figure 13. Relative contribution of all processes in the production of ECO feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

In figure 13, fishmeal and fish oil are visible (61% of total impacts), despite a much lower proportion than the Conv. feed offers, or a reduction of 24% combined. They are however not as visible as in the Conv. feed (75.6% of total impacts), which means that plant based ingredients such as rape seed meal and oil have a larger share. Figure 14 shows normalized results of the ECO feed production. Fishmeal and fish oil still make the single highest contribution combined but corn gluten meal, rape-seed meal and oil have considerable impact. Again, marine aquatic ecotoxicity is evidently the largest impact category, mainly from corn gluten meal, fishmeal and fish oil. The cumulative energy demand for the ECO feed production is 28.1 MJ versus 33.7 MJ for the production of the conventional ECO feed.

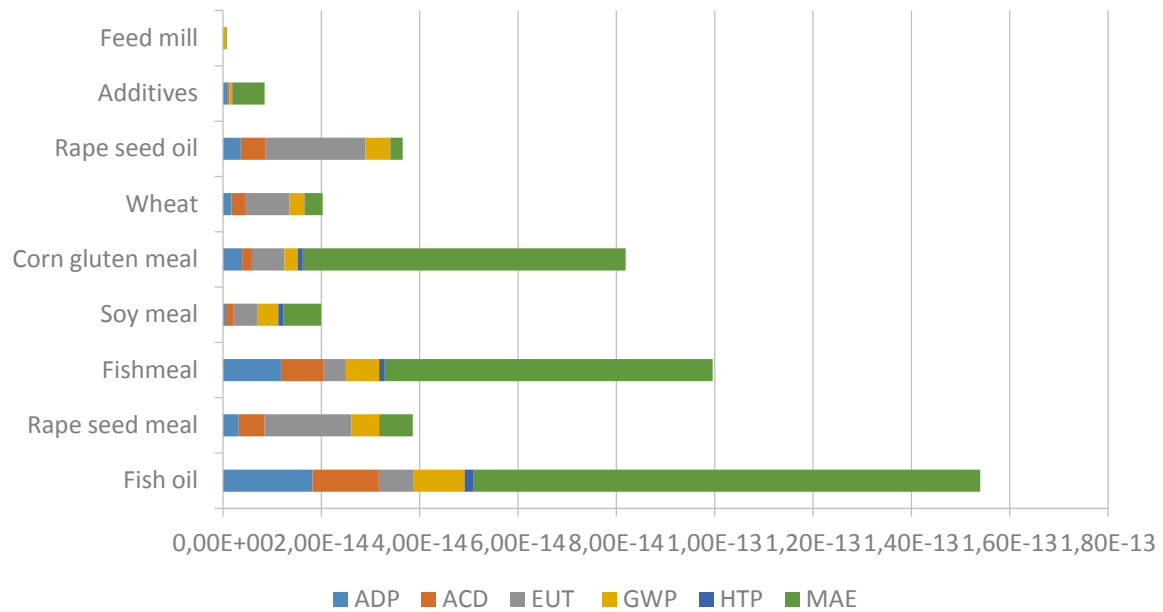


Figure 14. Normalized results for the production of ECO feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

4.3.3 BSF feed

As explained in chapter 3.1.3, the BSF feed is a prototype still in research and development phase, and much like the new ECO feed, still has not been tested. Its ingredient table is very interesting, considering the small amount of marine products it contains, and it was anticipated that the environmental impacts would be lower for the BSF production due to that reason. The BSF meal production however left uncertainty because it had never been assessed using LCA. Processes such as larvae feeding and growing, drying and milling had to be modeled according to literature and assumptions.

In figure 15, it can be seen that fish oil still remains with a big proportion of the overall environmental impacts (44.8%), but dominates only in abiotic depletion potential and marine aquatic ecotoxicity. Fish oil has a share of 17% of the total ingredients, much like in the ECO feed.

The BSF meal, which completely replaces fishmeal, still contributes relatively much to the overall environmental impacts (10.2%), mostly to acidification potential, eutrophication potential and cumulative energy demand.

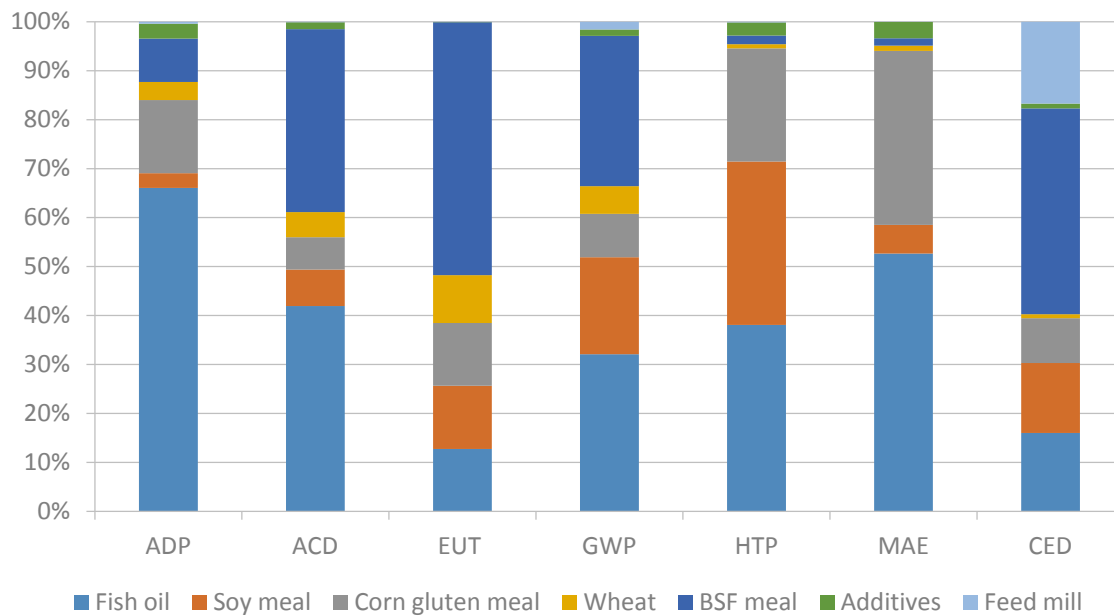


Figure 15. Relative contribution of all processes in the production of BSF feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

The factor which affects the BSF meal production is the feed, namely the larvae feed. For this study tomato and potato leftovers were chosen for larvae feed input. Therefore, tomato and potato production was taken into account but allocated according to the waste thrown which was assumed to be 10%. Electricity consumption during drying, milling and keeping the heat up for the larvae was considerable or 7.2 MJ.

Corn gluten meal and soy meal play a bigger role in the overall environmental impacts. In figure 16 the normalized results show the magnitude of fish oil and that of BSF meal and corn gluten meal, which are considerable. Eutrophication potential in the BSF meal was surprisingly high, and is largely related to potato and tomato production.

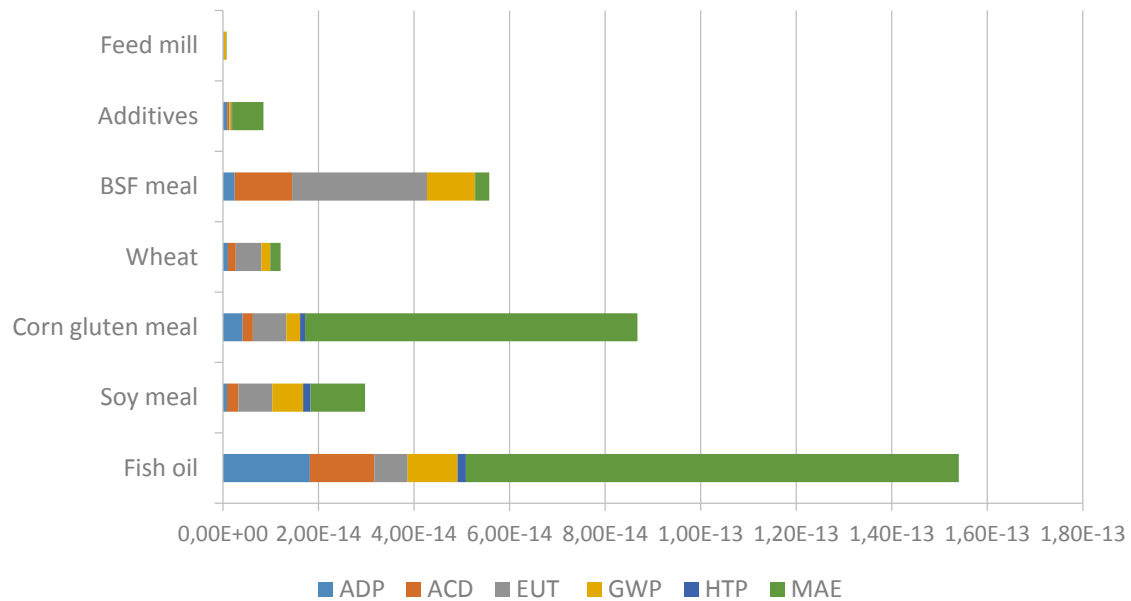


Figure 16. Normalized results for the production of BSF feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

4.3.4 Comparison

To realize the relative differences of environmental impacts between the feed types considered, a simple comparison models were created.

Figure 17 presents the characterized comparison between the feed types. The figure shows that the Conv. feed has the most environmental impacts in every category except for Eutrophication potential (47%) where the ECO (100%) and BSF feed (78%) have higher impacts. This is because the production of Rapeseed oil and Rapeseed meal for the ECO feed causes high amounts of Eutrophication, which the ECO feed has considerably more of than the Conv. feed due to the reduced amount of fishmeal. For the BSF feed, the production of tomatoes and potatoes for larvae feed causes high amounts of Eutrophication.

The BSF feed contributes most to Cumulative energy demand with 39.7 MJ while ECO and Conv. score 28.1 MJ and 33.7 MJ respectively. The high energy demand for the BSF feed derives from electricity usage for drying and milling the larvae and tomato and potato production.

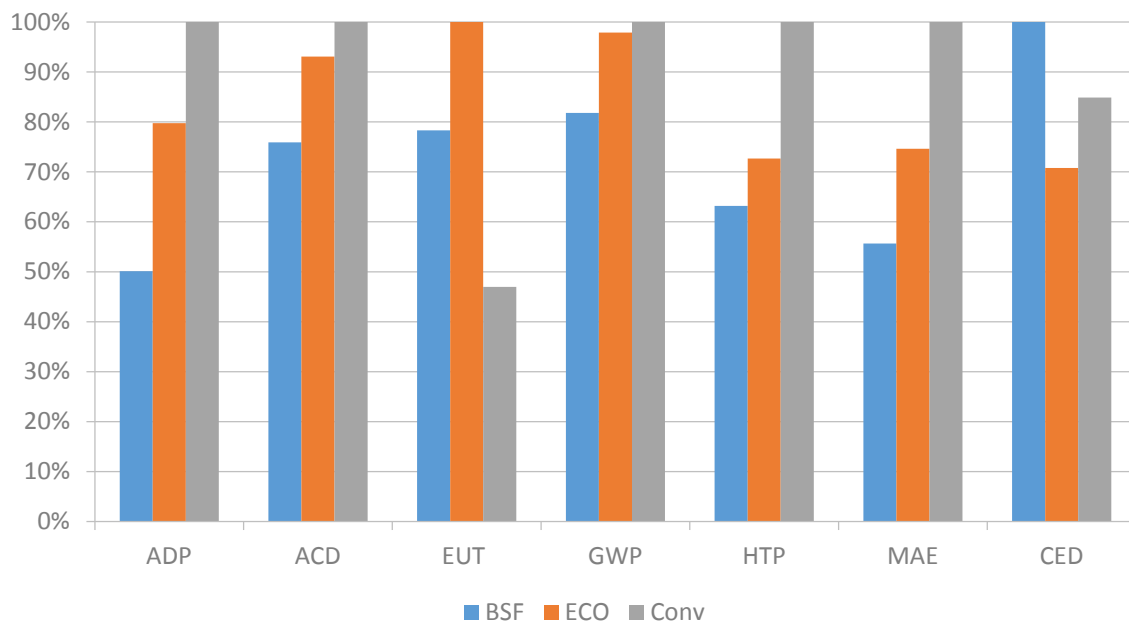


Figure 17. Relative contribution of the production of all feed types considered.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

Figure 18 shows the normalized results from the production of all three feed types considered. The largest contributing impact category by far is the Marine aquatic ecotoxicity potential, derived from the fishing stage (oil combustion for example) of marine ingredients and agricultural operations and inputs such as N, P and K fertilizers. It is evident how environmental impacts gradually decrease from the Conv feed down to the BSF feed which has the lowest overall impacts.

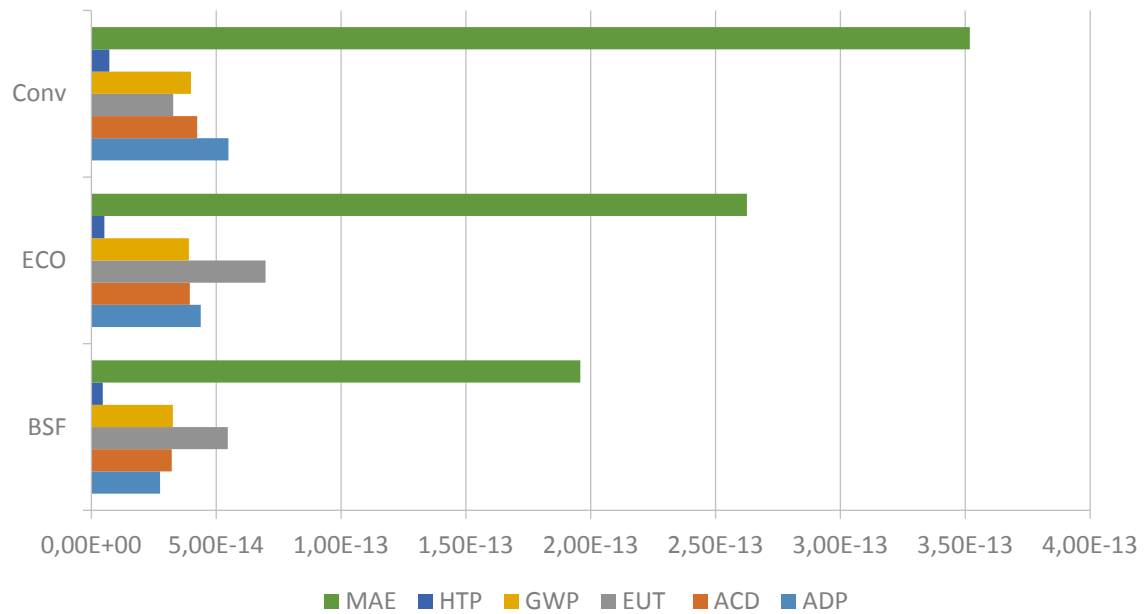


Figure 18. Normalized results from the production of all feed types considered.

MAE - Marine aquatic ecotoxicity potential, HTP - Human toxicity potential, GWP - Global warming potential, EUT - Eutrophication potential, ACD - Acidification potential, ADP - Abiotic depletion.

In table 5, the characterized values can be compared between the productions of the three feed types, with appropriate color assigned to each number. This is a good way to see and compare the hot spots for the production of each feed type. Green has the lowest impact, yellow second lowest and red has the most impact. The BSF feed has the lowest impact in 5 impact categories while ECO and Conv. hold 1 each, but the BSF also has 1 red impact categories. ECO has 1 red category, but holds 5 yellow while Conv. has 5 red impact categories.

Table 5. Characterized environmental impacts from BSF, ECO and Conv feed types with colors representing high and low values in terms of hot spot analysis. Red – high value, Yellow – medium value, green – low value.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

Impact category	BSF	ECO	Conv
ADP (kg Sb eq)	4.36E-03	6.93E-03	8.69E-03
ACD (kg SO ₂ eq)	1.04E-02	1.28E-02	1.37E-02
EUT (kg PO ₄ eq)	7.26E-03	9.27E-03	4.35E-03
GWP (kg CO ₂ eq)	1.44E+00	1.72E+00	1.76E+00
HTP (kg 1,4-DB eq)	2.73E-01	3.14E-01	4.32E-01
MAE (kg 1,4-DB eq)	1.48E+02	1.99E+02	2.67E+02
CED (MJ)	39.7	28.1	33.7

4.3.5 Comparison of fishmeal and BSF meal

Two very important factors when considering environmental impacts of the three feed types is the production of fishmeal and BSF meal because of their large contribution. As has been mentioned throughout this study, the use of fishmeal in aquafeed has many environmental and ecological consequences. Therefore researchers and producers are constantly searching for alternatives or improved types of fishmeal with less impact. The BSF meal introduced in this study has already shown improved environmental performance compared to the fishmeal.

When compared directly with the fishmeal as shown in table 19, the BSF meal shows higher impacts in 2 categories, namely eutrophication and cumulative energy demand, but the fishmeal dominates all other categories.

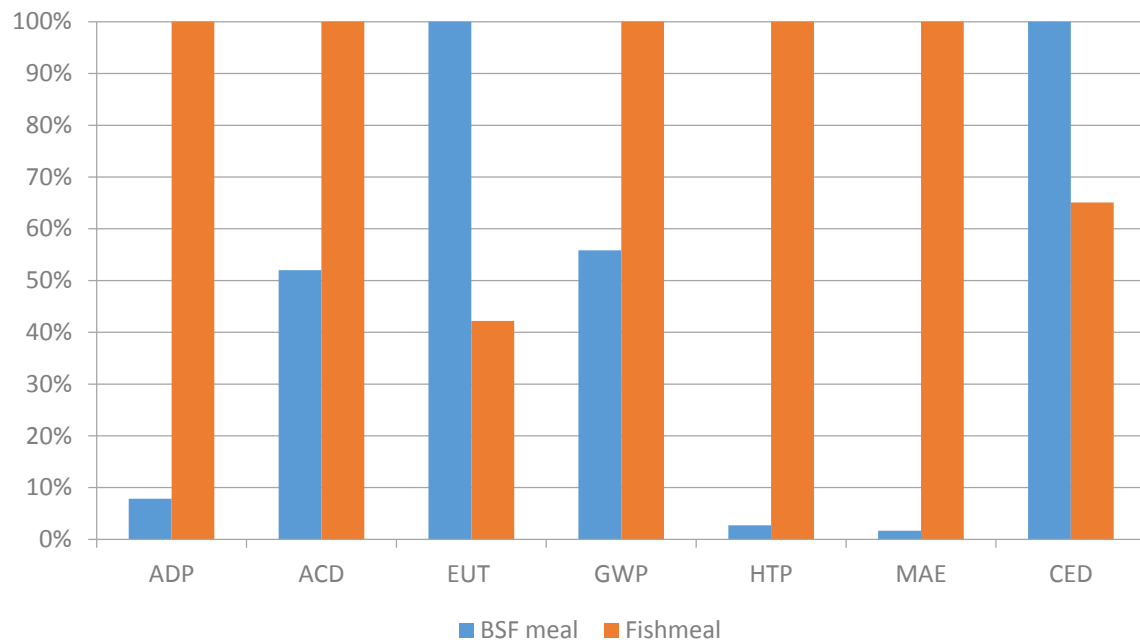


Figure 19. Relative contribution of the production of fishmeal and BSF meal.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

If those two categories are analyzed further, the eutrophication potential is derived mainly from crop and electricity production for the BSF meal but the fishing vessel with diesel combustion for the fishmeal. It might seem odd that the BSF meal uses more energy in terms of MJ per kg produced than the fishmeal, but contributes to a very small amount in the abiotic depletion impact category. The depletion of abiotic resources indicator is related to the extraction of minerals and fossil fuels and does not take into account the energy taken from electricity and other sources. Thus it can be seen very clearly in figure 19 where the normalized results of the production of fishmeal and BSF meal are presented, how dependent the fishmeal production is on fossil fuels, where BSF meal production relies more on electricity, and in this case renewable energy, hence its production in Iceland.

The marine aquatic ecotoxicity potential is almost nonexistent in the production of BSF meal compared to the fishmeal, which is because of the marine based ingredients in the fishmeal.

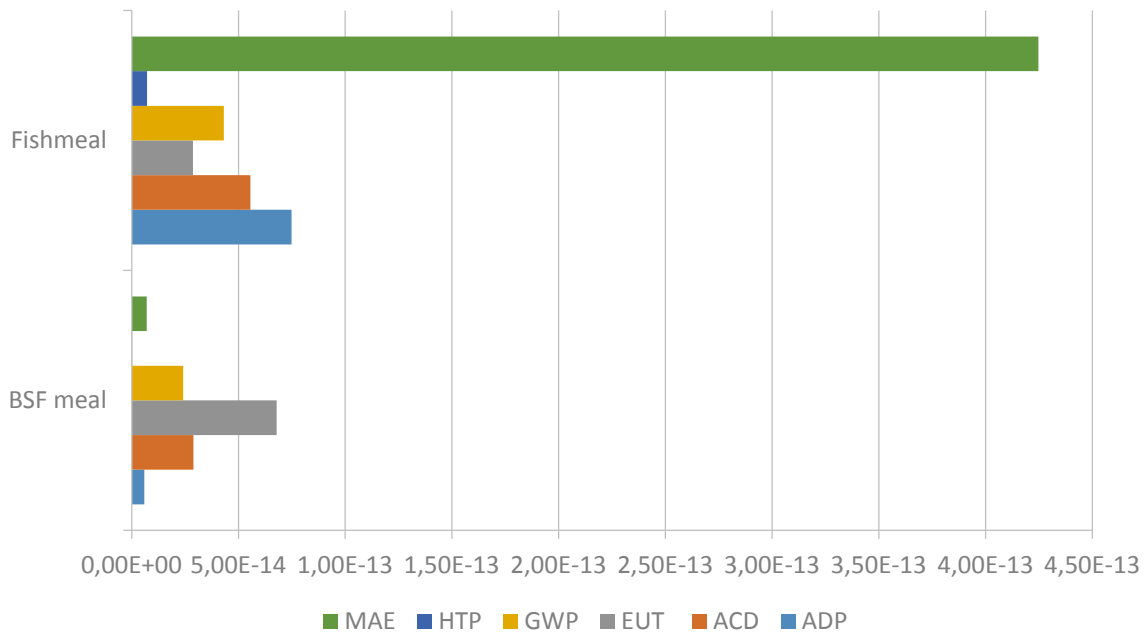


Figure 20. Normalized results from the production of fishmeal and BSF meal.

MAE - Marine aquatic ecotoxicity potential, HTP - Human toxicity potential, GWP - Global warming potential, EUT - Eutrophication potential, ACD - Acidification potential, ADP - Abiotic depletion.

4.3.6 Comparison of fish oil and rapeseed oil

Fish oil is derived from fish in the same manner as fishmeal, and is therefore very dependent on fossil fuels as demonstrated in chapter 4.3.4. Some studies have been conducted to compare feed types with high amount of marine ingredients versus plant-based ingredients. Boissy et al. (2011) studied the environmental impacts of plant-based salmonid diets and found that the use of plant-based ingredients does not decrease the environmental impacts by a large margin, but shows that its use instead of fish oil and fishmeal could drastically decrease the pressure on aquaculture on marine biotic resources.

In figure 21 we can see a similar trend to figure 19 in terms of abiotic depletion, cumulative energy demand, marine aquatic ecotoxicity potential and eutrophication, but the rape seed oil contributes to higher global warming potential and acidification potential contribution for both rape seed oil and fish oil is almost even. The difference in abiotic depletion is however not as vivid as rape-seed oil production includes some use of fossil fuels.

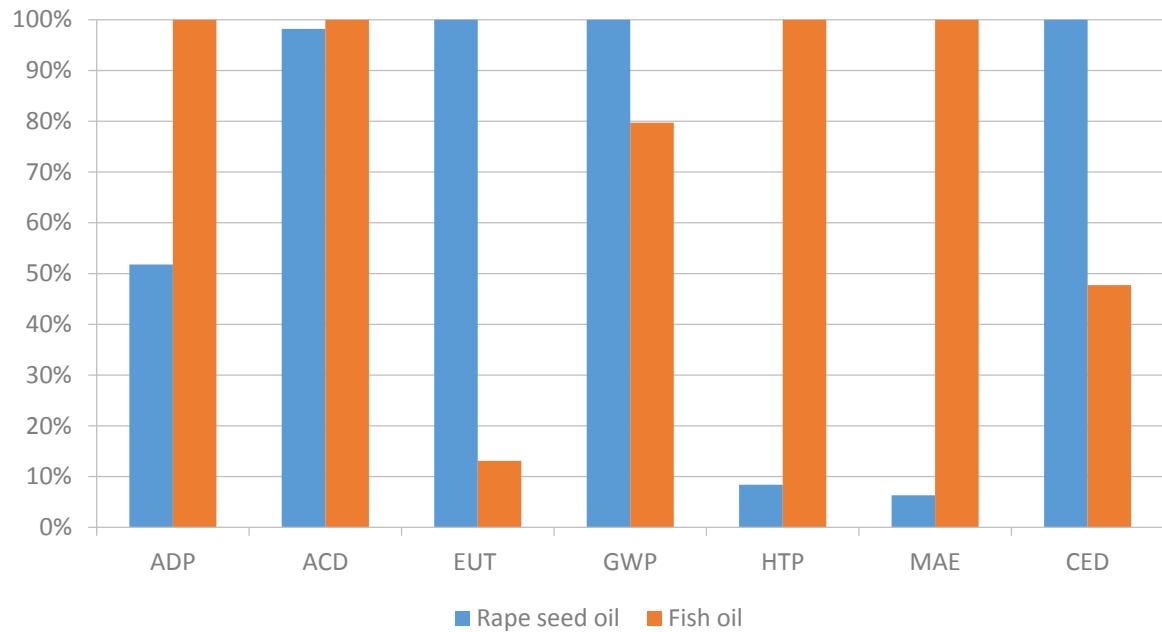


Figure 21. Relative contribution of the production of Rape seed oil and Fish oil.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

The same can be said for the normalized results in figure 22, that is, the trends are similar to the production of fishmeal and BSF meal. However the eutrophication potential is much higher when it comes to the rape-seed oil. The main contributors to eutrophication are the fertilizers used and diesel oil use in the rape seed crop production.

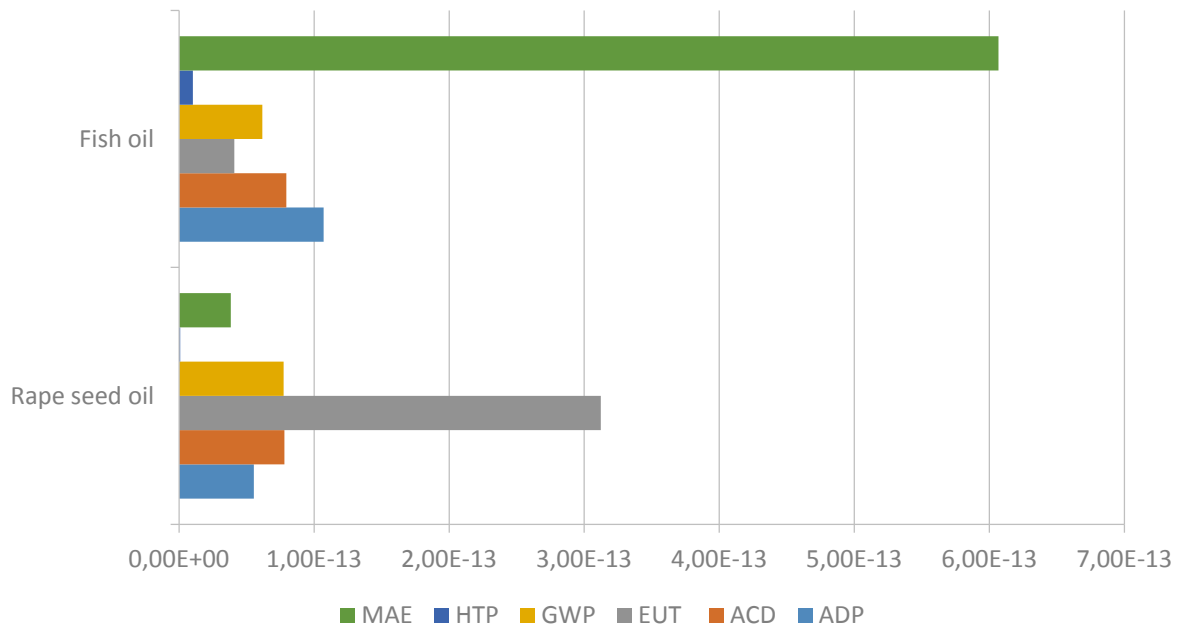


Figure 22. Normalized results from the production of Fish oil and Rape seed oil.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

4.4 Carbon footprint

Carbon footprint, global warming potential, greenhouse gas emissions and climate impact are all synonyms for weighted sums of emissions contributing to global warming. In recent years the focus on carbon footprint of products and product systems, and even human life, has been central to general environmental discussions, partly because it seems to be the impact category that most understand and can relate to. Therefore it is getting more and more common to show the carbon footprint of a product for example, given in a single score of CO₂ eq.

The source of the carbon footprint of aquaculture systems and fisheries is somewhat different. In fisheries, the carbon footprint is derived mainly from fuel use which explains why there is a correlation between energy use and greenhouse gas emissions. In aquaculture however, the agricultural production of feed ingredients is the main contributor with biogenic emissions in the form of methane and nitrous oxide which have a much higher climate potential than carbon dioxide (25 kg CO₂ eq./kg and 298 kg CO₂ eq/kg respectively) (Winther et.al., 2009). But aquaculture feed production shares the carbon footprint from both fishery and agriculture. It is therefore interesting to assess if less use of

marine ingredients at the cost of higher use of agricultural ingredients lowers the total carbon footprint.

In a recent study, Ytrestøyl et al. (2011) assessed five different feed compositions for carbon footprint, including feed with high content of marine ingredients, poultry by-products and high content of plant ingredients. They found out that only marginal difference was between feed compositions, and even changing the diet from 85% plant ingredients to 88% marine ingredients resulted in minor changes, or from 2.47 CO₂ eq./kg to 2.40 CO₂ eq./kg. This is in line with what Boissy et al. (2011) found about environmental impacts of high marine versus high plant ingredients.

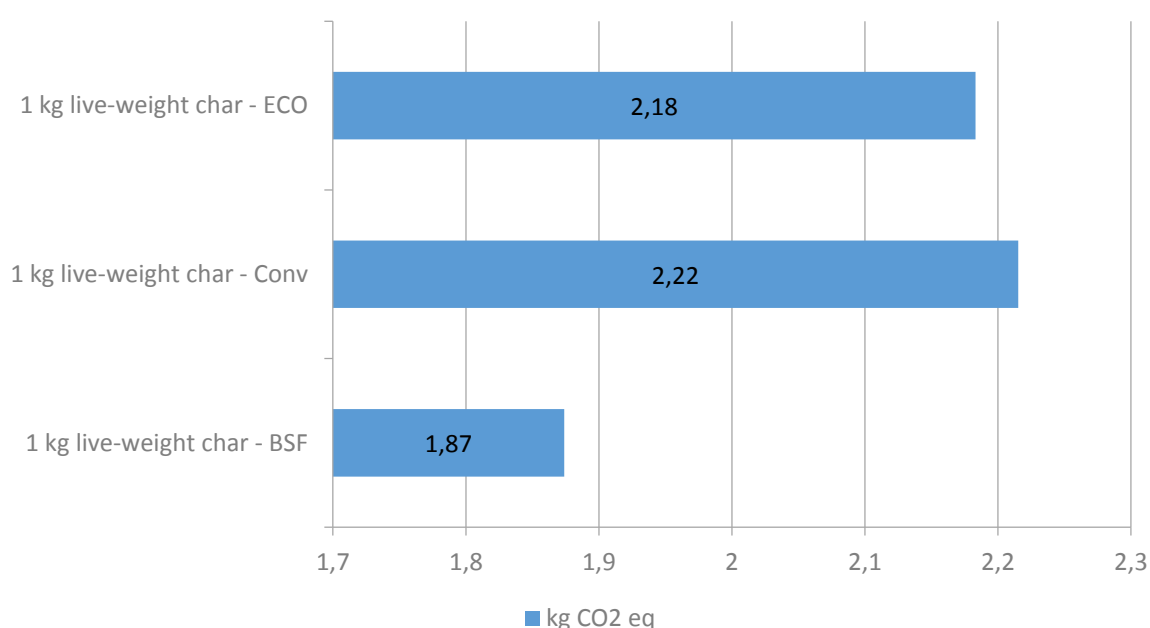


Figure 23. Carbon footprint of the functional unit with all feed types considered presented in CO₂ equivalents.

In figure 23 the carbon footprint of the functional unit is presented with all feed types considered in this study. The functional unit fed with the BSF feed scores a carbon footprint of 1.87 CO₂e/kg which is considerably lower than the functional unit fed with the Conv. and ECO feed.

In figure 24 the relative contribution of the main processes and substances contributing to the carbon footprint are shown. Naturally the fishing vessel contributes lowest in the BSF feed due to low marine ingredients, or 22%, while Conv. and ECO contribute 48% and 34% respectively.

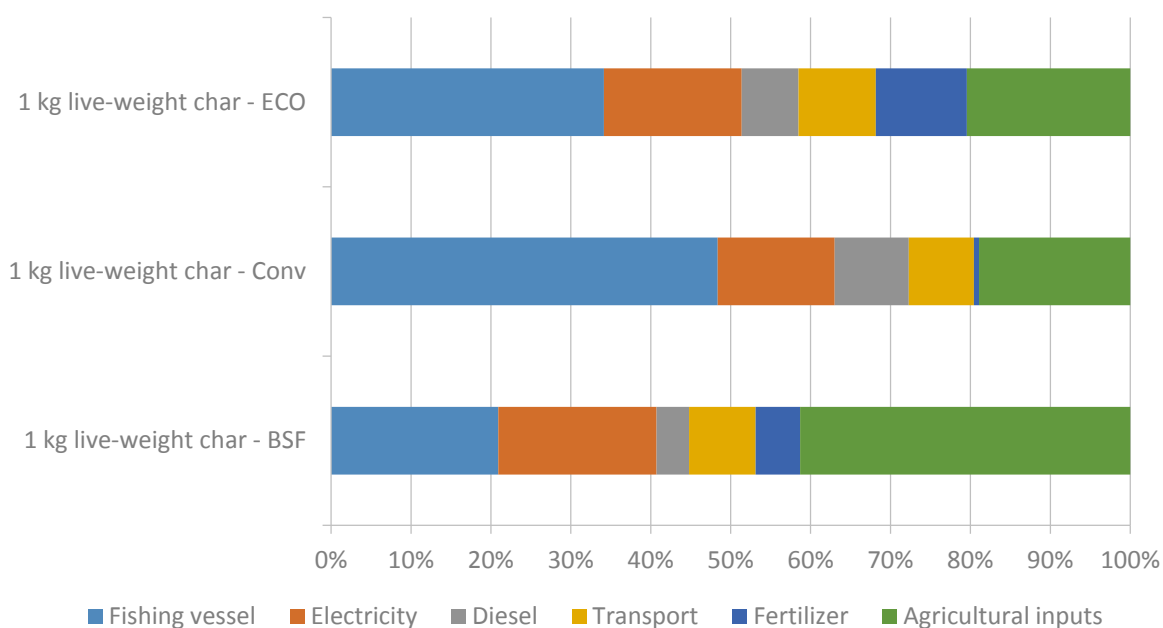


Figure 24. Relative contribution of the main processes and substances contributing to the carbon footprint of the functional unit fed with all feed types considered.

However, the share of agricultural inputs is much higher with the BSF feed compared to the others, or 32%. Electricity also has a larger share of carbon footprint due to emissions from hydro- and geothermal plants as presented in the ELCD database. The ELCD database has a specific electricity mix process for Iceland that was utilized. The CO₂ for every produced MJ is considered to be 0.00623 kg CO₂ eq. This does however not seem to increase the total carbon footprint of the BSF feed or put it on a pedestal with Conv. or ECO. The ECO feed scores a lower carbon footprint than the Conv. with less marine ingredients and higher agricultural ingredients.

5 Sensitivity and scenario analysis

Sensitivity analysis is often required in LCA studies to estimate the effects of the choices made regarding methods and data on the outcome of the study. This chapter could nonetheless be called a scenario analysis due to the nature of implemented changes.

5.1 Changing Feed Conversion Ratio to 0.8 and 1.2 in relation to carbon footprint

As mentioned in chapter 4.4, carbon footprint is at the center of discussions regarding environmental impacts, because it is the impact category that most understand and can relate to.

Although the FCR for the Arctic char could be considered very good, there is always room for improvements. Since feed is the most costly part, both in monetary and environmental terms, of the whole aquaculture process it would be a win-win situation to reduce the amount of feed needed. Following is a figure showing the carbon footprint of the functional unit fed with all feed types considered with FCR 0.8, 1 and 1.2.

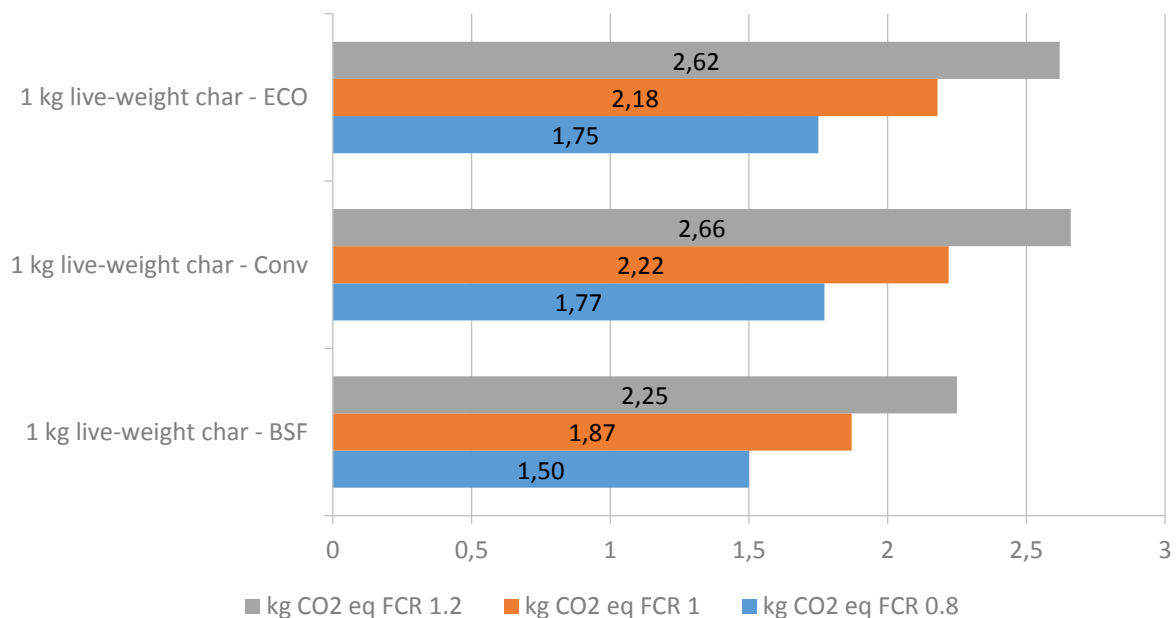


Figure 25. Carbon footprint of the functional unit fed with ECO, Conv. and BSF feeds, with FCR 1.2, 1 and 0.8. Presented in kg CO₂ equivalents.

Since the feed production always has the largest environmental impacts by far, the carbon footprint of every feed type follows the reduction or increase in FCR as can be seen in figure 25. Further, the weight transported, energy used and so on also increase or decrease with the FCR, which explains the almost flat increase or decrease in numbers. For example, by decreasing the FCR for Conv. feed to 0.8, the carbon footprint lowers from 2.22 kg CO₂ eq. to 1.77 kg CO eq., which is almost a flat 20% decrease.

5.2 BSF larva feed scenarios

One of the uncertainties associated with the BSF feed production was the bio-conversion of the BSF larva. Allocation issues arose when deciding the feed for the larva and how it was derived and described. The feed was modeled as leftovers from human consumption as explained in chapters 3.1.4 and 3.2.5. However, as this was an uncertain factor, sensitivity analyses are crucial.

It was decided to analyze how the BSF meal production changes with different allocation methods. In figure 26, BSF meal production with 90% allocation means that 10% is avoided as leftovers, and fed to the larvae, which could be called normal.

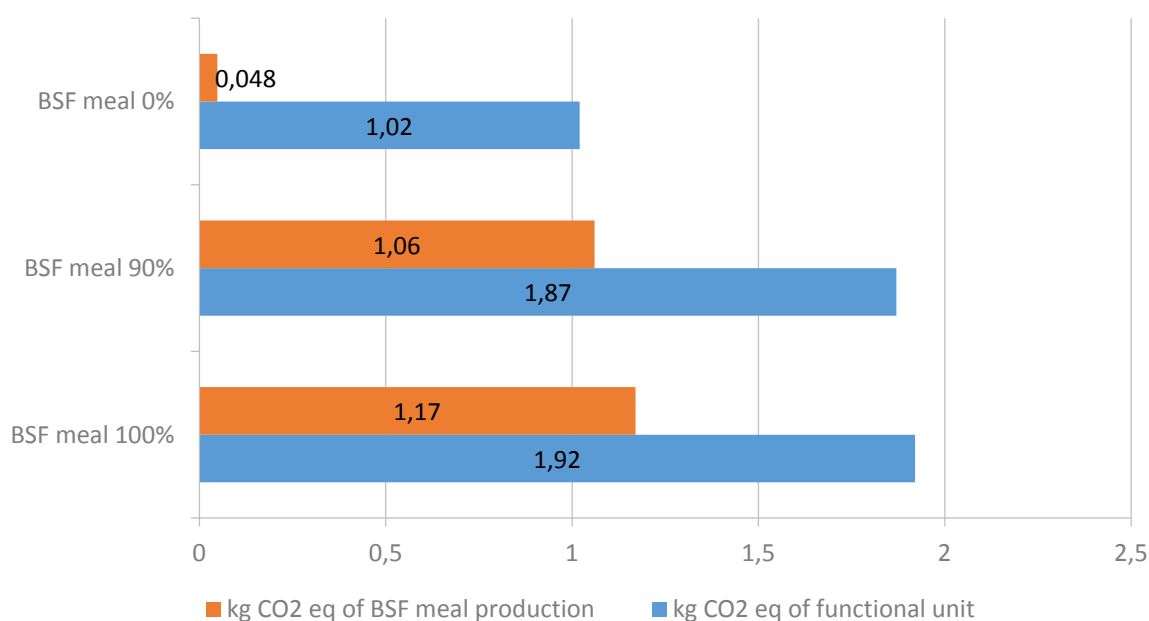


Figure 26. Carbon footprint of BSF meal production and functional unit fed with BSF feed, with 0%, 90% and 100% allocation. Presented in kg CO₂ equivalents.

A percentage of 100% means that the production of tomatoes and potatoes are 100% allocated to the production of BSF meal, as if they were specifically produced for BSF larvae production. A percentage of 0% means that the leftovers are neutral and considered waste from human consumption, removing the production of potatoes and tomatoes from the analysis. These changes are presented in kg CO₂ equivalents or carbon footprint in figure 26, as well as the changes in the total carbon footprint of the functional unit fed with BSF feed. It can be seen that by deciding to model the potato and tomato production as waste from human consumption and thus zeroing it out, the total carbon footprint of the functional unit lowers to 1.02 kg CO₂ eq., or 45.5% decrease, which is derived mainly from electricity production.

In figure 27 the normalized results from the production of BSF meal with 0%, 90% and 100% allocation as explained above are presented. Not surprisingly, total emissions increase by roughly 10% with 100% allocation, and are almost nonexistent with 0%.

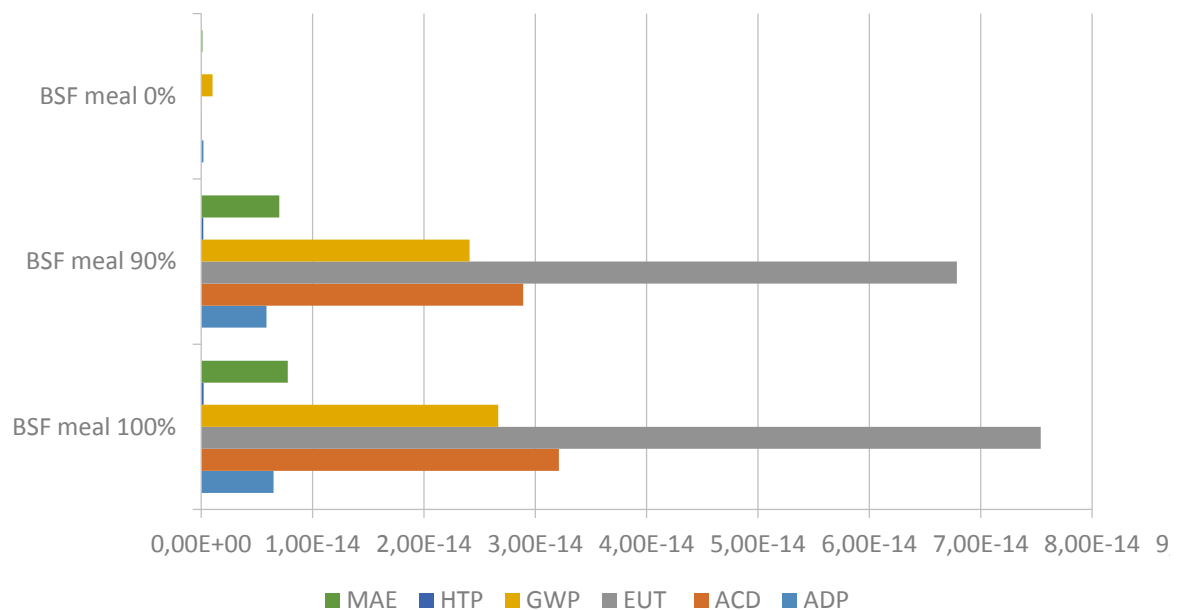


Figure 27. Normalized results from the production of BSF meal with 0%, 90% and 100% allocation.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential.

5.3 Water recirculation

In modern aquaculture settings, there are many ways to build and maintain fish farms in terms of technology and location. Of course, these factors are chosen in relation to which species is being farmed at a given time. This study assessed the environmental impacts of a land-based flow-through system, but how do the alternatives compare? Other types, such as marine net-pen systems, marine floating bag systems and land-based recirculating systems all have their special niches. Since the data for a land-based system has been gathered for this study, it is interesting and fairly easy to change it to a recirculating one and compare the impacts.

In figure 28 the comparison of the functional unit fed with Conv. feed with and without a recirculation system can be seen. Global warming potential shows 6% increase while Cumulative energy demand shows 25%. The tradeoff is visible in eutrophication potential with a reduction of roughly 70%. This confirms what Ayer and Tyedmers (2008) found in their study, and leaves the question open about whether this tradeoff is worth it.

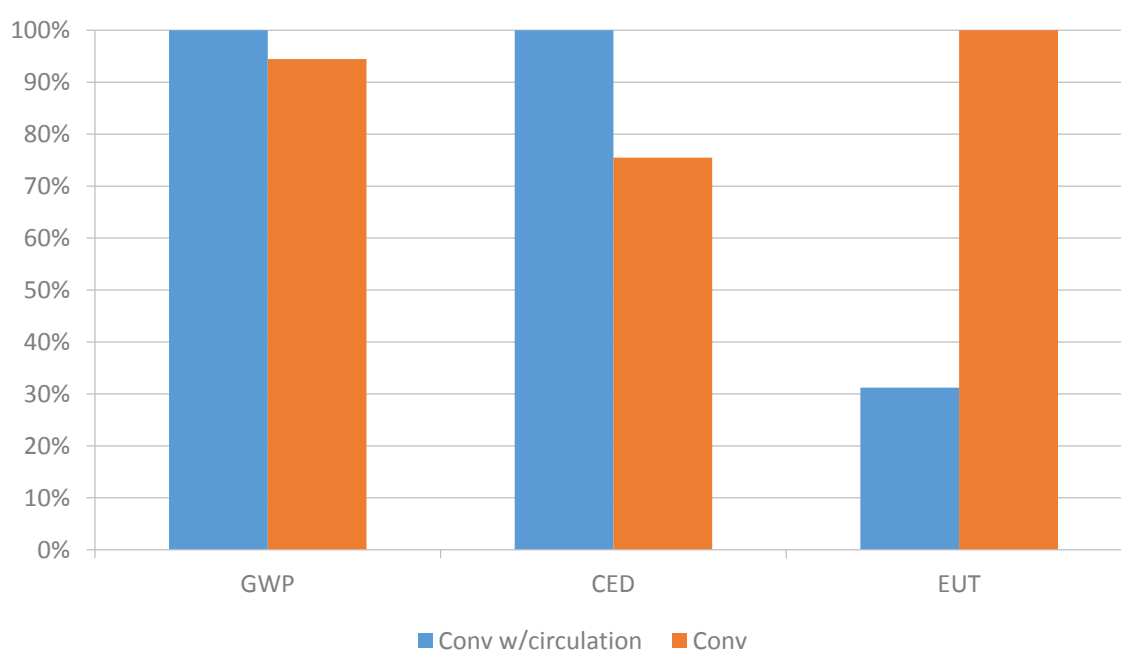


Figure 28. Relative contribution of the functional unit fed with Conv. feed with water recirculation and without water recirculation (normal).

GWP - Global warming potential, CED - Cumulative energy demand, EUT - Eutrophication potential.

5.4 Expanding the system boundaries

As explained in chapter 3.2.3, system boundaries were chosen to be comparable with other similar studies. However, the processing, distribution and end-life of a product is of course an important factor of a life cycle study that captures the impacts from cradle to grave. Thus it was decided to expand the system boundaries to capture the fish packaging as well as transportation to consumers in the United States of America, as this is a big market that Samherji Ltd. focuses on. It can however not be considered a full cradle to grave assessment since the end of life of the product, that is consumption and disposal was not taken into account because data was not available.

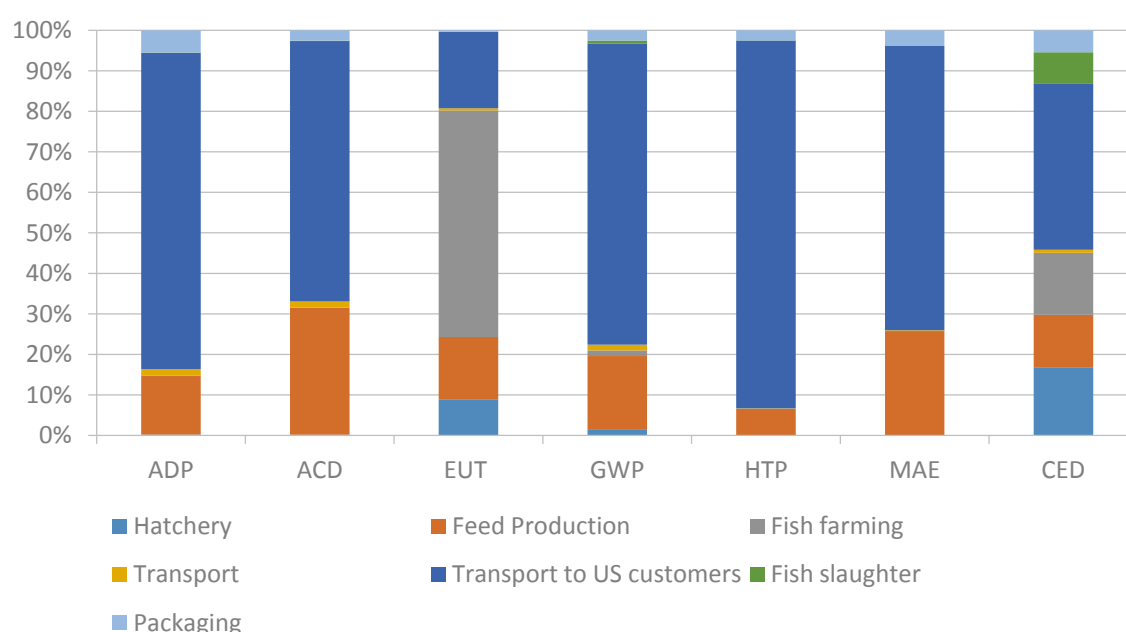


Figure 29. Relative contribution of the functional unit fed with Conv. feed with extended system boundaries including fish slaughtering and transport to the United States of America via air.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

The Arctic char was considered to be packed into EPS boxes containing two gel mats and two layers of food contact films and transported from Keflavík, Iceland via air to New York, USA. The functional unit holds, that is, 1 kg of fish is still transported and fed with Conv. feed.

Figure 29 shows the relative contribution of the functional unit fed with Conv. feed with the expanded boundaries. It is very visible how the transport to US customers has replaced the feed production from being the most dominant process. It contributes to 65% of the

total environmental impacts with the extended boundaries, while the feed production merely contributes to 23% of the total, as opposed to 77% with the original system boundaries. As a result, that is, how very dominant and taxing air transport is on the environment, transport via sea was also looked at. By replacing the air freight with an oceanic barge, transporting the fish the exact same distance, the environmental impacts lowered considerably as can be seen in figure 30. In fact the reduction was so great that transport to US customers only accounts for 1.5% of the total impacts.

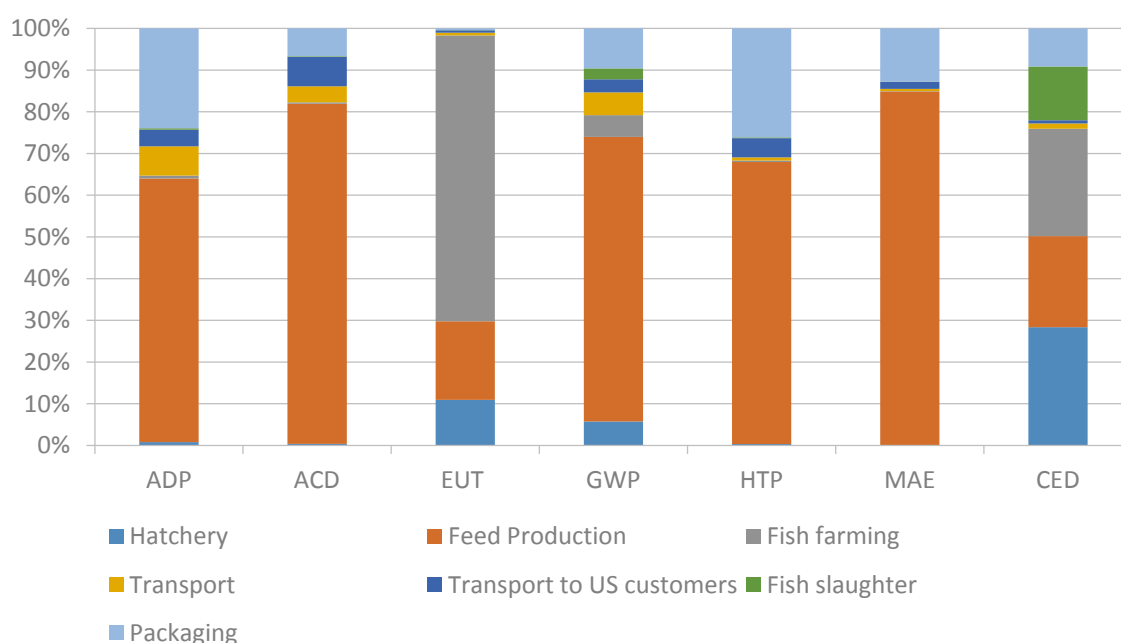


Figure 30. Relative contribution of the functional unit fed with Conv. feed with extended system boundaries including fish slaughtering and transport to the United States of America via sea.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

The best way to see the changes in environmental impacts in terms of carbon footprint is to compare the sea and air freight with the normal functional unit fed with Conv. feed. In figure 31 it can be seen how the air transport dominates with 9.74 kg CO₂ eq. per kg of fish transported to the United States. With ship transport, the carbon footprint increases from 2.22 kg CO₂ eq. with the normal functional unit, up to 2.58 kg CO₂ eq., only a 17% increase.

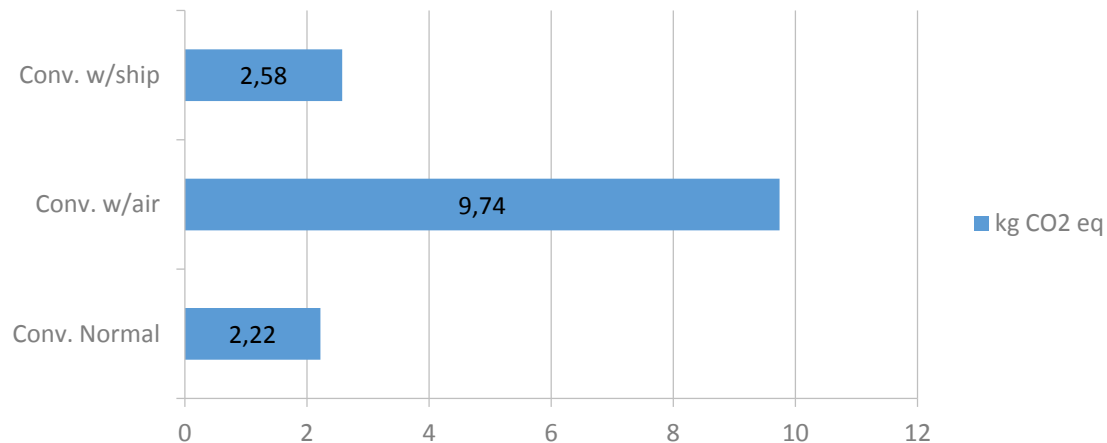


Figure 31. Carbon footprint of the functional unit fed with Conv. feed and with transportation to United States of America via sea and air. Presented in kg CO₂ equivalents.

5.5 All feed ingredients transported within Iceland

Although transportation only accounts for 1.17% of the total environmental impacts of the functional unit fed with Conv. feed, it is interesting to see if any measurable change can be expected if all feed inputs would be transported within Iceland instead of across the globe (with no changes in production). It has been argued (e.g. Ellingsen et al., 2008) that focus on the transportation phase should be minimal due to its low contribution, and more work should be put on balancing the feed production. The results so far indicate that the transportation phase has low overall environmental impacts compared to the feed production with the normal system boundaries, but it is nonetheless something that is interesting and worth studying because there is more than one method to transport goods, as was seen in chapter 4.2, and transportation has received much attention lately in terms of environmental impacts.

Figure 32 shows the difference between the original transportation phase and if all feed inputs were transported within Iceland. The difference is noticeable but not as much as expected. For example, the carbon footprint of the functional unit fed with Conv. feed and transported within Iceland with a truck lowers from 2.22 kg CO₂ eq. to 2.18 kg CO₂ eq. due to the fact that trucks consume more fuel oil per kg/km than a sea freighter, and that fuel consumption and CO₂ emissions are correlated. Recommended average emission

factors for transport is as follows: Deep-sea container – 8 gCO₂/ton-km, Road transport – 62gCO₂/ton-km (Cefic, 2011).

For the functional unit fed with Conv. feed, the overall weight of the materials transported via sea is 0.435 kg and the total distance is 41305 km. Therefore the transportation measures 17967 kg/km. In Iceland, the total transport distance is 511 km. The fishmeal and fish oil are transported 338 km and weight 0.565 kg and the total 1 kg of feed is transported 173 km with combined transportation measuring 364 kg/km. The overall transportation measures 18331 kg/km.

In the Iceland-only scenario, the total distance is 901 km. The fish oil is transported 338 km and weighs 0.565 kg. The rest of the materials are assumed to be produced in the Reykjavík capital area and are thus transported 390 km to the feed production plant in Akureyri. The total feed is then transported 173 km to Silfurstjarnan. The overall transportation measures 534 kg/km. The difference is considerable between the two scenarios, or 17797 kg/km.

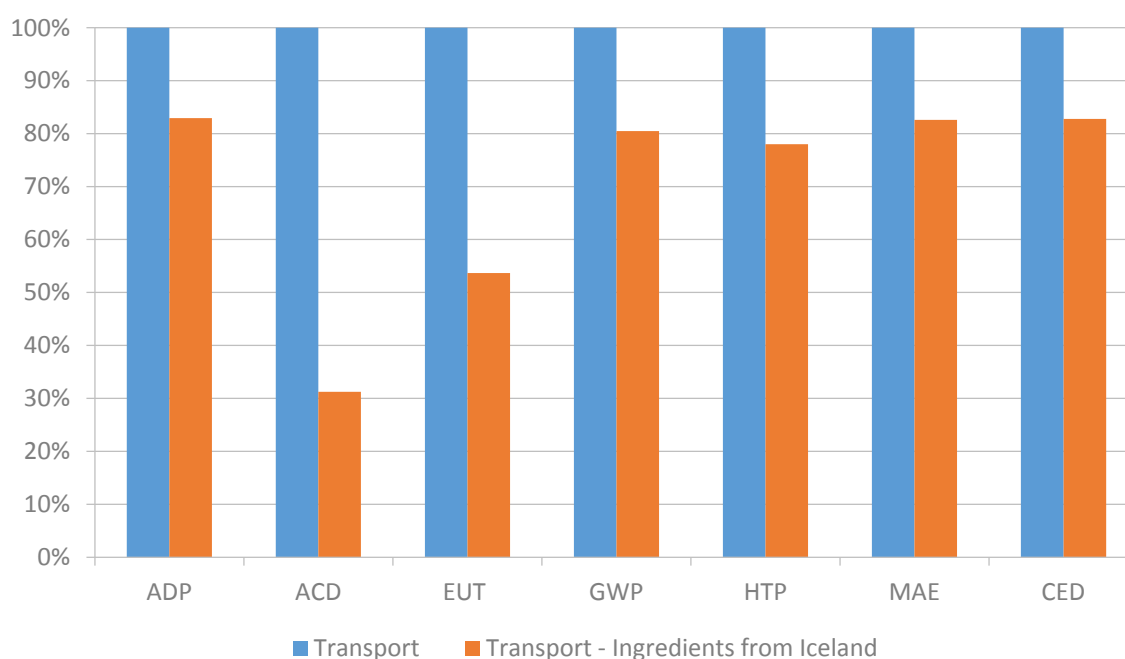


Figure 32. Relative contribution of the functional unit fed with Conv. feed with all feed ingredients coming from Iceland versus normal transportation.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

6 Discussion

The results presented in this study clearly indicate that the main environmental impacts of the life cycle considered are derived from the feed production, as many other similar studies conclude (e.g. Ytrestøyl et al., 2011 and Banze, 2011). Aquaculture has a large scope to improve its environmental impacts and resource use, and has to do so if to be considered sustainable. It has been demonstrated that the environmental impacts of the functional unit is low, naturally, if feed production is not taken into account. Based on these results, ways can be found to reduce the environmental impacts of the functional unit. The most logical way to move forward is to focus on feed inputs and optimize their production. The production of feed ingredients and to maximize its performance is a complicated procedure where many factors come to play. In this chapter, the results will be reflected upon, the study's research questions will be answered and possible improvements and limitations discussed.

6.1 Research questions

- **What are the cradle to gate environmental impacts associated with 1 kg of Arctic char farmed in Silfurstjarnan, a land based aquaculture in Iceland?**

As stated previously in this study, Samherji ltd. sought to confirm and demonstrate their claimed environmental performance and further strengthen the position of Icelandic aquaculture by showing the positive environmental performance and resource use. The latter is an important step to see where the Icelandic aquaculture sector stands amongst others as only one study had been conducted in Iceland on Atlantic salmon farmed in sea cages (Banze, 2011), and none on a land-based farm. It should be noted though, that to get a clear picture of the whole sector in Iceland, more farms have to be included. Despite that, the results from this study show, up to a point, the environmental performance of Icelandic aquaculture farms.

For the suite of environmental impact categories considered in this life cycle assessment, with the functional unit fed with Conv. feed, the feed production dominated abiotic depletion potential (88.1%), acidification potential (94.7%), global warming potential

(80.6%), human toxicity potential (97.9%) and marine aquatic ecotoxicity potential (99.2%), with the fish farming phase dominating eutrophication potential (69.3%) derived from feed and fish offal. The cumulative energy demand was divided between the hatchery phase (36.7%), feed production phase (28.2%) and the fish farming phase (33.4%). Interestingly, the transport phase only accounted for 1.65% of the cumulative energy demand and 1.17% of the total environmental impacts.

In the light of these findings, it can be concluded that the most important phase for improvements is the feed production. This underlines the need for continued research in aquafeed production and the need for balance between marine and agricultural ingredients, and even other forms of biotic ingredients as was demonstrated with the BSF feed.

The contribution to the overall environmental impacts of the fish farming phase, and to some extent, the hatchery phase in this study, largely depends on the emissions contributing to eutrophication derived from the feed and fish offal, as well as the energy needed to power water pumps, lights in the hatchery and so on. In this case, no chemicals are used in the aquaculture for better environmental performance. The N and P values were calculated from each feed's ingredient table and average fish uptake and feed utilization in Silfurstjarnan. The eutrophication values for the fish farming phase was 0.015 kg PO₄ eq/kg which is 80.2% of the total eutrophication potential. d'Orbcastel et al. (2008) reports 0.0187 kg PO₄ eq/kg of a standard flow-through trout production (+20%). These differences can be attributed to different FCR and ingredient compositions, with different protein, fat and phosphorus contents. Even though eutrophication potential differs between studies the feed is always the main contributor. Therefore, feed composition is the most important factor to consider reducing the environmental impacts.

The carbon footprint of the functional unit fed with Conv. feed measured to be 2.22 kg CO₂ eq/kg. This number is somewhat higher than reported by Pelletier et al. (2009) to be the global average carbon footprint, or 2.15 kg CO₂ eq/kg at farm-gate. Others have reported higher numbers. Ellingsen et al. (2008) reported 2.3 kg CO₂ eq/kg of salmon fillet leaving the slaughterhouse and Ytrestøyl et al. (2011) reported 2.6 kg CO₂ eq/kg edible product where the feed production contributed to 96% of the total carbon footprint. Since the system boundaries and farming techniques are not exactly the same for any of these studies, it is hard to draw a conclusion. It seems though that the main difference lies in the system boundaries and data for the feed production phase. The transportation phase seems

to be almost irrelevant, even in this study, where most of the ingredients have to be transported longer distances than studies conducted in mainland Europe, with the exception of the air transport with the extended system boundaries.

- **Where are the hot spots within the system and how can we reduce them?**

LCA is an effective tool to analyze production systems and identify where the hot spots of the production are in terms of environmental impacts and energy consumption. If the life cycle of the functional unit fed with Conv. feed is analyzed (table 6), it can be seen that the feed production holds 5 out of 7 impact categories, with hatchery and fish farming holding 1 each.

Table 6. Characterized environmental impacts of the functional unit fed with Conv. feed.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

Impact category	Hatchery	Feed Production	Fish farming	Transport
ADP	1.09E-04	8.69E-03	9.89E-05	1.16E-03
ACD	6.23E-05	1.37E-02	5.67E-05	2.08E-03
EUT	2.53E-03	4.35E-03	1.59E-02	2.77E-04
GWP	1.48E-01	1.76E+00	1.35E-01	1.74E-01
HTP	2.27E-03	4.32E-01	2.06E-03	6.49E-03
MAE	2.93E-01	2.67E+02	2.67E-01	2.04E+00
CED	43.8	33.7	39.8	2.38

The eutrophication potential from the fish farming was explained in the previous section, but the cumulative energy demand from the hatchery phase has yet to be explained. The main energy need comes from powering the lights, water pumps, heating and equipment needed. It needs considerably more power than the fish farming phase, which takes place outside, opposed to the hatchery, thus decreasing its energy need.

But what is it in the feed production that causes the main environmental impacts? Table 7 shows the characterized results of the Conv. feed production with hot spot analysis. The fishmeal production is the main contributor with the highest impacts in all categories with 41.1% of total environmental impacts.

Table 7. Characterized environmental impacts of the Conv. feed production.

ADP - Abiotic depletion, ACD - Acidification potential, EUT - Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE - Marine aquatic ecotoxicity potential, CED - Cumulative energy demand.

Impact category	Fishmeal	Soy meal	Wheat	Rape seed meal	Fish oil	Corn gluten meal	Additives	Feed mill
ADP	4.21E-03	1.32E-04	1.34E-04	1.44E-05	3.55E-03	4.30E-04	2.00E-04	1.88E-05
ACD	6.38E-03	7.84E-04	4.51E-04	2.42E-05	5.40E-03	4.53E-04	2.22E-04	1.08E-05
EUT	1.35E-03	9.44E-04	5.97E-04	0.00E+00	1.14E-03	6.14E-04	7.15E-06	1.92E-06
GWP	6.75E-01	2.87E-01	6.84E-02	2.01E-02	5.70E-01	8.42E-02	2.85E-02	2.55E-02
HTP	1.52E-01	9.17E-02	1.95E-03	5.06E-03	1.29E-01	4.17E-02	1.10E-02	3.92E-04
MAE	1.14E+02	8.71E+00	1.37E+00	3.36E+00	9.65E+01	3.48E+01	7.45E+00	5.06E-02
CED	9.28	5.71	0.272	0.034	7.84	2.4	0.585	7.62

Table 5 in chapter 4.3.4 presents a hot spot analysis of all the 3 feed types, where the Conv. feed has 5 hot spots out of 7 impact categories. BSF feed has the best environmental performance in 5 categories, but worst in 1, cumulative energy demand. It should be noted that though the BSF feed has the highest energy demand (MJ), it has the lowest in abiotic depletion. This means that most of its energy need is derived from renewable energy, opposed to ECO and Conv., where the fishery phase contributes substantially to abiotic depletion.

It can be concluded that the hot spots lie within the feed production in 5 out of 7 impact categories when the functional unit is fed with Conv. feed. When fed with ECO or BSF feed the same results appear.

- **Will the Black soldier fly feed and the new ECO feed have a better environmental performance than the standard ECO feed?**

This research question has already been answered to some extent in the previous section. From the results of this study, it can be concluded that both the new ECO feed and the BSF feed have better environmental performance than the Conv. feed. That was evident throughout chapter 4. The BSF feed had the best overall performance but fell short in eutrophication potential compared to Conv., where 51.6% came from the production of tomatoes and potatoes, mainly from fertilizer use. The quantity of those 2 feed inputs for the larvae are the main cause. In total, 18.4 kg of raw material is needed to produce 1 kg of larvae dry matter before the left-over allocation is taken into account, as explained in chapter 3.1.4. Therefore the amount of fertilizer inputs is in relation with this amount. The

Conv. feed production proved to have the lowest eutrophication potential due to the lowest share of agricultural inputs. However, the ECO feed had most eutrophication potential. That is due to the same reasons as with the BSF feed, more agricultural ingredients. It also had more sources contributing to eutrophication.

The cumulative energy demand was also highest in the BSF feed production, or 37.9 MJ/kg where 57% comes from the Icelandic electricity grid and thus from renewable energy sources. The Conv. feed production however only has 13.4 MJ from renewable sources out of 33.7 MJ/kg total. The BSF production is therefore the most energy intensive due to heavy industrial processes needed such as heating and drying.

The ECO feed proved to have the second best overall environmental impacts in every category except cumulative energy demand where it had the lowest out of the 3, or 28.1 MJ/kg.

It should be mentioned that the FCR for both ECO and BSF feeds was considered to be the same as when the Conv. feed is used. This was assumed because no real data on fish growth for the ECO and BSF feed existed. It was however noted by Dr. Jón Árnason that the FCR would probably increase by reducing the amount of marine protein in the diet. That could lead to increased environmental impacts from the ECO and BSF feed.

- **Will less marine based ingredients in feed improve environmental impacts?**

One of the things that have been discussed in this study is the replacement of marine based ingredients with agricultural ingredients. One-third of global wild-caught fish is used for fishmeal and oil production with growing demands and more pressure on the sustainability of wild fisheries (WWF, 2006). It is therefore important to find other ingredients for aquafeeds that can be produced in better harmony with the environment. But which is better, agricultural instead of marine based, or other forms of biotic ingredients?

As can be seen throughout chapter 4.3 and in previous sections, the BSF and ECO feed have lower overall environmental impacts than the Conv. feed. The first conclusion that can be drawn is that less marine based ingredients improve environmental impact, which answers the above question.

In figure 18 it can be seen how the environmental impacts gradually decrease from the Conv. feed through ECO and down to BSF. In table 8 it can also be seen how the agricultural inputs increase and marine inputs decrease in the same order. The global

warming potential (kg CO₂ eq.) also decreases in relation to the share of agricultural inputs, but the eutrophication potential increases, with highest level in the ECO feed. The actual amount of fertilizers used in the ECO feed production is 41.6 g, derived mainly from the rape-seed oil and meal production, or 34 g in total. ECO has the largest share of those two ingredients, or 6.5% and 17% respectively, opposed to only 7% Rape seed meal in Conv. and zero in BSF.

Table 8. The share of marine and agriculture ingredients and the eutrophication and global warming potentials of 1kg of feed production of all feed types considered.

	Conv.	BSF	ECO
Marine	56.5%	17.0%	32.7%
Agriculture	42.0%	82.3%	65.5%
kg PO₄ eq	0.00435	0.00726	0.00927
kg CO₂ eq	1.76	1.44	1.72

With that being said, it is realistic to say that with increased share of agricultural ingredients, the total environmental impacts can be reduced significantly. However, the increase in eutrophication can be considered a tradeoff.

This is also evident in chapter 4.3.5 and 4.3.6 where the comparison of 1 kg of fishmeal and BSF meal, and fish oil and rape seed oil is conducted. The eutrophication potential of the two agricultural ingredients is somewhat higher than the marine ingredients as well as the cumulative energy demand. Global warming potential is higher in the rape seed oil production compared to fish oil. Abiotic depletion potential is much higher from the marine ingredients as well as human toxicity potential and marine ecotoxicity potential.

If those findings are compared to similar studies that focus on comparing environmental impacts of feed types including higher shares of agricultural inputs, we get mixed results. Boissy et al. (2011), which assessed the environmental impacts of plant based salmonid diets at feed and farm scales, concluded that the use of plant based ingredients instead of marine based could decrease the pressure on marine biotic resources drastically. The replacement of marine ingredients with plant oils, glutens or oilseed meals did not substantially affect the overall environmental impacts. They also confirmed that the feed is the major contributor to the environmental impacts of fish farming except for eutrophication. They confirmed that for trout feed, eutrophication potential increased by 40% for feed with low marine ingredients. However, their study shows that energy

consumption for both marine based and agricultural based feed production is similar. Although this study did not show significant gain in environmental impacts by using plant based feed other than in biotic resource use, the conclusion is that it does have positive effect on the sustainability of aquaculture and fisheries.

However, Ytrestøyl et al. (2011) concludes that even by changing the feed ingredients from 88% marine to 85% plant, the carbon footprint increases from 2.40 CO₂ eq./kg to 2.47 CO₂ eq./kg.

This illustrates that results differ from study to study and is most likely affected by data and geographical situations. The general conclusion however is, even though the environmental performance does not increase by a large margin, that there is a choice to be made between agricultural and marine ingredients. It is known that we need to decrease the pressure on fisheries, and fishing fish to create fish creates sustainability issues. This study however showed that by increasing agricultural inputs at the cost of marine ingredients, a significant overall environmental gain could be reached. The question is though if by increasing agricultural ingredients in feed types, does that create similar problems elsewhere? Similar to fisheries, FAO (2012) states that demand growth over the coming decades will put increased pressure on natural resources in agriculture and significant increase in investment is needed to eradicate hunger and ensure its sustainability. The social tradeoff in marine against agricultural usage in aquafeed will however not be answered here and is a material for another study.

With the introduction of BSF feed in this study, another angle on this matter is visible. The methodology behind the BSF feed is to induct another form of biotic ingredient to aquafeed, namely the BSF larva. The process behind it of course requires inputs to feed the larva, but it has the advantage of being able to feed on organic materials derived from plants, animals and even humans to promote recycling of food waste and other organic matters (Wontae, et al., 2011). This gives the opportunity to lower the environmental impacts of aquafeeds considerably, as shown in this study. An important step in this evolution would be to systematically find the most efficient type of organic materials, in the form of waste or left-overs. This study suggested the use of potatoes and tomatoes as left-overs from human consumption as larvae feed. This decision was built on an assumption of what might be considered as feed for local conditions and the geographical location of the pending larvae production place considered. Therefore there is a large scope

for improvement and further studies to be made to optimize the performance specifically for aquafeed and environmental performance. However, a number of other factors have to be considered before a large industrial production of BSF feed could be carried out. One of them is the amount of land-use needed for large scale production, which is considerable. Björnsson (2012) mentions that to meet the estimated market demand in Iceland of 2,000 tons per year, a floor space of 23,923 m² will be theoretically needed for composting, not including space for personnel. Those are however assumed theoretical numbers, as no large scale production exists to date.

Since the feed production contributes to such large amount of the total environmental impacts, the FCR of aquaculture farms naturally plays a big role in environmental performance. If the feed production is 90% of the total impacts, a 10% decrease in FCR would decrease overall impacts by 9%. This is demonstrated in chapter 5.1 where the FCR is changed to 0.8 and 1.2 in relation to carbon footprint. This is just a simple example of how producers could drastically lower environmental impacts by optimizing the FCR.

Other factors that could influence the environmental impacts were assessed in the sensitivity and scenario analysis with mixed results. In chapter 5.3, water recirculation was assessed and compared to the flow-through system currently utilized. The results showed that energy demand increased by 25% due to substantially more water pump utilization, resulting in higher global warming potential of roughly 6%. However, the eutrophication potential lowered by 69% which is the result of less or no waste-water entering the environment. This has to be treated as a tradeoff, and the conditions and location of aquaculture farms have to be considered before taking a decision about farming techniques.

This is in line with what Ayer and Tyedmers (2008) concluded when they studied and compared a conventional marine net-pen system with reportedly environmentally friendly alternatives; marine floating bag system, land-based saltwater flow-through system and a land-based freshwater recirculating system. They found that the floating bag system demonstrated the best environmental performance, but the land-based freshwater recirculating system the worst. There were however tradeoffs with the recirculating system. It consumed substantially more energy, increasing impacts in all categories except Eutrophication potential, which is the result of less or no waste-water entering the environment.

The transportation of feed ingredients plays a big part in an aquaculture process chain and can often be complicated to assess and model. However, as the results show, the transportation of the functional unit fed with Conv. feed only contributes to 1.17% of the total environmental impacts. This confirms what Ellingsen et al. (2008) pointed out, that more focus should be put on balancing the feed production rather than the transportations. Even if all ingredients would be produced and transported within Iceland, the global warming potential only changes from 2.22 kg CO₂ eq. to 2.18 kg CO₂ eq. This confirms that transporting via sea does in fact have the lowest environmental impact.

By expanding the system boundaries to capture the packaging of the fish and the transport to customers in the United States by air, a broader view of the life cycle can be seen. As the company focuses on this market with this specific Arctic char production, this gives the producer and buyer a chance to evaluate the whole process. The results showed and confirmed that transporting via air has huge environmental impacts compared to sea transport. The air transport alone contributed to 65% of the total environmental impacts and increased the carbon footprint to 9.74 kg CO₂ eq. per kg of fish transported, compared to 2.58 kg CO₂ eq. per kg of fish transported via sea. The number for the air transport is considerably higher than reported by Ingólfssdóttir (2010), or 4.7 kg CO₂ eq. per kg of sea fish. In a recent study by Margeirsson et al. (2012) where the comparison of transport modes and packaging methods for fresh fish products was assessed, the results showed that by transporting fresh fish in a ship, the freshness of the fish holds for 11 days, compared to 9 days via air. Of course transporting via air takes considerably shorter time, but the environmental advantages are clear, and should be examined thoroughly by stakeholders.

6.2 Limitations and improvements

As with any research, limitations are an inevitable consequence of complicated methodologies and large scale data collection. This study is no exception. There were many factors that needed to be considered whether or not to include or utilize. LCA is a very useful methodology for business decision making for example, but lacks consensus between practitioners to be more holistic and fully acceptable methodology. The selected system boundaries for a production system in LCA's often do not include the overall life cycle of the product, which would apply to this study. In the same manner, sometimes all environmental impact categories of any given suite are not included, purposely or not, and

the choices of impact assessment methods differ from study to study. This might be a legitimate approach to LCA methodology, but steps of how to improve this system should be considered. The EROI methodology (Energy return on investment) could be considered similar as LCA in terms of data collection and system boundaries decisions. It has been discussed and suggested between EROI practitioners to create levels of EROI calculations depending on the boundaries they include. Murphy et al. (2011) introduced a detailed definition of boundaries which can be seen in table 9, with Atlason and Unnthorsson (2013) utilizing this method.

Table 9. System boundaries for the EROI methodology introduced by Myrphy et al. (2011).

Boundary for energy inputs	1. Extraction	2. Processing	3. End use
1. Direct energy and material inputs	EROI _{1.d}	EROI _{2.d}	EROI _{3.d}
2. Indirect energy and material inputs	EROI _{1.stnd}	EROI _{2.i}	EROI _{3.i}
3. Indirect labor consumption	EROI _{1.lab}	EROI _{2.lab}	EROI _{3.lab}
4. Auxiliary services consumption	EROI _{1.aux}	EROI _{2.aux}	EROI _{3.aux}
5. Environmental	EROI _{1.env}	EROI _{2.env}	EROI _{3.env}

They state that all EROI studies should at least include EROI_{1.stnd}, so all studies can be compared, which includes indirect energy and material inputs and the energy derived from extraction. This makes the whole process more transparent. Practitioners could simply choose from the list of boundaries suitable for their study and state their choice. Similarly, the same idea could be adopted for LCA, to make the process more transparent and consistent. It could even include sets of impact assessment methods. This could prove to be beneficiary for LCA in general, as lack of consensus has plagued this field, at least for the author of this study.

The inclusion and exclusion of impact categories can be a subjective matter between studies. As mentioned above, this could possibly be avoided by adopting something similar as the EROI practitioners have suggested. It is debatable whether this study includes all relevant impact categories or not, that might be subjective, but that was partly found out by conducting a thorough literature review to what are the most used impact categories in similar studies. It could be argued that some important categories are missing from this study, and one that comes to mind is a land-use characterization, where the environmental impacts of land-use and seafloor-use are considered. Agricultural operations can take massive amounts of land space, and since a large share of every aquaculture feed type

consists of agricultural ingredients it would be considered wise to include a land-use impact category, especially when comparing feed types with different amounts of agricultural ingredients like in this study. However, most feeds have a larger share of marine ingredients. One of the limitations of LCA is that it is not possible to estimate the effects the fishing gear has on the seafloor. Methods have been developed to calculate the seafloor impacts (Nilsson and Ziegler, 2007) but substantial data gathering and amount of time is required for that process. Other possibilities would be to calculate the area swept by the bottom trawl and treat it as a regular land-use impact, although the same area will more than likely be swept many times per year. To ensure fairness when comparing the environmental impacts of marine and agricultural ingredients, the land-use of both inputs has to be considered and the results thereby made comparable. It should also be noted that the CML 2 Baseline 2000 impact assessment method utilized in this study does not include a land-use impact category.

Water is a big factor for the operation of any land-based aquaculture farm, especially flow-through and recirculating farms. A huge amount of water is needed for the cultivation of fish. The need of water impact category within LCA is something worth looking into. As things stand now, the only way to include water is to compare the actual water dependency between farms and farming systems. However, the effects of its use cannot be measured from a sustainability perspective. This is of course very dependent on the geographical location and conditions of any farm under study. This is the reason why water was not included in any form of impact category in this study, although the actual water dependency could have been compared to similar studies.

The data collection is one of the most important factors of LCA studies, and any given study cannot be better than the quality of the data collected. Most studies rely both on background data from databases and real foreground data or site samples. The data collection phase for this study had the privilege of being able to contact companies and stakeholders involved directly, making it a smooth but long process. Data quality is therefore high for most parts of the study, although most of this data cannot be published due to confidentiality. However, some data could not be accessed or derived directly from the source, like the author had wished for. Gathering data for agricultural processes for example, turned out to be a long and complex web of endless sources. Therefore, most of the agricultural processes are background data gathered from the EcoInvent database, but

changed and optimized to represent each geographical location of processes. The producer of the feed ingredients gave as much information as possible to help with that.

6.3 Further studies

For the aquaculture sector to grow and become a food production that minimizes environmental impacts, further studies should be done to maximize its performance and optimization. As has been evident throughout this study, the feed production is where the focus should be. Whether to optimize current marine/agriculture based feed types or find new feed input sources such as the BSF feed introduced in this study, the environmental gains can be significant if done right. Since the BSF feed showed considerably better environmental performance compared to the other feed types, it would be interesting to carry out research where the feed inputs for the BSF larvae would be optimized. This study was limited to the production of potatoes and tomatoes as left-overs from human consumption as larva feed. Finding a balanced feed for the larvae and optimize the energy need of the process along with the right allocation method could drastically decrease its environmental impact even further. However, the FCR when using the BSF feed has to be considered and studied further to see the real gain in environmental impacts.

As mentioned in the previous chapter, the introduction of fixed system boundaries such as has been done for the EROI methodology could help LCA practitioners to select the boundaries suitable for their study. This could save a lot of time and make the method more complete. Further, it would make LCA studies more comparable and possibly create consensus throughout the LCA community. It should be noted however, that the LCA methodology can be quite more complex than EROI, and building such guidelines would require absolute knowledge of the LCA methodology and norms.

It has been evident, from the author's point of view, that discussion about environmental impacts of aquaculture, outside of LCA, focuses on impacts at farm level, such as escapes, solids, land use etc. The discussion does not revolve around life cycle thinking, that is, things that happen before and after the farm level such as the production of feed and transportation for example. The author welcomes the increase in LCA studies in this field to further broaden the view of environmental impacts from aquaculture focusing on life cycle perspectives. This study contributes to that quest.

7 Conclusion

By assessing 1 kg of live-weight Arctic char, cultivated in the Icelandic aquaculture farm Silfurstjarnan, fed with a) conventional feed, b) Black soldier fly feed, c) ECO feed with Life Cycle Assessment, it can be concluded that the feed production causes the greatest environmental impacts from all feed types considered. The BSF feed demonstrated the best environmental performance of the three feed types. Furthermore, it can be concluded that by increasing agriculture based ingredients at the cost of marine based ingredients, a better environmental performance can be reached. The hot spot analyses revealed that the feed production, with any feed type, included all the hot spots.

However, the BSF feed still has a large scope to improve in terms of presented environmental impacts due to allocation issues and choosing the best larva feed. As discussed in chapters 3.1.4 and 3.2.5, the feed used in this study was highly speculative and therefore factors such as allocation methods and bioconversion ratios can affect the results greatly.

This study also confirmed that the transportation of materials needed for the aquaculture process, including the feed materials, has very low environmental impacts, and even by replacing the materials transported long distances over sea with all domestic transportation had minimal impact changes. Transporting by air causes immense environmental impacts compared to sea transport. This study demonstrated the importance of feed production for aquaculture in terms of environmental impacts and showed that by decreasing the amount of feed consumed, reducing the amount of fishmeal and fish oil and even creating new types of feed from other forms of biotic ingredients can greatly reduce the overall impacts of aquaculture.

References

- Atlason, R. S., & Unnthorsson, R. (2013). Hot water production improves the energy return on investment of geothermal power plants. *Energy*, 273-280.
- Ayer, N. W., & Tyedmers, P. H. (2008). Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner production*, 362-373.
- Ayer, N. W., Tyedmers, P. H., Pelletier, N. L., Sonesson, U., & Scholz, A. (2007). Co-Product Allocation in Life Cycle Assessments of Seafood Production Systems: Review of Problems and Strategies. *International Journal of LCA*, 480-487.
- Banze, I. S. (2011). Life cycle assessment of Icelandic Atlantic salmon Aquaculture. *Masters thesis*, Háskóli Íslands.
- Baumann, H. (1996). LCA use in Swedish industry. *International Journal of LCA*, 122-126.
- Björnsson, S. F. (2012). *Aquafeed production from lower life forms. Preliminary process analysis of Single-Cell Protein and Black Soldier Fly Larvae production by converting organic waste to aquafeed ingredients. Masters thesis*. Aarhus University.
- Boissy, J., Aubin, J., Drissi, A., van der Werf, H. M., Bell, G. J., & Kaushik, S. J. (2011). Environmental impacts of plant-based salmonid diets at feed and farm scales. *Aquaculture*, 61-70.
- Buchspies, B., Jungbluth, N., & Tölle, S. J. (2011). *Life cycle assessment of high-sea fish and salmon aquaculture*. Uster: ESU-services ltd.
- Buonocore, E., Franzese, P. P., Mellino, S., Ulgiati, S., Viglia, S., & Zucaro, A. (2009). *Synergies in Multi-scale Inter-Linkages of Eco-social systems. Energy and LCA evaluation of the present dynamics of investigated case studies*. Seventh Framework Programme.
- Cefic. (2011). *Guidelines for measuring and managing CO2 emissions from freight transport operations*. Cefic.
- Climate Change. (2007). *IPCC Fourth Assessment Report*. The Physical Science Basis.
- De Silva, S. S., & Hasan, M. R. (2007). Feeds and fertilizers: the key to long-term sustainability. *FAO Fisheries Technical Paper No. 497*, 504.
- Diener, S., Zurbrugg, C., & Tockner, C. (2009). Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates. *Sage Publication*, 603-610.

- d'Orbcastel, E. R., Blancheton, J.-P., & Aubin, J. (2009). Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. *Aquaculture Engineering*, 113-119.
- Dreyer L, H. M. (2006). A framework for social life cycle impact assessment. *International Journal of LCA*, 88-97.
- Ellingsen, H., & Aanondsen, S. A. (2006). Environmental impacts of wild caught cod and farmed salmon - A comparison with chicken. *International Journal of LCA*, 60-65.
- Ellingsen, H., Olaussen, J. O., & Utne, I. B. (2008). Environmental analysis of the Norwegian fishery and aquaculture industry - A preliminary study focusing on farmed salmon. *Marine Policy*, 479-488.
- Emerson, C. (1999). *Aquaculture impacts on the environment*. Cambridge Scientific Abstract.
- European Commission - Directorate - General Environment. (2012). *Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste*. European Commission.
- European Commission - Joint Research Centre - Institute for Environment and Sustainability. (2010). *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*. Luxembourg: Publications Office of the European Union.
- European Commission. (2012, 11 6). *Integrated Product Policy. European Platform on Life Cycle Assessment (LCA)*. Retrieved from European Commission Web site: <http://ec.europa.eu/environment/ipp/lca.htm>
- FAO . (2012). *The state of food and agriculture*. Rome: FAO.
- FAO. (2013). *World inventory of fisheries. Impact of aquaculture on environment. Issues Fact Sheets. Text by Uwe Barg. In: FAO Fisheries and Aquaculture Department*. Rome: FAO.
- FAO Fisheries and Aquaculture Department. (2011). *World aquaculture 2010*. Rome: Food and Agriculture Organization of the United Nations (FAO).
- Frischknecht, R., & jungbluth, N. (. (2007). *Implementation of Life Cycle Impact Assessment Methods*. Dübendorf: Swiss Centre for Life Cycle Inventories.
- Grönroos, J., Seppälä, J., Silvenius, F., & Mäkinen, T. (2006). Life cycle assessment of Finnish cultivated rainbow trout. *Boreal Environment Research*, 401-414.
- Gunnarsson, V. I. (2006). Staða bleikjueldis á Íslandi, samkeppnishæfni og stefnumótun rannsókna og þróunarstarfs. *Sjávarútvegurinn - Vefrit um sjávarútvegsmál*, 1-62.
- Henriksson P, G. J. (2011). *Proposed LCA methodology revisions for aquaculture SEAT Life Cycle Assessment studies. Focusing on South-East Asian Aquaculture Systems for Tilapia (Oreochromis spp.), Catfish (Pangasius spp.), Shrimp (Penaeid spp.) and Freshwater prawn (Macrobrachium spp)*. SEAT.

- Huntington, T. C., Frid, C., Boyd, I., Goulding, I., & Macfadyen, G. (2003). *Determination of Environmental Variables of Interest for the Common Fisheries Policy Capable of Regular Monitoring*. European Commission.
- Huntington, T. C., Roberts, H., Cousins, N., Pitta, V., Marchesi, N., Sanmamed, A., . . . Brockie, N. (2006). *Some Aspects of the Environmental Impact of Aquaculture in Sensitive Areas. Report to the DG Fish and Maritime Affairs of the European Commission*. Poseidon Aquatic Resource Management Ltd.
- Ingólfssdóttir, G. M. (2010). *Application of Environmental Indicators for Seafood*. Master's thesis. Faculty of Industrial Energy. University of Iceland.
- Iwama, G. K. (1991). Interactions between aquaculture and the environment. *Critical Reviews in Environmental Controls*, 177-216.
- Johnson, L. (1980). *The arctic charr, Salvelinus alpinus*. In E.K. Balon (ed.) *Charrs: Salmonid fishes of the genus Salvelinus*. The Hague.
- Landssamband fiskeldisstöðva. (2009). *Staða fiskeldis á Íslandi, framtíðaráform og stefnumótun Landssambands fiskeldisstöðva í rannsókn- og þróunarstarfi 2010-2013*. Landssamband fiskeldisstöðva.
- Margeirsson, B., Smáráson, B. Ö., Ólafsdóttir, A., Reynisson, E., Gestsson, Ó., & Þórðarson, G. (2012). *Comparison of transport modes and packaging methods for fresh fish products - storage life study and life cycle assessment*. Reykjavík: Matís.
- Ministry of Fisheries and Aquaculture. (2012, November 3). Retrieved from Information centre of the Icelandic Ministry of Fisheries and Aquaculture: www.fisheries.is
- Mungkung, R., & Gheewala, S. H. (2007). Use of life cycle assessment (LCA) to compare the environmental impacts of aquaculture and agri-food products. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber and B. Harvey (eds). *Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons*. FAO/WFT Expert Workshop. FAO., 87-96.
- Murphy, D. J., Hall, C. A., Dale, M., & Cleveland, C. (2011). Order from chaos: a preliminary protocol for determining the EROI of fuels. *Sustainability*, 1888-1907.
- Newton, G. L., & Sheppard, D. C. (2004). *The Black soldier fly, Hermitia illuscens, as manure management/resource recovery tool*. Agricultural and Life Sciences.
- Nilsson, P., & Ziegler, F. (2007). Spatial distribution of fishing effort in relation to seafloor habitats of the Kattegat, a GIS analysis. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 421-440.
- Papatryphon, E., Petit, J., & Van der werf, M. G. (2003). The development of life cycle assessment for the evaluation of Rainbow trout farming in France. *Life cycle assessment in the agri-food sector*. Horsens: UMR Sol Agronomie Spatilisation, Institut National de la Recherche Agronomique.

- Papatryphon, E., Petit, J., Kaushik, S. J., & van der Werf, H. M. (2004). Environmental impacts assessment of salmonid feeds using Life Cycle Assessment (LCA). *Ambio*, 316-323.
- Parker, R. (2012). *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*. Sea Fish Industry Authority.
- Pelletier, N. L., Ayer, N. W., Tyedmers, P. H., Kruse, S. A., Flysjo, A., Robillard, G., . . . Sonesson, U. (2007). Impact Categories for Life Cycle Assessment Research of Seafood Production Systems: Review and Prospectus. *International Journal of LCA*, 414-421.
- Pelletier, N., & Tyedmers, P. (2007). Feeding farmed salmon: Is organic better? *Aquaculture*, 399-416.
- Pelletier, N., Tyedmers, P., Robb, D., & Buttle, L. (2011). *Life cycle analysis model quantifies ecological footprints of salmon feeds*. Global Aquaculture Advocate.
- Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., . . . Silverman, H. (2009). Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems. *Environmental Science and technology*, 8730-8736.
- PRé Consultants. (2008). *SimaPro Database Manual. Methods library*. PRé Consultants.
- Scientific Applications International Corporation (SAIC). (2006). *Life Cycle Assessment: Principles and Practice*. Cincinnati: National Risk Management Research Laboratory Office of Research and Development.
- Sheppard, C., Burtle, G., & Newton, L. (2008). *The future of aquafeeds in 2013. Fishmeal Replacement with Black Soldier Fly Prepuae*. A predictive report prepared for the NOAA Aquaculture program and the NOAA-USDA Alternative Feeds Initiative.
- Silvenius, F., & Grönroos, J. (2003). *Fish farming and the environment. Results of inventory analysis*. Helsinki: Finnish Environment Institute.
- Subasinghe, R. (2009). *Aquaculture development: the blue revolution*. Stockholm: Royal Swedish Academy of Agriculture and Forestry.
- Thorarensen, H., Gústavsson, A., Karlsson, H., & Sigurgeirsson, Ó. I. (2011). Vöxtur bleikjueldis á Íslandi. *Málstofa F - Vatnalíf*. Háskólinn á Hólum.
- Tidwell, J. H., & Allan, G. L. (2001). Fish as food: aquaculture's contribution. *EMBO reports*, 958-963.
- Weidema, B. (2000). Avoiding Co-Product Allocation in Life-Cycle Assessment. *Journal of Industrial Ecology*, 11-33.
- Winther, U., Ziegler, F., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2009). *Carbon footprint and energy use of Norwegian seafood products*. Trondheim: SINTEF.

- Wontae, K., Sungwoo, B., Kwanho, P., Sangbeom, L., youngcheol, C., Sangmi, H., & Youngho, K. (2011). Biochemical characterization of digestive enzymes in the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). *Journal of Asia-Pacific Entomology*, 11-14.
- World Wildlife Fund (WWF). (2006). *Aquaculture and the Environment. Information report*. WWF.
- Ytrestøl, T., Aas, T. S., Berge, G. M., Hatlen, B., Ruyter, B., Hognes, E. S., . . . Sund, V. (2011). *Recourse utilisation and eco-efficiency of Norwegian salmon farming in 2010*. Norway: Nofima.

Appendix

Inventory analysis for the functional unit.

	Sub.	Source
Aquaculture		Silfurstjarnan/Samherji
	Power	Silfurstjarnan/Samherji/ELCD
Conv. Feed		
	Fishmeal	Samherji
	Fish oil	Samherji
	Wheat	Laxá/Ecoinvent
	Hipro soy meal	Laxá/Ecoinvent
	Corn gluten meal	Laxá/Ecoinvent
	Rapeseed meal	Laxá/Ecoinvent
	Vitamins/minerals	Laxá/Ecoinvent
	Aquasta natural colorant	Laxá/Ecoinvent
ECO feed		
	Fishmeal	Samherji
	Fish oil	Samherji
	Wheat	Laxá/Ecoinvent
	Soya	Laxá/Ecoinvent
	Corn gluten meal	Laxá/Ecoinvent
	Wheat gluten meal	Laxá/Ecoinvent
	Rapeseed oil	Laxá/Ecoinvent
	Rapeseed meal	Laxá/Ecoinvent
	Vitamins/minerals	Laxá/Ecoinvent
BSF feed		
	Fish oil	Samherji
	Black soldier fly larvae	Matís/Björnsson (2012)/Dr.Jón Árnason
	Wheat	Laxá/Ecoinvent
	Soya	Laxá/Ecoinvent
	Corn gluten meal	Laxá/Ecoinvent
	Wheat gluten meal	Laxá/Ecoinvent
	Vitamins/minerals	Laxá/Ecoinvent
Feed production		
	Mill/production	Laxá
	Packaging	Laxá
	Power	Laxá/ELCD
	BSF production	Matís/Björnsson (2012)/Dr.Jón Árnason
Transportation		
	Distances	Samherji/Eimskip/Laxá
	Fuel consumption	Eimskip
	Vehicles	ELCD

Data from results not presented in the study. Sorted by chapters.

Overall environmental impacts.

Characterization:

Impact category	Hatchery	Feed		Transport	Total
		Production	Fish farming		
ADP	6.88E-16	5.49E-14	6.25E-16	7.35E-15	6.36E-14
ACD	1.93E-16	4.24E-14	1.75E-16	6.42E-15	4.92E-14
EUT	1.91E-14	3.28E-14	1.19E-13	2.09E-15	1.73E-13
GWP	3.36E-15	3.99E-14	3.05E-15	3.95E-15	5.03E-14
HTP	3.79E-17	7.22E-15	3.45E-17	1.08E-16	7.40E-15
MAE	3.87E-16	3.52E-13	3.52E-16	2.69E-15	3.55E-13
CED	43.8	33.7	39.8	2.38	120

Transport

Overall characterization:

Impact category	From Hatchery	Fishmeal and oil	Oceanic carrier	From feed mill	Total
ADP	0.000724	8.68E-05	0.000274	7.86E-05	0.001163
ACD	0.000485	5.94E-05	0.001481	5.38E-05	0.002079
EUT	0.000111	1.36E-05	0.00014	1.23E-05	0.000277
GWP	0.105186	0.012565078	0.04481	0.011381	0.173942
HTP	0.003876	0.000428099	0.001798	0.000388	0.00649
MAE	1.264296	0.15157742	0.486002	0.137293	2.039168
CED	1.48	0.177	0.559	0.161	

Normalization:

Impact category	From Hatchery	Fishmeal and oil	Oceanic carrier	From feed mill	Total
ADP	4.58E-15	5.49E-16	1.73E-15	4.97E-16	7.35E-15
ACD	1.50E-15	1.84E-16	4.57E-15	1.66E-16	6.42E-15
EUT	8.35E-16	1.03E-16	1.05E-15	9.29E-17	2.09E-15
GWP	2.39E-15	2.85E-16	1.02E-15	2.58E-16	3.95E-15
HTP	6.47E-17	7.15E-18	3.00E-17	6.48E-18	1.08E-16

MAE	1.67E-15	2.00E-16	6.42E-16	1.81E-16	2.69E-15
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Conv. feed.

Characterization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE	CED
Fishmeal	4.21E-03	6.38E-03	1.35E-03	6.75E-01	1.52E-01	1.14E+02	9.28
Soy meal	1.32E-04	7.84E-04	9.44E-04	2.87E-01	9.17E-02	8.71E+00	5.71
Wheat	1.34E-04	4.51E-04	5.97E-04	6.84E-02	1.95E-03	1.37E+00	0.272
Rape seed meal	1.44E-05	2.42E-05	0.00E+00	2.01E-02	5.06E-03	3.36E+00	0.034
Fish oil	3.55E-03	5.40E-03	1.14E-03	5.70E-01	1.29E-01	9.65E+01	7.84
Corn gluten meal	4.30E-04	4.53E-04	6.14E-04	8.42E-02	4.17E-02	3.48E+01	2.4
Additives	2.00E-04	2.22E-04	7.15E-06	2.85E-02	1.10E-02	7.45E+00	0.585
Feed mill	1.88E-05	1.08E-05	1.92E-06	2.55E-02	3.92E-04	5.06E-02	7.62
Total	8.69E-03	1.37E-02	4.35E-03	1.76E+00	4.32E-01	2.67E+02	33.7

Normalization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE
Fishmeal	2.66E-14	1.97E-14	1.02E-14	1.53E-14	2.54E-15	1.51E-13
Soy meal	8.36E-16	2.42E-15	7.11E-15	6.50E-15	1.53E-15	1.15E-14
Wheat	8.49E-16	1.39E-15	4.50E-15	1.55E-15	3.26E-17	1.80E-15
Rape seed meal	9.13E-17	7.48E-17	0.00E+00	4.57E-16	8.45E-17	4.44E-15
Fish oil	2.25E-14	1.67E-14	8.59E-15	1.29E-14	2.15E-15	1.27E-13
Corn gluten meal	2.72E-15	1.40E-15	4.62E-15	1.91E-15	6.96E-16	4.60E-14
Additives	1.27E-15	6.85E-16	5.39E-17	6.48E-16	1.84E-16	9.83E-15
Feed mill	1.19E-16	3.32E-17	1.44E-17	5.80E-16	6.55E-18	6.68E-17
Total	5.49E-14	4.24E-14	3.28E-14	3.99E-14	7.22E-15	3.52E-13

ECO feed

Characterization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE	CED
Fish oil	0.002877	0.004367	0.000924	0.461792	0.104026	78.14966	6.35
Rape seed meal	0.000501	0.001713	0.002344	0.248269	0.007291	5.081753	1.02
Fishmeal	0.00186	0.002823	0.000597	0.298535	0.06725	50.52146	4.1
Soy meal	8.82E-05	0.000523	0.000629	0.191002	0.061107	5.809987	3.81
Corn gluten meal	0.000614	0.000647	0.000877	0.120287	0.059511	49.73375	3.42
Wheat	0.000269	0.000901	0.001194	0.136868	0.003907	2.730315	0.544
Rape seed oil	0.00057	0.00164	0.002696	0.22146	0.003332	1.884522	1.16
Additives	0.000134	0.000148	4.77E-06	0.019028	0.007341	4.964522	0.39
Feed mill	1.81E-05	1.04E-05	1.85E-06	0.024665	0.000379	0.048895	7.3
Total	0.00693	0.012773	0.009268	1.721906	0.314143	198.9249	28.094

Normalization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE
Fish oil	1.82E-14	1.35E-14	6.96E-15	1.05E-14	1.74E-15	1.03E-13
Rape seed meal	3.16E-15	5.29E-15	1.77E-14	5.64E-15	1.22E-16	6.71E-15
Fishmeal	1.18E-14	8.72E-15	4.50E-15	6.78E-15	1.12E-15	6.67E-14
Soy meal	5.58E-16	1.61E-15	4.74E-15	4.34E-15	1.02E-15	7.67E-15
Corn gluten meal	3.88E-15	2.00E-15	6.60E-15	2.73E-15	9.94E-16	6.56E-14
Wheat	1.70E-15	2.78E-15	8.99E-15	3.11E-15	6.53E-17	3.60E-15
Rape seed oil	3.60E-15	5.07E-15	2.03E-14	5.03E-15	5.56E-17	2.49E-15
Additives	8.45E-16	4.57E-16	3.59E-17	4.32E-16	1.23E-16	6.55E-15
Feed mill	1.15E-16	3.21E-17	1.39E-17	5.60E-16	6.32E-18	6.45E-17
Total	4.38E-14	3.95E-14	6.98E-14	3.91E-14	5.25E-15	2.63E-13

BSF feed.

Characterization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE	CED
Fish oil	0.002877	0.004367	0.000924	0.461792	0.104026	78.14966	6.35
Soy meal	0.000132	0.000779	0.000939	0.284911	0.091151	8.666564	5.68
Corn gluten meal	0.000651	0.000686	0.00093	0.127504	0.063081	52.71777	3.63
Wheat	0.00016	0.000536	0.00071	0.081437	0.002325	1.624537	0.324
BSF meal	0.000386	0.003892	0.003749	0.441694	0.00484	2.210871	16.7
Additives	0.000134	0.000148	4.77E-06	0.019028	0.007341	4.964522	0.39
Feed mill	1.65E-05	9.44E-06	1.68E-06	0.022423	0.000344	0.04445	6.63
Total	0.004355	0.010418	0.007258	1.438789	0.273108	148.3784	39.704

Normalization:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE
Fish oil	1.82E-14	1.35E-14	6.96E-15	1.05E-14	1.74E-15	1.03E-13
Soy meal	8.32E-16	2.41E-15	7.07E-15	6.47E-15	1.52E-15	1.14E-14
Corn gluten meal	4.12E-15	2.12E-15	7.00E-15	2.89E-15	1.05E-15	6.96E-14
Wheat	1.01E-15	1.66E-15	5.35E-15	1.85E-15	3.88E-17	2.14E-15
BSF meal	2.44E-15	1.20E-14	2.82E-14	1.00E-14	8.08E-17	2.92E-15
Additives	8.45E-16	4.57E-16	3.59E-17	4.32E-16	1.23E-16	6.55E-15
Feed mill	1.04E-16	2.92E-17	1.27E-17	5.09E-16	5.75E-18	5.87E-17
Total	2.75E-14	3.22E-14	5.47E-14	3.27E-14	4.56E-15	1.96E-13

Comparison of fishmeal and BSF meal.

Characterization:

Impact category	BSF meal	Fishmeal
ADP	0.000928	0.011846
ACD	0.009355	0.017984
EUT	0.009012	0.003803
GWP	1.061765	1.901498
HTP	0.011635	0.428342
MAE	5.314594	321.7927
CED	40.1	26.1

Normalization:

Impact category	BSF meal	Fishmeal
ADP	5.86E-15	7.49E-14
ACD	2.89E-14	5.56E-14
EUT	6.79E-14	2.86E-14
GWP	2.41E-14	4.32E-14
HTP	1.94E-16	7.15E-15
MAE	7.02E-15	4.25E-13

Comparison of fish oil and rapeseed oil.

Characterization:

Impact category	Rape seed oil	Fish oil
ADP	0.008763	0.016923
ACD	0.02523	0.025691
EUT	0.041474	0.005433
GWP	3.407069	2.716425
HTP	0.051262	0.611917
MAE	28.99265	459.7039
CED	37.3	17.8

Normalization:

Impact category	Rape seed oil	Fish oil
ADP	5.54E-14	1.07E-13
ACD	7.80E-14	7.94E-14
EUT	3.12E-13	4.09E-14
GWP	7.73E-14	6.17E-14
HTP	8.56E-16	1.02E-14
MAE	3.83E-14	6.07E-13

Carbon footprint.

1 kg live-weight char - BSF	1 kg live-weight char - Conv	1 kg live-weight char - ECO
0.38267687	1.032102	0.63006621
0.362395	0.312377	0.31825
0.07433969	0.19797029	0.13109067
0.152591	0.173942	0.178736
0.101667	0.013577	0.21027759
0.755813215	0.403702329	0.377286

Changing feed conversion ratio to 0.8 and 1.2 in relation to carbon footprint.

	1 kg live-weight char - BSF	1 kg live-weight char - Conv	1 kg live-weight char - ECO
kg CO2 eq FCR			
0.8	1.5	1.77224	1.75
kg CO2 eq FCR			
1	1.87	2.22	2.18
kg CO2 eq FCR			
1.2	2.25	2.66	2.62

BSF larva feed scenario.

Impact category	BSF meal 100%	BSF meal 90%	BSF meal 0%
ADP	6.49E-15	5.86E-15	2.08E-16
ACD	3.21E-14	2.89E-14	5.83E-17
EUT	7.54E-14	6.79E-14	2.53E-17
GWP	2.67E-14	2.41E-14	1.02E-15
HTP	2.15E-16	1.94E-16	1.15E-17
MAE	7.78E-15	7.02E-15	1.17E-16

Water recirculation.

Impact category	Conv w/circulation	Conv
GWP	1.00E+00	9.45E-01
CED	1.00E+00	7.55E-01
EUT	3.12E-01	1.00E+00

Expanding the system boundaries.

Characterization via air:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE	CED
Hatchery	0.000109	6.23E-05	0.002531	1.48E-01	2.27E-03	2.93E-01	4.38E+01
Feed Production	0.008689	0.013724	0.004353	1.76E+00	4.32E-01	2.67E+02	3.37E+01
Fish farming	9.89E-05	5.67E-05	0.01585	1.35E-01	2.06E-03	2.67E-01	3.98E+01
Transport	0.000965	0.000649	0.000149	1.40E-01	5.06E-03	1.68E+00	1.97E+00
Transport to US customers	0.046905	0.028166	0.00535	7.240262	6.030845	727.0452	1.07E+02
Fish slaughter	4.95E-05	2.83E-05	5.05E-06	0.067269	0.001032	0.13335	1.99E+01
Packaging	0.003291	0.001122	0.000101	0.246954	0.167177	40.01357	1.41E+01

Characterization via sea:

Impact category	ADP	ACD	EUT	GWP	HTP	MAE	CED
Hatchery	0.000109	6.23E-05	0.002531	0.147992	0.002271	0.293371	43.8
Feed Production	0.008689	0.013724	0.004353	1.758828	0.432296	266.5286	33.7
Fish farming	9.89E-05	5.67E-05	0.01585	0.134538	0.002065	0.266701	39.8
Transport	0.000965	0.000649	0.000149	0.139987	0.005062	1.68411	1.97
Transport to US customers	0.000548	0.001185	0.000133	0.081611	0.029463	5.416765	1.18
Fish slaughter	4.95E-05	2.83E-05	5.05E-06	0.067269	0.001032	0.13335	19.9
Packaging	0.003291	0.001122	0.000101	0.246954	0.167177	40.01357	14.1

CO2 eq:

	kg CO2 eq
Conv. Normal	2.22
Conv. w/air	9.74
Conv. w/ship	2.577

All ingredients transported within Iceland.

Characterization:

Impact category	Transport	Transport - Ingredients from Iceland
ADP	1.16E-03	0.000965
ACD	2.08E-03	0.000649
EUT	2.77E-04	0.000149
GWP	1.74E-01	0.139987
HTP	6.49E-03	0.005062
MAE	2.04E+00	1.68411
CED	2.38	1.97

CO2 eq:

	Conv	Conv - Ingredients from Iceland
kg CO2 eq	2.22	2.18