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RESEARCH PAPER

Life Cycle Assessment of Icelandic Arctic Char Fed Three Different Feed Types

Birgir Örn Smárason[1,*], Ólafur Ögmundarson[1], Jón Árnason[1], Rannveig Björnsdóttir[1], Brynhildur Davíðsdóttir[2]

[1] Matís ltd.–Icelandic food and biotech R&D, 113 Reykjavík, Iceland.
[2] Faculty of Economics and faculty of Environmental and Life Sciences, University of Iceland, 101 Reykjavík, Iceland.

* Corresponding Author: Tel.: +3544225193;
E-mail: birgir@matis.is

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Abstract

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; standard feed with high inclusion levels of marine ingredients (Conv.), experimental feed with high inclusion levels of agricultural ingredients (ECO) and a hypothetical Black soldier fly larvae based feed (BSF). Results of the study indicated that the feed production causes the greatest environmental impacts from all feed types considered. The Black soldier fly based 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 demonstrated the importance of feed production for aquaculture in terms of environmental impacts and showed that byoptimizing feed consumption, reducing the amount of fishmeal and fish oil and even creating new types of feed from novel ingredients, the overall impacts of aquaculture can be greatly reduced.

Keywords: Aquaculture, Arctic char, Life cycle assessment, fishmeal replacement, insect feed, Iceland

Introduction

Aquaculture remains a growing, ever evolving and important production sector for high protein food sources. It continues to be the fastest growing animal food sector accounting for more than 50% of the world's fish consumption in 2014, producing 74.3 million tons (FAO, 2015). Aquaculture, like most other food industries cause various impacts on the environment. Pollution, damage to sensitive coastal habitats and aquatic biodiversity must be reduced to assure sustainability and balance in ecosystems.

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 review by Parker (2012), the feed production accounted for 87% of greenhouse gas emissions (GHG) from Atlantic salmon and Rainbow trout aquaculture production, when reviewing 45 aquaculture studies. This is explained by 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 reduced into oil and meal, and many plant based ingredients have to be dried, milled and improved. In 2014, 40 million tons of aquafeed was produced (IFIF, 2014).

Capture fisheries supply the aquaculture sector with important and valuable feed ingredient. In 2013, about 14% of the world's marine fish catch went to farmed animals and of that, 16.3 million tons are reduced into fishmeal and fish oil (FAO, 2014).

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 (De Silva and Hasan, 2007). As Pelletier and Tydemers (2007) and Boissy *et al.* (2011) have pointed out, increasing plant materials in aquafeed, and even a total substitution of fishmeal and fish oil can lower environmental impact and decreases the pressure on wild fish stocks.

Life cycle assessment (LCA) is a methodology used to estimate and evaluate the environmental impacts of a product's life cycle. In recent years, LCA has increasingly been applied to assess the environmental impacts of aquaculture systems

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(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). Feed compositions and different diets have also been explored (e.g. Boissy *et al*., 2011, Pelletier & Tydemers, 2007).

The objective of this study was to utilize the LCA methodology to evaluate the environmental performance of three different Arctic char (Salvelinus alpinus) feed types in terms of global warming, acidification, eutrophication, abiotic depletion, human toxicity potential, marine ecotoxicity potential and cumulative energy demand. Existing feed type (Conv.) used on the aquaculture farm was compared with new feed types under development, the BSF larvae based feed (BSF) and the ECO feed. The goal of the development of the new feed types is to reduce the environmental impacts associated with aquaculture feeds by substituting, in part or in full, conventional feed ingredients with organic waste material and plant protein.

Material and Methods

Project Design

LCA methodology was used to assess the cradle to gate life cycle environmental impacts associated with the production of 1 kg of Arctic char fed three different feed types. The functional unit of this study was 1 kg of live-weight Arctic char, cultivated in an Icelandic aquaculture farm, fed with a conventional feed (Conv.), a Black soldier fly larvae based feed (BSF) and an ECO feed (ECO). The system boundaries were chosen to be in line with similar studies in this field to ensure high comparability.

The functional unit is divided into four main phases; hatchery, feed production, fish farming (on-growing phase) and transport. 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 (Figure 1). The transport phase includes transport of raw materials for the feed between countries and domestic transport between feed production plant and the trout farm. Feed conversion ratio (FCR) for the char in the aquaculture is 1:1 with the Conv. feed. Since the BSF and ECO feeds had not previously been tested for the fish, the FCR of 1 was assumed since the currently used feed had the FCR of 1 according to data from the station manager and no data for the two other feed types presented in this study have been produced. This decision was backed up with the fact that protein of plant origin in aquafeed has not been found to increase FCR as is evident in Norway for example, where FCR has lowered since 1990 but proteins from plant origin increased from 0% in 1990 to roughly

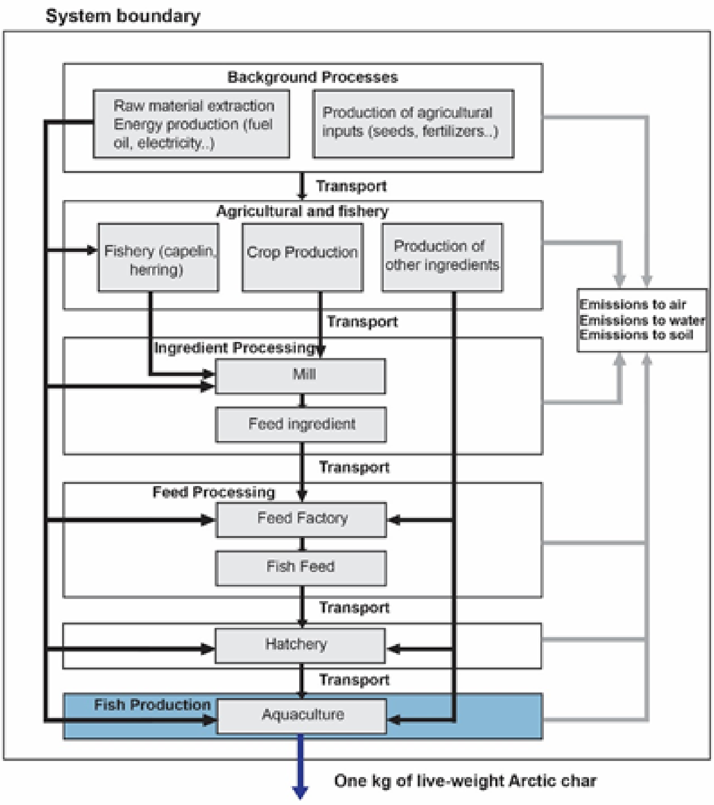

Figure 1. System boundaries of the functional unit.

37% in 2013 (Ytrestøyl *et al*., 2015; Crampton *et al*., 2010).

Life Cycle Inventory

Data was collected through interviews with facility managers, questionnaires and on-site measurements. Official data was used wherever possible. If information was not available, estimations had to be used or secondary data from the Ecoinvent database. 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.

Data gathered for the feed production stage, which was the most data intensive, was derived from the manufacturer of the feed used at the aquaculture production site, the fishery company involved 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 BSF feed was derived from Björnsson (2012), and Dr. Jón Árnason (personal communications, 2012).

The majority of feed raw materials are imported from abroad and transported via sea to either Reykjavík, Iceland's capital or Akureyri in northern Iceland where the feed production plant is located. The BSF eggs were imported from Germany and hatched in a hatching room built specially for small scale research production. The room contained a fly cage for reproduction, boxes for larvae and substrate, a humidifier and a temperature control device. Environmental conditions were derived from Björnsson (2012) where temperature was kept between 25-29° C and humidity between 70-90%. The larvae were grown to optimum size, then dried and transported to the feed mill for feed production. All feed types were transported 173 km to the aquaculture farm by trck following production. Country specific electricity mixes were used in the inventories and proportion of electric energy sources were adapted to national contexts.

Fishery products inventories were based on numbers from the owner of the fishing vessel used. Capelin and herring fisheries were used for fishmeal and fish oil and mass allocation was utilized as allocation method for by-catch. Construction and maintenance of fishing vessel were 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.

Feed Types

The feed used for the char production (Conv.) is a conventional aquafeed with high values of fishmeal and fish oil, developed by Laxá Feedmill in Akureyri, Iceland (Table 1). The feed is produced for Arctic char bred in Icelandic conditions for maximum growth and nutrition.. The second feed type considered is a new model called the ECO feed (ECO), which is still at the research and developmental stage and had not been tested by the Icelandic 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. The BSF feed contained much lower values of marine ingredients, replacing fishmeal completely and lowering the share of fish oil from 21% to 17%.

The BSF, a wasp like the fly of the genus Stratiomyidae, is found throughout the Western Hemisphere. . It 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). Since the BSF feed

Table 1. Arctic char feed composition: ingredients and origin for Conv., ECO and BSF feed. Shown as g/kg dry matter

Ingredient (g/kg)	Conv.	ECO	BSF	Origin
Fishmeal	355	157		Iceland
Fish oil	210	170	170	Iceland
BSF meal			416	Iceland
Wheat	100	100	80	UK
Soya		120	148	Brazil
Hipro soy meal	180			Brazil
Corn gluten meal	70	100	106	China
Wheat gluten meal		100	73	UK
Rapeseed oil		6.50		Denmark
Rapeseed meal	70	170		Denmark
Vitamins/minerals	10	10	10	Germany
Natural colorant	5			USA

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 were used in accordance with Björnsson (2012). The current formula assumes 416 g of BSF larvae dry matter for 1 kg of feed.

The bioconversion rate of the BSF larvae is a highly important factor. It varies depending on diet and ambient conditions. The larvae have a potential daily feeding capacity of 3-5 kg/m^2 and 6.5 kg/m^2 when fed with market waste and human feces (Diener *et al*., 2009). Assuming 4 kg/m^2 of daily feeding capacity and bioconversion rate of 15% will yield 0.6 kg per day or 219 kg/m^2 per year of pre-pupae (Björnsson, 2012). For this study, tomato and potato leftovers (by-product) were considered as raw material inputs for BSF. Using leftovers from the company kitchen both reduces production costs and the environmental impacts of the production itself. Domestic production of tomatoes and potatoes was modelled for human consumption and it was assumed that 10% would go to waste and used as larvae feed and the allocation was calculated accordingly.

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, 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 composting using BSF larvae has been increasing rapidly for the last years, resulting in more knowledge.

Allocation

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, although Henriksson et.al. (2011) explained 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. 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), especially when dealing with the unstable nature of the Icelandic currency.

Allocation problems arose in several instances throughout the present 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. In the BSF production phase, allocation problems arose when considering the feed for the larvae. Tomato and potato leftovers from human consumption were used as feed for the larva. 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 but rather 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 were 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) a 90/10 allocation based on mass was deemed adequate. However, as this is an uncertain factor, it was decided to analyse how the BSF meal production changes with different allocation, described above and presented in the results. The BSF meal production was analysed with 90% allocation, meaning that 10% is avoided as leftovers, and fed to the larvae, which was the preferred method used. Allocation of 100% means that the production of tomatoes and potatoes would only be produced for feeding the BSF larvae. Allocation of 0% means that the leftovers are neutral and considered waste from human consumption, thereby removing the production of potatoes and tomatoes from the analysis.

Impact Assessment

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). 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 within the currently available methods and includes a balanced set of impact categories (Buonocore *et al*., 2009). In addition to 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 (Table 2).

Table 2. Impact categories and characterization

Impact category	Description	Characterization
Global warming potential	Greenhouse gases released into the air cause climate change	CO_2 equivalents
Abiotic depletion	Depletion of fossil fuels	
Acidification potential	Contributes to acid deposition	PO_4 equivalents
Eutrophication potential	Excessive levels of micro-nutrients	PO_4 equivalents
Human toxicity potential	Toxic substances on human health	1,4-dichlorobenzene equivalents
Marine toxicity potential	Toxin substances entering the marine ecosystem	1,4-dichlorobenzene equivalents
Cumulative energy potential	Industrial energy use over life cycle	MJ

Results

Overall Environmental Impacts

The results from the overall environmental impacts were obtained with the Conv. feed in mind because that is the feed type currently in use. The characterized results of the functional unit, 1 kg of live-weight Arctic char cultivated in an Icelandic aquaculture farm fed with Conv. feed are presented in Table 3.

Table 3 and Figure 2 show that the feed production generated the highest environmental impact by far, through all categories except eutrophication potential and cumulative energy demand.

The fish farming phase contributes mainly to eutrophication potential and cumulative energy demand. Eutrophication in this phase is caused by nitrogen and phosphorus release into the 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 reflects the current Icelandic situation, 73.8% hydro and 26.2% geothermal (National Energy Authority, 2010).

The hatchery phase has only minimal contribution to the overall impacts. 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. The production of fishmeal and oil dominates all impact categories except cumulative energy demand. 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 CO_2 emissions from agricultural operations.

Feed types

It has already been demonstrated that the feed production has the most overall environmental impacts when assessing the functional unit with the Conv. feed.

To realize the relative differences of environmental impacts between the feed types considered, a comparison model was created. Figure 3 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. 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 as well as for the tomato and potato production.

Comparison Between Meals and Oils

The BSF meal introduced in this study has already shown improved environmental performance compared to the fishmeal. When compared directly with the fishmeal, the BSF meal shows higher impacts in 2 categories, eutrophication and cumulative energy demand, but the fishmeal dominates all other categories (Figure 4). If those two categories are analysed further, it can be seen that the eutrophication potential in the BSF meal production is derived mainly from crop and electricity production, while it is derived mainly from fuel combustion in the fishing vessel for the fishmeal production. Figure 5 shows a comparison between rapeseed oil and fish oil. The rapeseed oil contributes to higher eutrophication potential, global warming potential, cumulative energy demand and acidification potential is almost

Table 3. Total environmental impacts of the functional unit fed conv. feed

Impact category	Hatchery	Feed Production	Fish farming	Transport	Total
ADP (kg Sb eq)	0,0001	0,0087	0,0001	0,0012	0,0101
ACD (kg SO2 eq)	0,0001	0,0137	0,0001	0,0021	0,0159
EUT (kg PO4 eq)	0,0025	0,0044	0,0159	0,0003	0,0230
GWP (kg CO2 eq)	0,1480	1,7600	0,1350	0,1740	2,2200
HTP (kg 1,4-DB eq)	0,0023	0,4320	0,0021	0,0065	0,4430
MAE (kg 1,4-DB eq)	0,2930	267,0000	0,2670	2,0400	269,0000
CED (MJ)	43,8	33,7	39,8	2,38	120

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

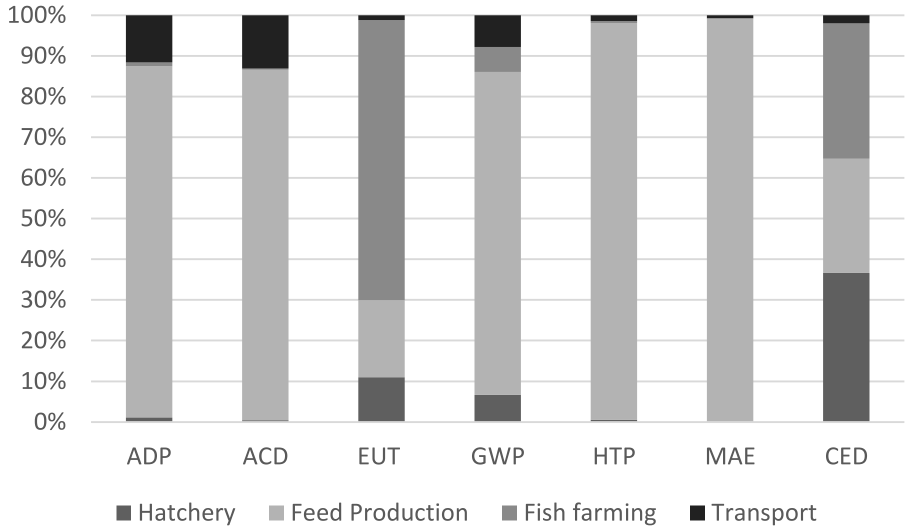

Figure 2. Relative contribution of the functional unit fed Conv. feed. ADP-Abiotic depletion, ACD-Acidification potential, EUT-Eutrophication potential, GWP - Global warming potential, HTP - Human toxicity potential, MAE-Marine aquatic ecotoxicity potential, CED-Cumulative energy demand.

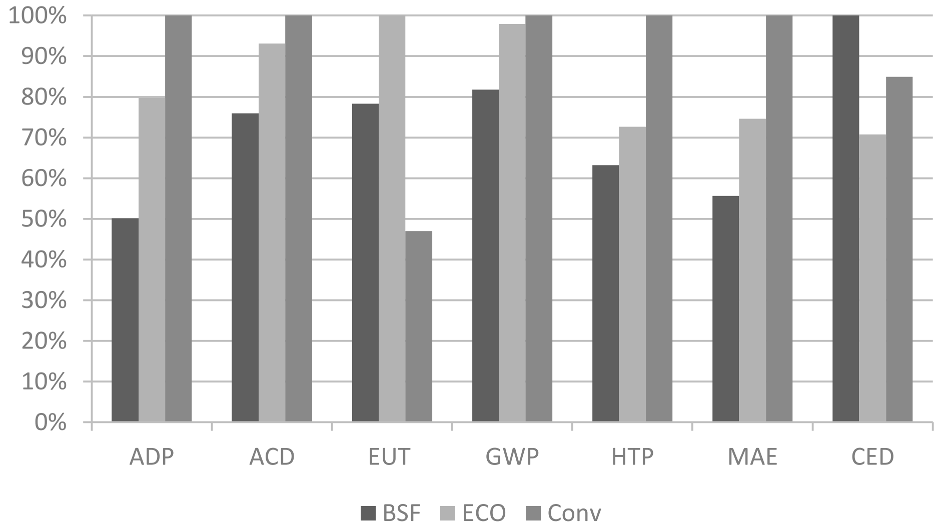

Figure 3. Relative contribution of the production of all feed types considered. ADP-Abiotic depletion, ACD-Acidification potential, EUT-Eutrophication potential, GWP-Global warming potential, HTP-Human toxicity potential, MAE-Marine aquatic ecotoxicity potential, CED-Cumulative energy demand.

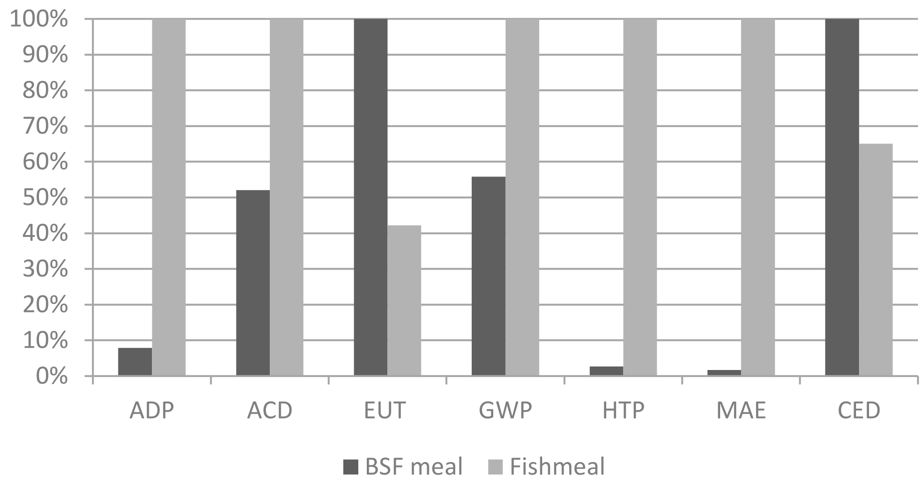

Figure 4. Relative contribution of the production of fishmeal and BSF meal. ADP-Abiotic depletion, ACD-Acidification potential, EUT-Eutrophication potential, GWP-Global warming potential, HTP-Human toxicity potential, MAE-Marine aquatic ecotoxicity potential, CED-Cumulative energy demand.

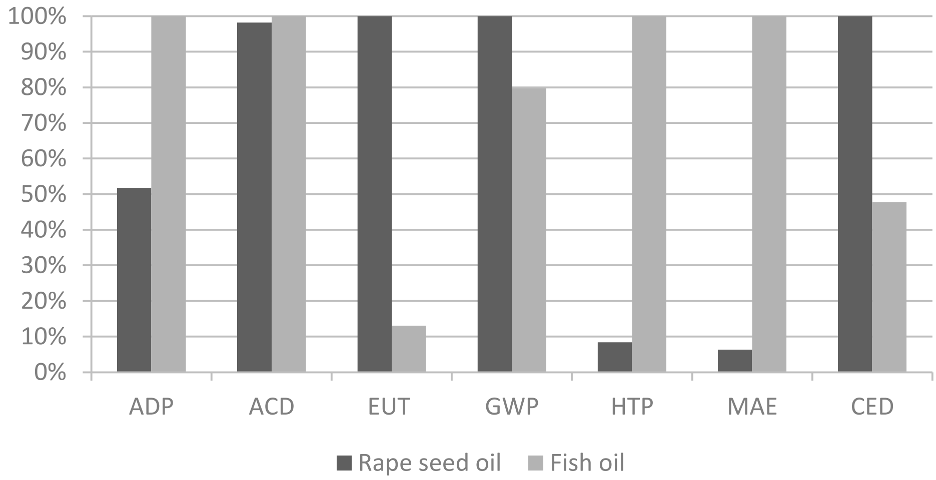

Figure 5. Relative contribution of the production of rapeseed oil and Fish oil. ADP-Abiotic depletion, ACD-Acidification potential, EUT-Eutrophication potential, GWP-Global warming potential, HTP-Human toxicity potential, MAE-Marine aquatic ecotoxicity potential, CED-Cumulative energy demand.

even.

The allocation of the BSF larvae feed was an uncertain factor. Figure 6 shows a sensitivity analysis described in the Allocation section. These changes are presented in kg CO_2 equivalents (eq.) as well as the changes in the total carbon footprint of the functional unit fed with BSF feed. Figure 6 shows that by modelling the potato and tomato production as waste from human consumption and thus zeroing it out, lowers the total carbon footprint of the functional unit to 1.02 kg CO_2 eq., representing a 45.5% decrease, which is derived mainly from electricity production.

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 in order to be considered sustainable. In our opinion, the most logical way to move forward is to focus on aquafeed raw material inputs and optimize their production. But the production of aquafeed and maximizing its performance is a complicated procedure where many factors come to play. This underlines the need for continued research in aquafeed production and the need for balance between marine and agricultural ingredients in feed and, more importantly, other forms of organic novel ingredients as was demonstrated with the BSF feed.

The contribution to the overall environmental impacts of the fish farming phase, and to some extent,

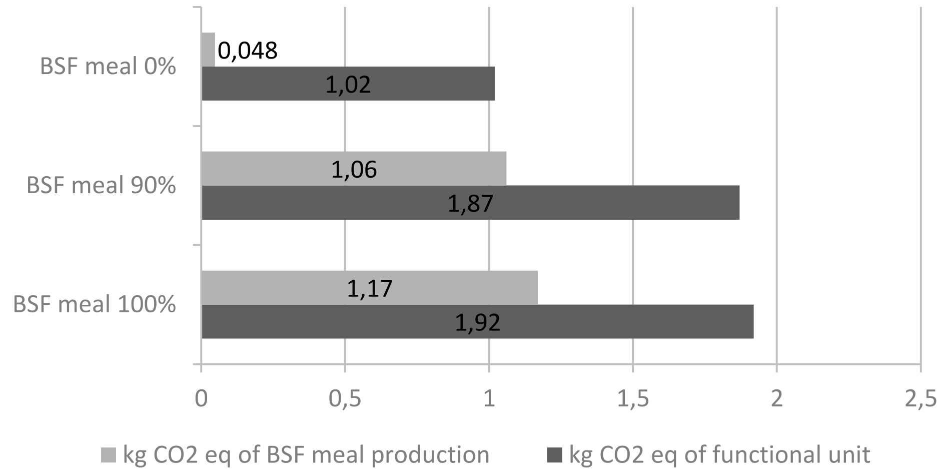

Figure 6. Carbon footprint of BSF meal production and functional unit fed with BSF feed, with 0%, 90% and 100% allocation. Presented in kg CO2 equivalents. ADP-Abiotic depletion, ACD-Acidification potential, EUT-Eutrophication potential, GWP-Global warming potential, HTP-Human toxicity potential, MAE-Marine aquatic ecotoxicity potential, CED-Cumulative energy demand.

the hatchery phase in the present 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 were used in the aquaculture for better environmental performance. The N and P values were calculated from the feed's ingredient tables, feed utilization at the farm and average fish uptake . The eutrophication values for the fish farming phase was 0.015 kg PO4 eq/kg, which corresponds 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 when reducing environmental impacts.

The carbon footprint of the functional unit fed with Conv. feed was 2.22 kg CO2 eq/kg. This is somewhat higher than the global average carbon footprint reported by Pelletier *et al*. (2009) which was 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 the present study, where most of the ingredients have to be transported longer distances than in studies conducted in mainland Europe.

The ECO feed and the BSF feed have better environmental performance than the Conv. feed. The BSF feed had the best overall performance but had higher 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. Therefore, the amount of fertilizer inputs is in relation with this amount. The Conv. feed production proved to have the lowest eutrophication potential. However, the ECO feed had the most eutrophication potential. 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.

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 lowest overall environmental impacts in every category except cumulative energy demand, using 28.1 MJ/kg which was the lowest energy needed out of all feed types. It should be mentioned that the FCR for both ECO and BSF feeds was considered to be the same as for the Conv. feed. This was assumed because no real data on fish growth for the ECO and BSF feed existed. However, the FCR could increase by reducing the amount of marine protein in the diet and therefore could lead to increased environmental impacts from the ECO and BSF feed.

One of the things that have been discussed in this study is the replacement of marine based ingredients with agricultural ingredients. The BSF and ECO feed have lower overall environmental impacts as compared with the Conv. feed. The first conclusion that can be drawn is that less marine based ingredients reduce the environmental impacts. Table 4 also shows how the agricultural inputs increase and marine inputs decrease in the same order. The carbon footprint (kg CO2 eq.) also decreases in relation to the share of agricultural inputs, but the eutrophication potential increases, with the highest level in the ECO feed. The actual amount of fertilizers used in the ECO feed production was 41.6 g, derived mainly from the rapeseed oil and meal production, or 34 g in total. ECO had the largest share of those two ingredients, or 6.5% and 17%, respectively, opposed to only 7% rapeseed meal in Conv. and none in BSF.

Hence, 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 trade-off. This comes evident where the comparison of 1 kg of fishmeal and BSF meal, and fish oil and rapeseed oil is conducted. The eutrophication potential as well as the cumulative energy demand of the two agricultural ingredients are somewhat higher than for the marine ingredients. Global warming potential is higher in the rapeseed 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.

The present study shows that by increasing agricultural inputs at the cost of marine ingredients, an overall environmental gain could be reached. However, the question is if increased agricultural ingredients in feed will create new problems elsewhere. FAO (2012) states that the demand growth of aquaculture that is expected over the coming decades will put increased pressure on natural resources in agriculture, possibly shifting the pressure off wild fisheries due to decreasing shares of marine ingredients in aquafeed. They also state that significant increase in investment will be needed in order to eradicate hunger and ensure the industry´s sustainability. The social trade-off 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 could be visible. The methodology behind the BSF feed is to induct another form of organic ingredient to aquafeed, namely the BSF larva. The process behind it obviously 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 and to introduce potentially lost nutrition back into the loop, as shown in the present study. An important step in this evolution would be to systematically find the most efficient type of organic materials, in the form of currently wasted co-products or by-products. There is a large scope for improvement and further studies to be made to optimize the performance specifically for aquafeed and environmental performance.

Conclusion

A Life Cycle Assessment of 1 kg of live-weight Arctic char cultivated in an Icelandic aquaculture farm and fed with conventional feed, BSF feed and ECO feed reveals that the feed production causes the greatest environmental impacts. 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 improving the best larva feed. The feed used in this study was highly speculative and therefore factors such as allocation methods and bioconversion ratios can greatly affect the results. The feed was modelled as leftovers from human consumption as explained in the allocation section. However, as this was an uncertain factor. The study demonstrates the importance of feed production for aquaculture in terms of environmental impacts and

Table 4. 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 PO_4 eq	0,00435	0,00726	0,00927
kg CO_2 eq	1,76	1,44	1,72

showed that a decrease in the amount of feed consumed, reducing the amount of fishmeal and fish oil and adopting modern and sustainable feed ingredients from novel organic sources can greatly reduce the overall impacts of aquaculture.

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