UNIVERSITY OF GOTHENBURG

DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL SCIENCES

STARTING FROM THE BOTTOM: USING LOW TROPHIC SPECIES IN SALMON FEEDS

Assessing the environmental performance of novel salmon feeds with LCA

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Abstract

Over the past 30 years, the formulation of salmon feeds has shifted from being based on marine ingredients like fishmeal and fish oil towards more plant-based ingredients. This shift was caused by limited supply of wild fish and general sustainability concerns related to using forage fish for feed, so they were mainly replaced with vegetable-protein. Previous studies of farmed Norwegian salmon have shown that feed use is the most important sustainability input factor of the whole industry, both economically and environmentally.

Using Life Cycle Assessment (LCA), this study compares the resource use and emissions caused by conventional feeds to those caused by novel feed formulations in which a part of the marine inputs, and in some cases soy, were replaced by seaweed or blue mussel silage. Different feed formulations are compared per ton of feed and data from a fish trial done in Norway is then used to estimate emissions for a salmon production scenario using those novel feeds. The analysis of the feeds covers greenhouse gas emissions and agricultural land use. The estimation of the emissions caused by the salmon production covers greenhouse gas emissions and marine eutrophication. The results show that replacing fishmeal with 1-4% seaweed silage in the feed lowered the greenhouse gas emissions marginally by up to 5% compared to the conventional reference feed. The replacement of fishmeal and soy protein with blue mussel silage (up to 11% in the feed) reduced greenhouse gas emissions by up to 10%. Replacing soy protein also results in lower land use. However, applying these feeds in a salmon production scenario shows that the overall emissions increase when replacing common ingredients with novel ingredients, mainly due to an increased feed use. These findings should be considered when applying novel feed formulations in salmon farming for ecological benefit.

Key words: LCA – Salmon aquaculture – novel feeds – seaweed – blue mussel

Table of Content

List of Abbreviations

BMS	Blue mussel silage
CO_2	Carbon Dioxide
EU	European Union
FAO	Food and Agriculture Organization
FCR	Feed Conversion Ratio
FCR	Feed Conversion Ratio
GHG	Greenhouse Gas
GWP	Global warming potential
Ha	Hectare
IMR	Institute of Marine Research
IMTA	Integrated multi trophic aquaculture
ISO	International Organization for Standardization
Kg	kilogram
LC n-3 PUFA	Long chain n-3 polyunsaturated fatty acid
LCA	Life Cycle Assessment
Mton	Million tons
NGO	Non-governmental organisation
OPP	Other plant proteins
RISE	Research Institutes of Sweden
SPC	Soy Protein Concentrate
SWS	Seaweed Silage
tkm	ton kilometre
USD	United States Dollar

List of Tables & Figures

1. Introduction

Salmon farming in Norway

Farming Atlantic salmon (*Salmo salar*) in Norway roots back to the 1970's, when first trials for the grow out of salmon in open net cages were carried out. Since then, the industry has developed at a rapid rate, from a production of only 50 tons in 1970 to approximately 1.2Mtons in 2020 (FAO, 2020). Today, the industry produces salmon worth almost 8 billion USD per year and has grown to become the second largest contributor to Norwegian exports, only surpassed by the oil and gas industry (Statistics Norway, 2021). Though the growth in production has been stagnant over the past couple of years, Norway aims at increasing the current production volume by 400% by 2050 (Directorate of Fisheries, 2019).

The rapid growth of the industry has soon sparked scrutiny from the public about the ecological compatibility of the industry. Concerns regarding the impact on wild populations of Atlantic salmon are especially focussed on genetic interferences between wild salmon and escaped farmed salmon, transmission of diseases from farms to wild populations as well as eutrophication caused by salmon farms (Mente et al., 2006; Taranger et al., 2015). In addition to the discussion of the aquaculture operation itself, the impact of the industry including the whole value chain has received more and more attention. Supply chain impacts are commonly analysed using the Life Cycle Assessment methodology (LCA), which allows to estimate the resource use and environmental impacts of goods and processes by taking the whole value chain into account. As a tool, LCA is standardized by ISO (ISO, 2006a, b). Previous studies investigating salmon aquaculture using LCA have quantified the impact of farming on various impact categories. Results have shown that the production of salmon feed dominates the life cycle impacts of the industry through greenhouse gas emissions and land use. The feed can account for up to 80% of the total greenhouse-gas-emissions of farmed Norwegian salmon (Liu et al., 2016; Winther et al., 2020). One explanation of this is the high inclusion rate of soy-protein concentrate (SPC), which has a particularly large environmental impact. But even with lower inclusion rates of soy, feed was the dominant driver of emissions (Berardy et al., 2015; Dalgaard et al., 2007; Pelletier et al., 2009).

The importance of salmon feed

Thus, feed is of major importance for the greenhouse gas emissions and other environmental impacts of salmon production and the environmental sustainability of the industry going forward. In addition to the relevance for the environmental footprint, feed is also a dominant economic factor in intensive salmon farming. The use of feed surpasses the production volume of salmon and contributes to more than half of the total production costs (Aas et al., 2019; Asche & Roll, 2013). Originally, these feeds were mainly based on marine ingredients, especially fishmeal and fish oil, which are produced from wild forage fish, often small pelagic species, but increasingly also from trimmings from fish processing, which today add up to around 25% - 35% of the fishmeal (FAO, 2020). These ingredients were rather cheap and provide the protein and fatty acids required by the fish in aquaculture (Cottrell et al., 2020). Atlantic salmon demands a balance of proteins, amino acids and lipids in its feed, where especially the long-chain n-3 polyunsaturated fatty acids (LC n-3 PUFAs) are of major importance. These fatty acids are considered as healthy both for the fish and for the consumer (Peterson et al., 2019). Increasing expansion of the aquaculture industry cannot be based on the use of fishmeal and fish oil, because the availability of these resources is limited and production regressive (FAO, 2020). The resulting increasing prices coupled with NGO campaigns against feeding farmed fish with wild fish have driven a major change in the composition of feed for Atlantic salmon

towards plant based protein sources, mainly soy (Aas et al., 2019; Naylor et al., 2021; Shepherd & Jackson, 2013).

Novel feed ingredients need to fulfil several requirements in order be suitable as a feed ingredient for intensive salmon production. Firstly, the ingredients need to meet the nutritional requirements needed by the fish (Pelletier et al., 2018). Secondly, it should be possible to scale up in terms of production to meet the increasing demand, i.e. not be dependent on limited resources. Third, their production must be environmentally, economically and socially sustainable to be competitive. (Pelletier et al., 2018)

Over the last two decades, SPC has become the main replacement for marine proteins since it is widely available and provides vital protein sufficiently. However, SPC cannot provide the important PUFAs and amino acids in a digestible form, which is why it does not substitute fishmeal and fish oil completely. Besides, the environmental costs of soy-protein concentrate are high when originating in countries with expanding agricultural land like Brazil. (Aas et al., 2019; Berardy et al., 2015; Dalgaard et al., 2007)

Motivated by these deficits, there is an urgent need for new feed ingredients and a lot of research is currently being done, evaluating the functionality and feasibility of feed ingredients that can provide the fish with all the needed nutrients while impacting the environment less. Four examples of these new ingredients are briefly described below.

Novel feed inputs in salmon feed

1. *Microalgae*

Various microalgal species show amino acid profiles very similar to those that are found in fish meal, making these a potentially plausible alternative for fish-meal protein (Becker, 2007). Sørensen et al. (2016) used the microalgae *Phaeodactylum tricornutum* as a substitute for fish meal protein in trial feeds for Atlantic salmon. The inclusion of 3-6% microalgae had no negative effects on the growth performance, the nutrient digestibility, or the utilization of the feed. Kiron et al. (2012) also included products based on marine microalgae in trial feeds for Atlantic salmon, although in higher concentration (5% and 10%). Like Sørensen et al. (2016), they did not determine any significant differences in growth performance. Furthermore, Shah et al. (2017) find that the use of microalgae could reduce the environmental costs of aquafeeds drastically. However, small production volumes and high costs for production of microalgae make their use not yet economically feasible (Rosas et al., 2019; Shah et al., 2017).

2. *Insects*

Protein from insects form another promising group of alternative aquafeed ingredients. Especially black soldier fly larvae show a well-balanced amino acid profile which is very similar to the one in fishmeal, making this species potentially feasible for fish feeds (Barroso et al., 2013; Liland et al., 2017). Belghit et al. (2018) tested various feeds on Atlantic salmon, in which up to 100% of the protein from fishmeal and soy were replaced by meal from black soldier fly larvae. No significant differences were found in the feed conversion, feed intake and daily growth of fish fed with the trial feeds compared to control feeds. Similarly, Fisher et al. (2020) tested feeds based on black soldier fly larvae on Atlantic salmon for both, digestibility and growth. They find that salmon fed with feeds containing 20% insect meal show no significant difference in growth. However, higher inclusion rates affected the growth performance negatively.

3. Macroalgae

Norambuena et al. (2015) show that some marine macroalgae contain all the necessary amino acids, even though the protein content may vary (8%-50% dry weight). Besides, they are found to be rich in LC n-3 PUFA, which is also demanded by the salmon. Thus, they are a possible alternative feed ingredient, especially for the replacement of fishmeal and fish oil (Aas et al., 2019; Norambuena et al., 2015). Feeding trials have shown that low inclusion rates of a mix of macroalgae in salmon feed (2,5% - 10%) do not affect the feed utilization and disease resistance of the tested fish negatively, and keeping the growth rate at a level comparable to the conventional control feed (Norambuena et al., 2015). Kamunde et al. (2019) included brown kelp in salmon feed and tested it in 30-day feeding trials on smolt with inclusion levels ranging between 3-10%. The authors found that, depending on the inclusion rate, the added seaweed affects the growth performance, food consumption and the feed conversion ratio (FCR) positively. Wilke et al. (2015) show that salmon fed with feeds that contained 15% of a seaweed blend have a notably higher concentration of LC n-3 PUFAs in their flesh.

However, a lot is still unknown about the bioavailability of nutrients in seaweeds and the use is also limited by the high content of iodine and other undesired substances that might affect the fish negatively.

4. Blue Mussel

Blue mussels (*Mytilus etulis*) have a high protein content and contain amino acids which are similar to the ones found in fishmeal (Jönsson et al., 2009). Vidakovic et al. (2016) test blue mussel meal in feeding trials with Arctic Char (*Salvelinus alpinus*). They replaced 40% of the fishmeal content with blue mussel meal and did not find any significant differences between the growth rate or feed conversion ratios. Using the same feed formulations as Vidakovic et al. (2016), Langeland et al. (2016) found that Arctic char fed with blue mussel enriched feeds showed improved digestibility, compared to a conventional feed.

Environmental assessments of novel feed inputs in salmon feeds

Several studies have investigated the environmental footprints of alternative aquafeed ingredients in comparison to conventional ingredients. Philis et al. (2018) conducted a material- and substance flow analysis to compare the environmental performance of soybean- and seaweed based aquafeed ingredients for the case of Norway. Both ingredients are in a dried form. They found that while the seaweed production only relies on phosphorous taken up from the surrounding environment, soy uses an additional 26 kg/ton as fertilizer. However, they also find that the drying of seaweed is still very energy-intensive due to the small scale. Seghetta et al. (2016) confirm in their LCA of seaweed that the seaweed farming lowers marine eutrophication, caused by the bio extraction of nitrogen during the growth-phase. On the other hand, the production of the equipment used in seaweed farming drives the greenhouse gas emissions up, since this production is usually quite energy-demanding. When delivered in a dried form, the drying process also shows a high energy demand which might result in high greenhouse gas emissions, depending on the source of the energy (van Oirschot et al., 2017).

LCA studies on blue mussel faming also showed the positive ecosystem services that the cultivation provides for the marine environment. Using LCA, Henriksson et al. (2018) show that the blue mussel cultivation countereffects marine eutrophication, producing an uptake of 18 kg of nitrogen-equivalent per ton of mussel. Thomas et al. (2021) find that blue mussel cultivation in Sweden takes up 5 kg of phosphorous-equivalent per ton of mussel (fresh weight). The carbon emissions are also negative, with an uptake 42.8 kg of CO2-equivalent per ton fresh weight on the west coast and 106 kg uptake per ton on the east coast. However, the actual uptake

of carbon, phosphorous and nitrogen is very location specific and thus should not be generalized.

Following the future potential that low trophic marine species, such as the blue mussel and seaweeds like sugar kelp (*Saccharina latissima*), have as an additive to salmonid feeds, the Norwegian Institute for Marine Research (IMR) has started the "SIS Ocean to Oven" project. This thesis is part pf that project, which is carried out in cooperation with in cooperation with RISE Sweden, Lerøy Seafood ASA and Cargill Norway Inc. The project aims at investigating the applicability of low-trophic species for human consumption or in aquafeeds. The combination of beneficial nutritional composition and low environmental impacts in their cultivation make sugar kelp and blue mussels particularly interesting for the project. The project includes feeding trials in which juvenile salmon were fed feeds with different inclusion rates of seaweed silage or blue mussel silages. The processing form of silage was chosen over drying because of the lower production costs and an expected higher digestibility. This study uses the data gathered from the feeding trials for parts of the analysis.

Aim of the study

This study aims at assessing the environmental impact of novel feeds that include seaweed silage or blue mussel silage, compared to a conventional control feed. In a second step, the aim is to compare the potential environmental impact of salmon fed with these novel feeds to salmon fed with regular feeds. The thesis is targeted at professionals within the field of salmon aquaculture and especially aquafeed-industry.

The specific research questions are:

1. How does the inclusion of seaweed silage or blue mussel silage in salmon feeds affect the environmental impact as compared to conventional feed?

2. How does the use of novel feeds for on- growth of farmed salmon affect the environmental impact as compared to conventional feeds?

2. Methodology

This study uses Life Cycle Assessment methodology (LCA) to estimate the environmental impact that the different salmon feeds and farmed fish have on pre-defined impact categories. LCA is a method designed to map all the environmental impacts that a product has along the value chain. This includes the sourcing of the raw materials, their processing, the production of the final product and all the logistics in between the steps. LCA is deployed in four steps, which shape the further structure of this study. The first step is the definition of the goal and scope of the study. In this step, the study object, included and excluded processes, the target groups and other central method choices are made. The second step is the Life Cycle inventory, which includes the data-collection for the in- and outputs of all steps along the product's value chain. These data are collected from primary sources and literature sources. Due to the iterative character of LCA, the data inventory is refined as the analysis proceeds. The third step is the Life Cycle Impact Assessment. Here, all the resource use and emissions resulting from the inventory that the different production- and transportation steps are sorted, and the previously defined impact categories get estimated and quantified. A sensitivity analysis identifies critical points in data sources or underlying assumptions and shows how changes influence the results of the assessment. The final step is the interpretation. Here, the results of the Life Cycle Assessment get evaluated with focus on the defined scope of the analysis. (Baumann & Tillman, 2004; Hauschild et al., 2017)

3. LCA methodology applied in this study

In this section, the LCA methodology applied in this study will be described. The assessment will be carried out in line with the four steps described above.

3.1 Goal and Scope

The first goal of this assessment is the evaluation of the environmental footprint of novel salmon feeds that include macroalgae or mussels. These footprints will be compared to a reference feed that is based on a standard feed used in the Norwegian salmon industry today. The second goal is the evaluation of farmed salmon fed the novel feeds. Again, the results are put in comparison to the environmental impact of salmon fed with the industry-standard reference feed. The study is directed at professionals working towards a more sustainable aquaculture industry in Norway, especially feed producers and salmon producers.

System Boundaries

The scope of the assessment is twofold. The fist scope covers the value chain of the feed production. The second one covers the value chain behind the salmon production, including the feeds as defined in the first scope. Figure 1 displays the system boundaries of the feed production, Figure 2 the system boundaries of the salmon grow-out.

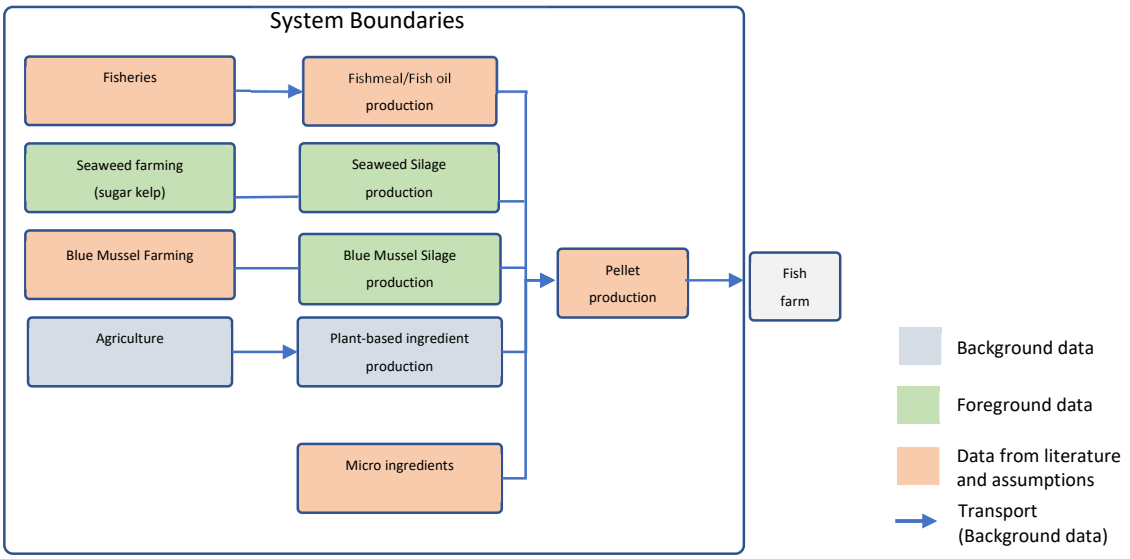

Figure 1: *System boundaries for the feeds*

As displayed in Figure 1, the system boundaries of the feed LCA include the sourcing of all agricultural, marine (both conventional and novel) and nutritional feed additives (here referred to as *micro ingredients*) for the feed, their processing, and the pellet production. Furthermore, all transportation between the different production steps and the transportation from the feed mill to the salmon producer is included. Thus, the assessment follows the life cycle from cradle to-farm entry. The feed production-system that was modelled is situated in Norway, since this is where the feed used in the feeding trials was produced. The raw materials however, are coming from various regions inside and outside the EU. The seaweed farming and blue mussel farming as well as the silage production is only included in the system boundaries of the feeds that contain these ingredients.

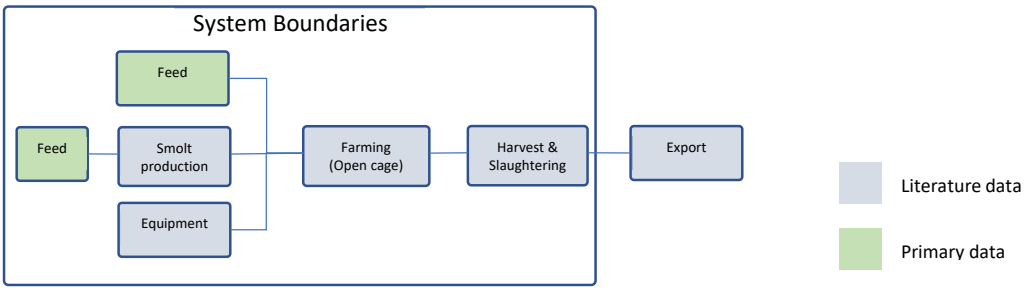

Figure 2: *System Boundaries for salmon farming*

Figure 2 shows the system boundaries of the salmon grow-out system that was modelled. The system covers the whole salmon production, from cradle-to-gate of slaughtering plant. This includes also the smolt production and -feeding, the grow-out of the salmon, including feeds used, production of the farming equipment used and the transportation between the different production steps including the harvest and the slaughtering. The feed inputs were modelled by using the environmental footprints of the different feeds as modelled in the previous step. The second assessment does not include any transportation, because the different sites are usually very close to each other. Logistics from the slaughtering plant to the retailer or consumer is excluded from the analysis because the distances and modes of transport used in these steps vary so widely that it is not possible to generalize emissions.

Lifetime

A lot of the equipment used in the production of the feeds and the salmon is used for many production cycles. Thus, it is necessary to define a maximum lifetime which limits the equipment to be relevant for the production of a ton of feed or salmon. In this study, the maximum lifetime is set at 10 years. This covers all of the "permanent" equipment used in the seaweed farming, but excludes emissions caused by the construction of longer-living equipment like the factory building used for slaughtering and processing or the boats used in the farming steps.

Impact Categories

The impact categories represent the different environmental factors that are being affected by the product. Since the environmental impact usually is manifold, this study attempts to narrow down on the most relevant ones for the given product, which are then respected in the LCA. The choice of impact categories was based on the relevance for the targeted audience and on the specific characteristics of the products, here aquafeeds and farmed salmon. The choice was limited by the availability of relevant data and calculation methods. The impact categories used in this research are shown in Table 1.

Table 1: *Impact categories included*

Impact Category	Description	Unit	Source
Global warming potential (for feeds & Salmon grow out)	The contribution to the radioactive forcing in the earth's atmosphere	Kg CO2-equivalents (eq.)	IPCC (2019) Joos et al. (2013)
Marine eutrophication potential (for Salmon grow out)	Contribution to biological oxygen consumption	Kg N-eq.	(Nixon, 1995)
Land use (for feeds)	Agricultural area used	ha	Curran et al. (2014 de Baan et al. (2013)

The first chosen impact category is Global Warming Potential (GWP). GWP was chosen because the severity of the climate crisis is putting the climate impact of products at core of public awareness. Thus, the GWP of salmon feeds and salmon themselves is considered as of high interest for the target audience, policy makers and consumers and expressed in *greenhouse gas emissions* or CO_2 *eq*. The marine eutrophication potential is regarded as a central impact category because of the debate about the role of salmon aquaculture in marine eutrophication. Organic effluents of the farm, mainly faeces and uneaten feed, can cause eutrophication in the benthic sphere underneath the farms and in the waters surrounding the open net-cage farms, by far the most used farm system in Norway (Bannister et al., 2014; Morrisey et al., 2000; Taranger et al., 2015). Besides, the use of agricultural products is generally associated with land- and water eutrophication (Boesch & Brinsfield, 2000; Ulén et al., 2007).

Like eutrophication potential, land use naturally plays an important role in agricultural products. Thus, the role of agricultural land use became more important as the feed formulations evolved from being marine-based to more vegetable based. This is particularly important for the case of the Brazilian soy which is studied here. This soy is often associated with degradation of primary rainforest and thus enjoys significant public awareness, since it not only causes loss of biodiversity and social injustice (Weinhold et al., 2013).

All impact categories were estimated with the with the ReCipe Midpoint method. This method was developed by several institutions and is one of the most widely used LCA-methods (Dekker et al., 2020; Huijbregts et al., 2017).

Other potentially relevant, but not included impact categories are the impacts of the salmon-feed and salmon production on biodiversity and social implications. However, a lack of data and, especially for the case of biodiversity, methodology made that inclusion impossible within the scope of this research. (Winter et al., 2017)

Functional Unit

For the comparison of the environmental impacts of the different feeds, the chosen functional unit is 1ton of feed pellets as they leave the feed mill. This study uses 1 ton over 1 kg since it is more commonly used in the industry.

The functional unit for the second LCA, the assessments of the salmon fed with the different feeds, is 1ton of fresh, gutted salmon as it leaves the slaughtering plant because this is the way the product most often enters the market. Again, ton was chosen over kg since it represents the industrial scale better. This is of higher interest to the target group.

Allocation

The allocation addresses the problem that different production processes produce multiple products. Thus, environmental burdens need to be divided over all the products that result from the given process. The most common ways to do this are economic allocation and mass allocation. In the first method, the emissions get distributed to co-products according to their respective economic value. Mass-based allocation distributes the environmental burdens according to each co-product's share of the output weight. This study follows the recommendation of ISO which is mass allocation over economic allocation. This allocation is more suitable since prices can vary over time and across different markets. (ISO, 2006a, 2006b).

Sensitivity analysis

In the sensitivity analysis, the study evaluates the importance of choices of data-sources, data-points and assumptions that could have a large effect on the results of the LCA. The goal is to

highlights dependencies that the main results of the study have on choices the author has made regarding, data-sources, methods and other assumptions that were necessary to make due to imperfect data.

3.2 Data inventory

Feed formulation

The study relies on data from different sources. The composition of the different feeds represents the exact compositions that were used in the feeding trials at IMR. The composition of the different feeds is shown in Table 2.

Table 2: *Compositions of the tested feeds*

	Ref. Feed	**Seaweed Feeds**				**Blue Mussel Feeds**		
Name of the feed	**Ref**	**SW1**	**SW2**	**SW3**	**SW4**	**BM3**	**BM7**	**BM11**
Ingredient (in %)								
Fish Oil	10.2	10.3	10.4	10.5	10.6	10.3	10.4	10.4
Fishmeal	25.0	23.3	21.6	19.9	18.2	20.3	15.4	10.5
Rapeseed Oil	13.9	13.6	13.4	13.2	12.9	13.3	12.4	11.6
Soy Protein Concentrate	20.0	20.0	20.0	20.0	20.0	21.0	19.7	16.5
Raw Wheat	11.0	11.0	10.9	10.5	10.0	11.0	10.4	10.5
Other Plant Proteins*	16.8	17.5	18.3	19.4	20.6	17.8	21.2	24.9
Micro Ingredients**	3.17	3.29	3.40	3.51	3.60	3.30	3.45	3.62
Yttrium Oxide	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Seaweed Silage	-	1.00	2.00	3.00	4.00	-	-	-
Blue Mussel Silage	-	-	-	-	-	3.00	7.00	11.0
Total	100	100	100	100	100	100	100	100

* Other plant proteins modelled as 40% faba beans, 40% corn gluten and 20% pea protein concentrate

**see Appendix A1

Table 2 shows the composition of the tested feeds. The naming of the different feeds is based on the type and amount of the novel ingredient used in the respective feed. For example, SW3 is the feed which contains 3% of seaweed silage und BM7 contains 7% blue mussel silage. The seaweed used in the feed formulations is sugar kelp (*Saccharina latissima*). The data originates from IMR and the producer of the trial feeds. The exact composition of "other plant proteins" (OPP) is considered as confidential and thus cannot be shared. In this study it is assumed that this ingredient consists of 40% faba beans, 40% corn gluten and 20% pea protein concentrate. This assumption is based on the most used feed ingredients in Norwegian aquaculture (Aas et al., 2019; Langeland, pers. comm.). The exact composition of the micro ingredients is also confidential. Based on Winther et al. (2020), this study assumes that the micro ingredients consist of a mixture of amino acids, phosphate, pigments and a premix of vitamins and minerals. This study assumes that the amounts of astaxanthin used in each feed are remain constant and only the amounts of phosphate and the vitamin-mineral mix change with the inclusion level of micro ingredients (Langeland, pers. comm.). The exact compositions of the micro-ingredients as used in the analysis can be found in Appendix A1.

Emission data for aquafeed

For the LCA, the emissions of each raw material, the production processes and the transportation of the goods are needed. For agricultural feed ingredients, emission data from the Agrifootprint database (version 4.1) were used. Emissions of the micro-ingredients were partially drawn from the Ecoinvent database (version 3.7.1) and derived from literature. The two databases were chosen because they are widely used in comparable literature and the agricultural raw materials of the feeds are well represented in them. An overview of the inventory data and their sources for the agricultural and chemical ingredients can be found in Appendix A2 and Figure 1. The databases were accessed through the SimaPro-software (multiuser-version 9.2.0.2 and 9.3.0.3).

The raw ingredients for the fishmeal and fish oil were assumed to be Atlantic herring (*Clupea harengus*), Blue Whiting (*Micromesistius poutassou*), Sandeel (*Hyperoplus immaculatus*) and Sprat (*Sprattus sprattus*). This assumption is based on personal communication with the producer of the trial feed and the most used fish species in Norwegian fishmeal and fish oil production (Winther et al., 2020). The calculated emissions of these two ingredients are 2.26kg CO_2 eq./kg. The basis of that calculation can also be found in Appendix A3.

The data for the emissions of the blue mussel silage were derived from literature. The blue mussel silage used in the feeding trials originated in Denmark, but due to the lack of Danish data this study uses emissions from blue mussel produced in Sweden (Thomas et al., 2021). The estimated emissions of blue mussel silage, including the fermentator are 0.13kg CO_2 eq./kg. The emissions exclude the uptake of carbon of the mussel during it's life cycle. This exclusion is made because the carbon taken up by the mussels is not stored away but transformed into aquafeeds which will eventually be released back to the sea within a short amount of time. The underlying literature data and further assumptions are described in Appendix A4.

The emissions of the seaweed silage were modelled based on a seaweed farm in western Norway, operated by a project partner. This firm is also the origin of the silage used in the feeding trials. The estimated emissions for the seaweed silage are 0.46 ton CO_2 eq./ton. The detailed calculations that led to this estimation as well as the underlying processes and raw materials are displayed in Appendix A5.

The emissions of the micro ingredients are specific to each feed formulation since the composition differs slightly (see Appendix A1). They range between 39.9ton CO_2 eq./ton and 45.4ton CO_2 eq./ton The main part of the emissions can be drawn back to the highly energy intensive production of astaxanthin and amino acids. The exact composition of the emissions, the underlying literature and assumptions are displayed in detail in Appendix A6.

Following Winther et al. (2020), the emissions for the production processes of the aquafeed are based on the estimated energy consumption of the process, the fuel consumption and waste production. The estimated GHG emissions of the feed production process are 12.2kg CO_2 eq./ton. The underlying assumptions and specific emission data for the individual processes are displayed in Appendix A7.

The emissions caused by the transport of the raw materials to the feed mill and of the pellets to the farming site are dependent on the place of origin of the raw materials, which on the other hand depends on the raw material itself. The production site is set to be in Norway. Furthermore, the mode of transport also influences emissions. An overview of the different modes of transport and the respective distances is shown in Appendix A9.

Figure 3 summarizes the greenhouse gas emissions of the different feed ingredients in a comparative graph.

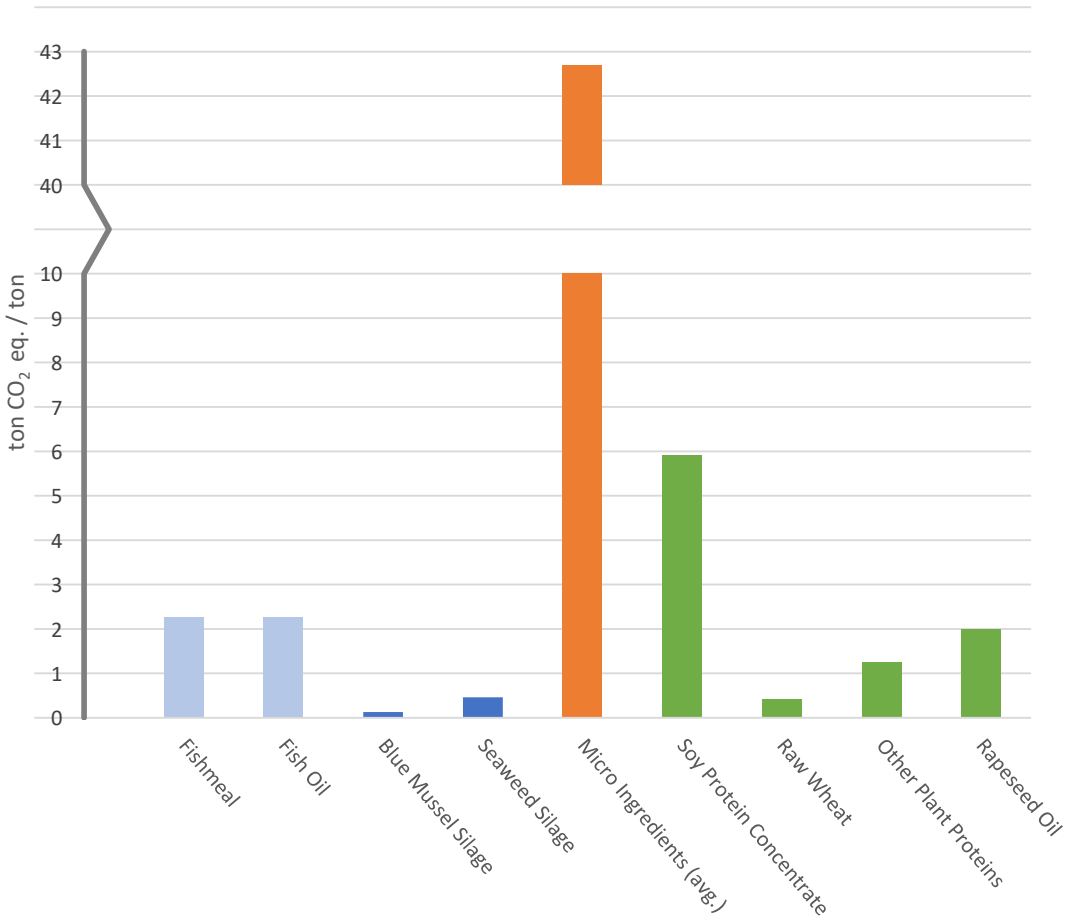

Figure 3: Overview of greenhouse gas emissions of feed ingredients

Figure 3 displays the conventional marine ingredients in light blue and the novel marine ingredients in dark blue. Artificial feed additives are marked in orange and agricultural ingredients in green.

Data inventory for the salmon aquaculture

Following the system boundaries that identify the parts of the value chain that are included in this study, this section describes the inventory data used for the determination of the environmental performance of the salmon farming, including the feeds that were tested earlier. The inventory closely follows Winther et al. (2020) and only scarcely contains some additional primary data gathered as part of this research.

Following Winther et al. (2020) and the industry standard, the smolt production was assumed to be a recirculating aquaculture system and it was assumed that the feed given to the smolt is the same feed as the one given to the fish in later stages. Thus, the analysis respects smolt fed with all eight variations of feed as described in Table 2. Depending on the feed used, the emissions caused by smolt production range between 3.8kg CO_2 eq./kg and 5.7kg CO_2 eq./kg. The detailed composition of these emission values is described in Appendix A8.

The farm operations and contributing boat services were drawn from Winther et al. (2020). The equipment used in salmon farming was assessed using the findings of Hognes & Skaar (2017). Combined, the emissions of all operations and the used equipment are estimated to be at 76.3kg CO_2 eq./ton. These emissions are also derived in detail in Appendix A8.

The emission data underlying the estimation of the marine eutrophication potential come from two sources. The nitrogen emissions from the agricultural ingredients are drawn from the Agrifootprint database (version 4.1). The estimated emissions of nitrogen from the effluents of the fish-farming in open net-pens are drawn from Grefsrud et al., 2021. They estimate that a total of around 52.100 tons of dissolved nitrogen are emitted by Norwegian aquaculture annually. Combined with the annual production of 1.25 Mtons (Aas et al., 2019), this results in estimated nitrogen emissions of 0.042ton N eq./ton from the fish farming operation.

Feed conversion

As briefly described in section 1 of this research, the main input factor that influences the emissions of salmon farming is the feed. The results from the LCA of the different feeds are the emission values that were used in the assessment of the salmon's footprint. Besides the emissions that are produced in the value chain and the resources used of the feed itself, the amount of feed needed during the production of the salmon is of major importance. The amount of feed needed to grow out a salmon is usually expressed as the feed conversion ratio (FCR). (Pelletier et al., 2009; Winther et al., 2020)

The FCR values of the feeds tested in this study were provided by the IMR. They ran a trial for each feed as described in Table 2. Each feed was tested in 3 different tanks for 76 days. Each tank contained 65 fish with a total biomass of 13kg per tank, thus approximately 200g per fish. After the test-period, the fish have grown to approximately 500g each, with a slight variation between the different test feeds. The FCRs resulting from the feeding trials are shown in Table 3.

The FCR as determined by the IMR is expressed in Equation (1).

$$FCR = \frac{[(\sum_{t=0}^{t} m_F) - m_F^t]}{[m_B^t - m_B^{t=0}]} \qquad (1)$$

The numerator describes the dry mass of the feed, here m_F, consumed by the fish in the period $t = 0$ until t as the difference between the sum of all the feed added and the feed that is left at the end of the observed period in t. Since the left feed is wet, the dry weight was estimated for comparability. The denominator describes the growth of the total biomass m_B in the same period. Thus, the FCR is the factor that determines how much feed has been used for biomass growth within a specific period of time. Since the total biomass has been measured rather than single fish, the FCR also takes mortalities into account.

Since the aim of the study is a comparison of the environmental performance of the novel feeds with each other and with the reference feed, this study focusses on the relative change of the FCRs of the different feeds, compared to the reference feed. The FCR for the reference feed was used as a base. The FCRs that were observed for the feeds that include the novel feed ingredients were then compared to the FCR of the reference feed to determine the relative change that the application of seaweed silage and blue mussel silage caused on the FCR. These relative changes are then being applied to FCR values that the study received from our project partner, which represent a real-world scenario better because they cover all life-stages of the fish and not only the smolt stage. Though the values base on salmon fed with another feed, this study assumes that they are comparable because both feeds are composed as a standard feed

which's formulation does not differ too much from the reference formulation used in the trials (see Table 2). The "real-world" FCR values for each growth stage are shown in Table 3.

This study calculated a weighted FCR value out of the FCRs per growth stage. This average is **1.18**. This value represents the weighted average, whereby the different values were weighted according to amount of weight gained in the respective period. The calculation is presented in Equation 2.

$$FCR^{Ref} = \frac{(1*0.9)+(2*0.95)+(6*1.1)+(10*1.3)}{19} = 1.18 \qquad (2)$$

As mentioned, the weighting is in accordance with the weight gain of each individual value. This mass gain is expressed in "growth steps" of 250g. Thus, the FCR value for 250g – 500g is weighted with 1, whereas the FCR value for the growth from 2500g – 5000g is weighted with 10 ([5000 – 2500] / 250 = 10). There are 19 of these steps in total. The resulting value is the FCR^{Ref}.

In the following course of the study, this FCR^{Ref} replaces the reference FCR as observed in the feeding trials. The relative change of the observed FCRs in comparison to the reference feed are then applied to FCR^{Ref} to determine the assumed FCRs for each tested feed. The values are displayed in Table 3.

Table 3: *FCR values as observed by IMR and per life cycle stage in common salmon farming*

	Ref. Feed	**Seaweed Feeds**				**Blue Mussel Feeds**		
Name of the feed	**Ref**	**SW1**	**SW2**	**SW3**	**SW4**	**BM3**	**BM7**	**BM11**
FCRs as observed in trial								
FCR (Relative change to Ref)	0.68 (+/- 0)	0.73 (+7%)	0.74 (+9%)	0.77 (+13%)	0.74 (+9%)	0.80 (+18%)	0.86 (+26%)	1.08 (+49%)
FCR reference (per life cycle phase)								
250g – 500g	0.9	-						
500g – 1000g	0.95							
1000g – 2500g	1.1							
2500g – 5000g	1.3							
FCR based on FCR^{Ref}	**Ref**	**SW1**	**SW2**	**SW3**	**SW4**	**BM3**	**BM7**	**BM11**
FCR	**1.18**	**1.27**	**1.28**	**1.33**	**1.28**	**1.38**	**1.49**	**1.88**

The calculated FCR which are displayed in the bottom row of Table 3 are the values that were applied to the Life Cycle Assessment model of this study.

4. Results

This section introduces the main results of the life cycle assessment. For the feeds, the results comprise the greenhouse gas emissions and the agricultural land use potential, which is only relevant for the feeds since it solely relies on the production of the agricultural ingredients. The salmon grow out-model uses the modelled feeds and applies them to a salmon grow-out scenario. As described in Table 1, the model in addition includes marine eutrophication potential, which might be affected by the feed itself but also by the farm operations in the open sea.

4.1 Feed

Feeds including seaweed silage

The results for the feeds show how the replacement of fishmeal with seaweed silage affects the greenhouse gas emissions caused by the feeds. These emissions are displayed in Figure 4.

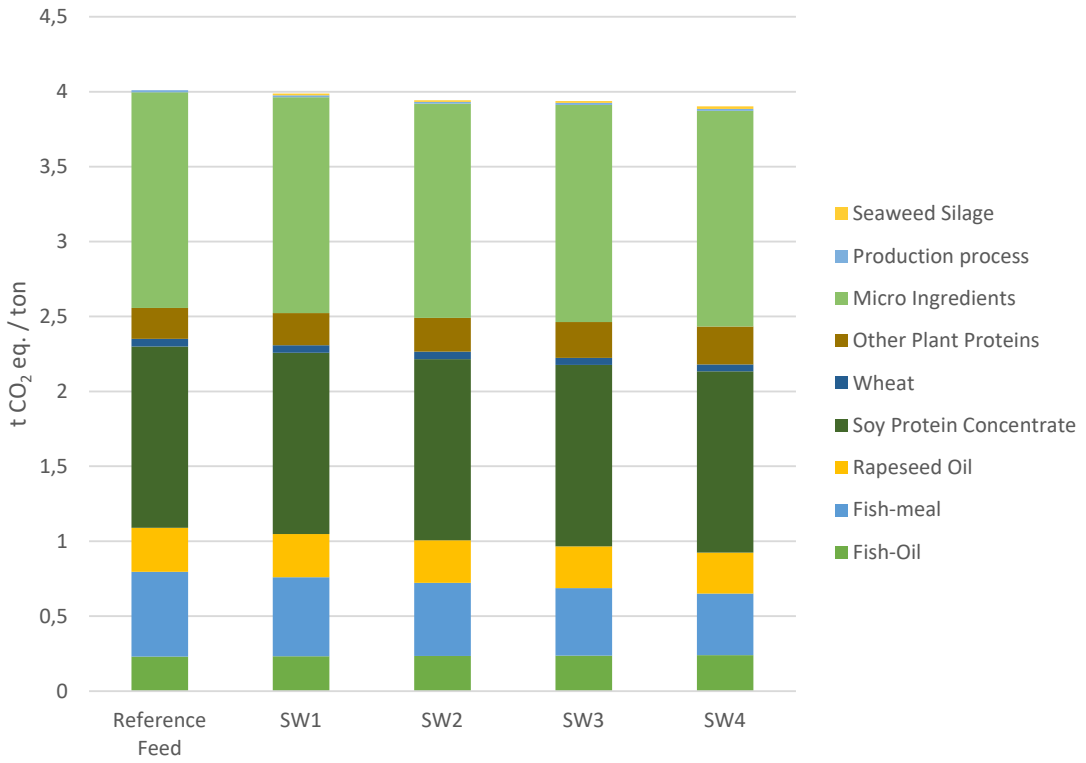

Figure 4: *Estimated greenhouse gas emissions of reference feed and feeds with seaweed silage*

With 4tons CO_2 eq./ton, the reference feed shows the highest environmental footprint of all the tested feeds. Furthermore, the results also show that the inclusion of seaweed silage and at the same time the reduction of the fishmeal content reduces the greenhouse gas emissions, which are at 3.9tons CO_2 eq./ton of feed for the SW4 feed formulation. This represents a drop of GHG emissions of 5%. The feeds SW1, SW2 and SW3 lie between these values. The largest contributors to the overall greenhouse gas emissions are the micro ingredients (36%) and the SPC (28%). Wheat, rapeseed oil and other plant proteins add up to 0.55tons CO_2 eq./ton of feed, which is a contribution rate of 14% to overall emissions.

To highlight the effects that the change of the feed formulations have on the GHG emissions of the feeds, Figure 5 shows the GHG output of the feeds excluding the emissions that remain constant over the different formulations.

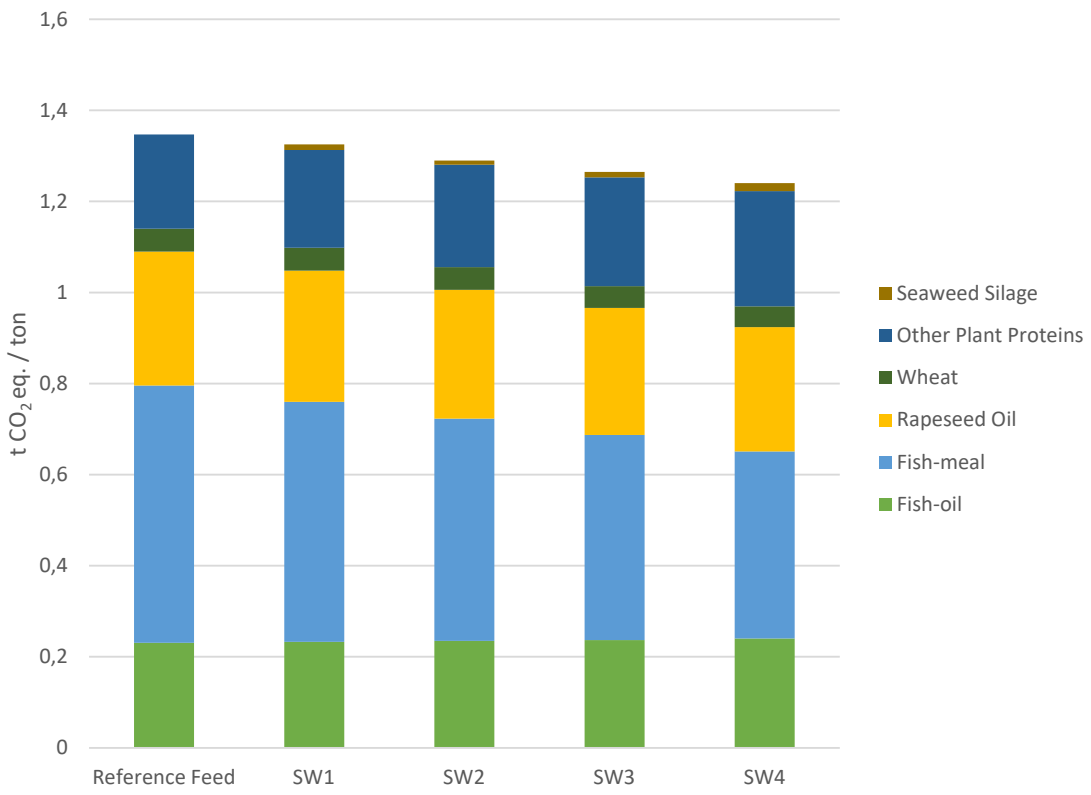

Figure 5: *Estimated greenhouse gas emissions of reference feed and feeds with seaweed silage, excluding constants*

Figure 5 shows more clearly the effects of the change of feed formulations. The reduction of the overall GHG emissions can mainly be drawn back to the reduction of fishmeal, which is more intensive in GHG emissions than the replacing novel feed ingredients. Following Table 2, the amount of fishmeal gets reduced by 27,2% when comparing the inclusion rates of the reference feed (25%) and the SW4 formulation (18%). The GHG emissions of the fishmeal share drop accordingly (from 0.57tons CO_2 eq./ ton of feed to 0.41tons CO_2 eq./ ton of feed).

Feeds including Blue Mussel Silage

A more pronounced reduction of GHG-emissions can be seen for the feeds that contained blue mussel silage (Figure 6).

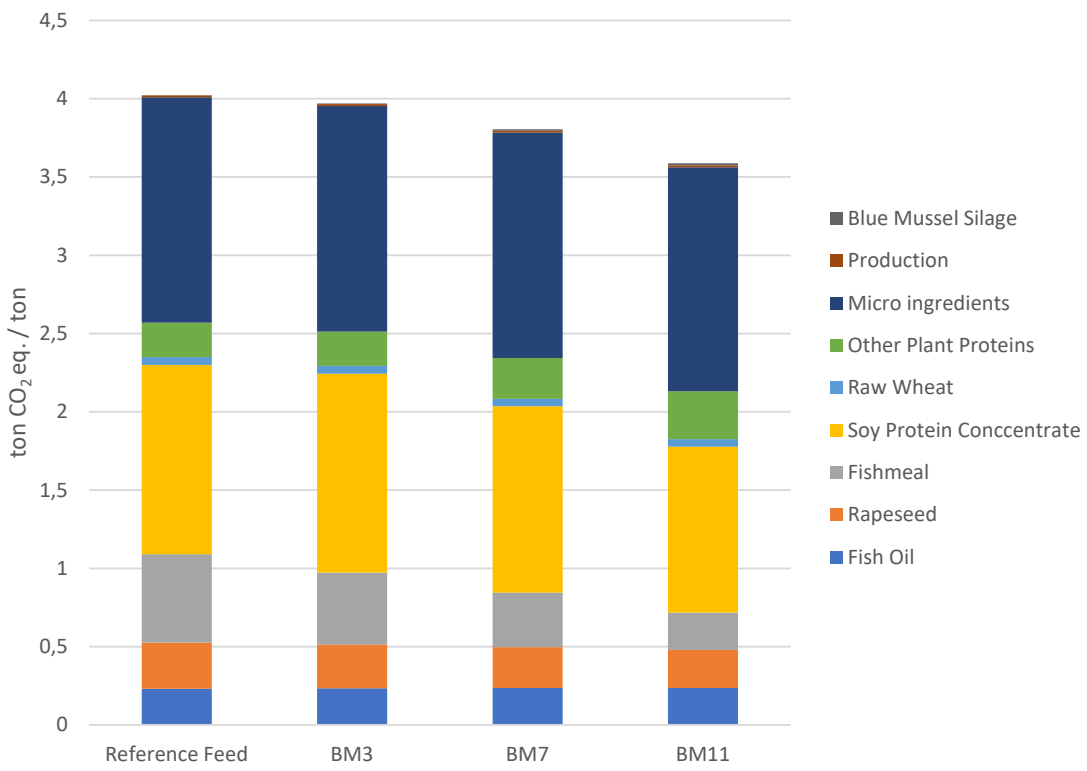

Figure 6: *Estimated greenhouse gas emissions of reference feed and feeds with blue mussel silage*

Like the feeds that include seaweed silage (Figure 4), Figure 6 shows lower GHG emissions with rising inclusion of blue mussel silage. Again, the lower inclusion of fishmeal is a contributor to the decreasing greenhouse gas emissions. However, the emissions of BM11 show that the reduction of soy protein concentrate has also had a reductive effect on the GHG emissions. Contrary to the seaweed silage formulations, the inclusion of soy protein concentrate has not remained constant (see Table 2). This lets the emissions from this ingredient drop from 1.21tons CO_2 eq. / ton of feed for the reference feed and BM3 drop to 1ton CO_2 eq. / ton of feed in BM11. The slightly higher inclusion of other plant proteins that goes with the higher inclusion rates of blue mussel silage countereffect the decreasing emissions caused by the reduction of fishmeal and SPC slightly, because other plant proteins show much higher GHG emissions that blue mussel silage, which's emissions are very low. They range from 0.004tons CO_2 eq. / ton of feed (BM3) to 0.014tons CO_2 eq./ton of feed (BM11).

Agricultural land use

The agricultural land use is closely linked to the use of agricultural ingredients in the feed. Figure 7 shows the total land use of the different feed formulations and each ingredient's contribution to overall land use. Ingredients with an agricultural land use of less than 0.001 ha/ton were excluded from the analysis.

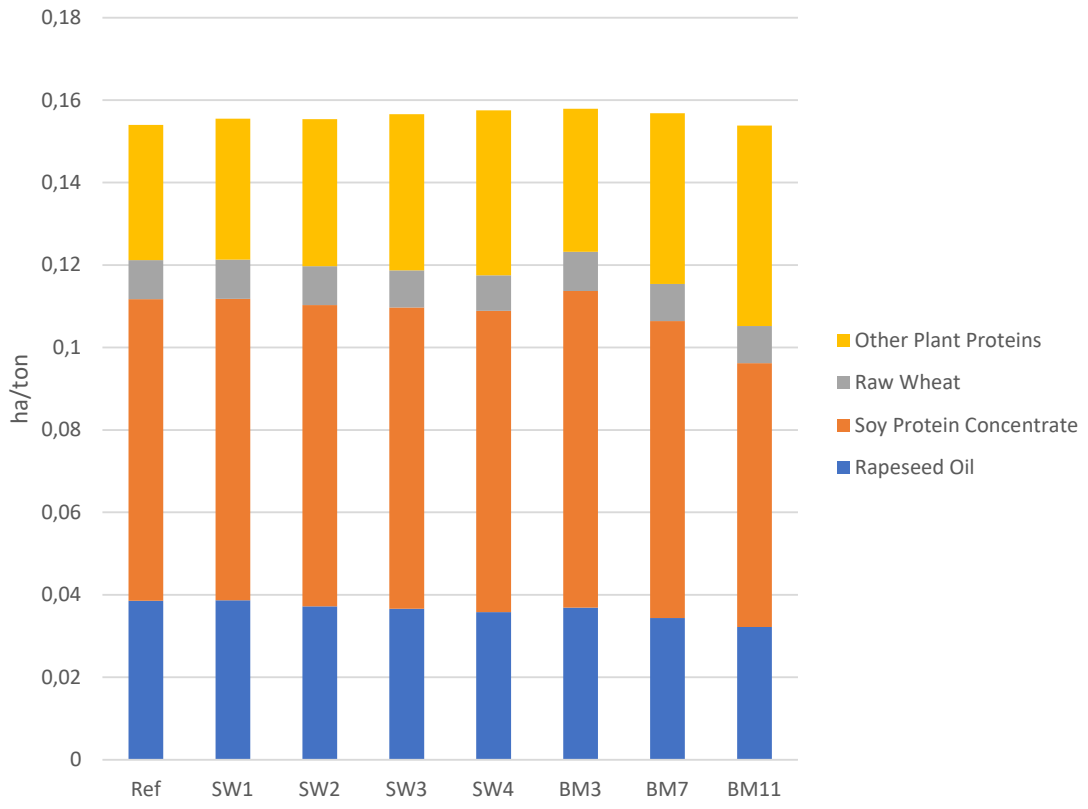

Figure 7: *Estimated land use of the tested feed formulations*

The agricultural land use remains quite stable at just over 0.15 ha/ton for all the feeds. At 0.154 ha/ton, the reference feed and the BM11 feed both have the lowest agricultural land use potential. For the seaweed feeds, the estimated land use increases gradually from 0.155 ha/ton of feed in the case of SW1 to 0.158 ha/ton (SW4). This is an increase by 2.5% from the reference feed. For the blue mussel feeds, the land use potential decreases as the inclusion rate of blue mussel silage increases. While BM3 has a land use potential of 0.158 ha/ton, the land use goes down to 0.157 ha/ton (SW7) and 0.154 ha/ton (BM11).

Figure 7 shows that soy protein concentrate is by far the largest contributor to the overall land use potential. For the reference feed and the seaweed-feeds, the soy protein concentrate contributes about 50% to the overall land use. The results indicate that the proportion of SPC to the overall land use potential is slightly decreasing with the inclusion of blue mussel silage, from 49% (BM3) to 41% (BM11). This decrease is counter effected by an almost equally increasing contribution of the other plant proteins. This is in line with the feed formulations displayed in Figure 2, which show a decrease of SPC for the blue mussel feeds and a simultaneous increase of the other plant proteins in the feed formulations.

4.2 Salmon

Salmon fed with seaweed feeds

Following the system boundaries defined in Figure 2, the emissions of the salmon include the whole production from the hatchery and smolt production to the slaughtering and gutting. The finished product is salmon, fresh, gutted with head on as it leaves the gates of the slaughtering plant. The results for the GHG emissions are displayed in Figure 8.

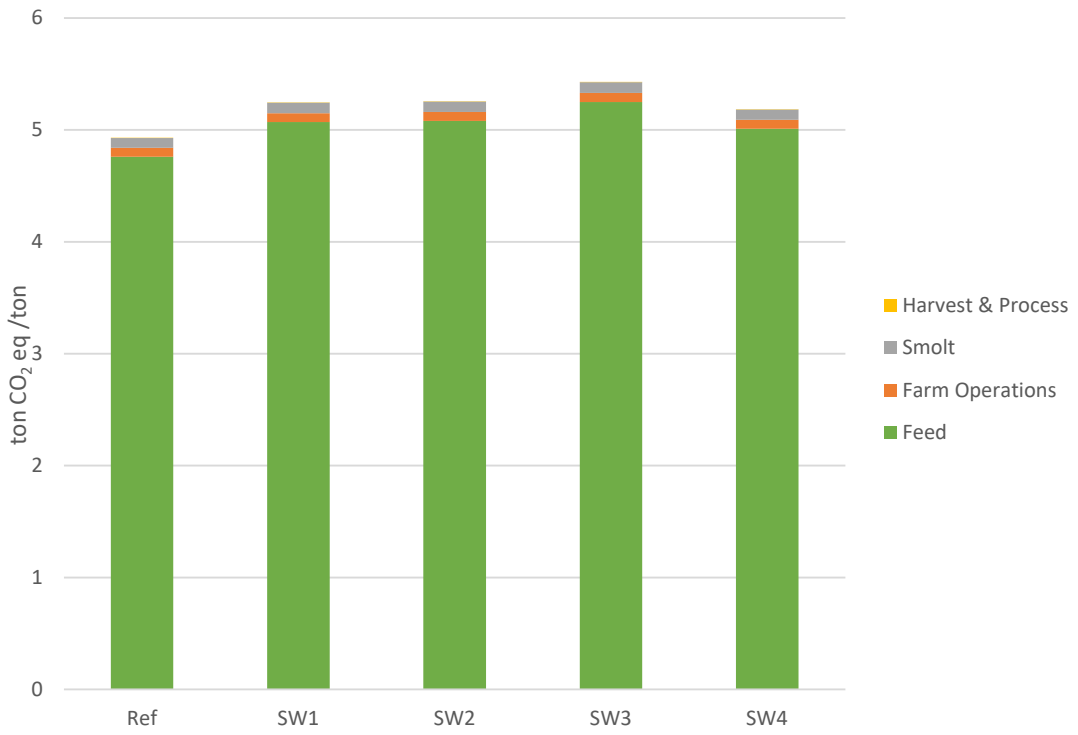

Figure 8: *Estimated greenhouse gas emissions of salmon fed with reference feed and seaweed feeds*

Figure 8 shows clearly how dominant the feed-production is in the overall GHG emissions of farmed salmon. Though the feed production emissions get lower with higher inclusion rates of seaweed silage (see Figures 3 & 4), the overall emissions when applied in a farming scenario rise by 10% from 4.9tons CO_2 eq./ton of salmon (Ref) to 5.4tons CO_2 eq./ton of salmon (SW3). SW4 shows lower emissions again (5.1tons CO_2 eq./ton of salmon). The development of the overall emissions ca be directly linked to the respective values of the FCR, which determines how much feed is needed to grow a mass unit of life weight fish (see Table 3). The farm operations, the harvesting and processing as well as the smolt production are only of low importance, since they only contribute a very small share to the overall emissions.

Salmon fed with Blue Mussel Feeds

Figure 9 shows the estimated GHG emissions of the salmon fed with the feeds that include blue mussel silage.

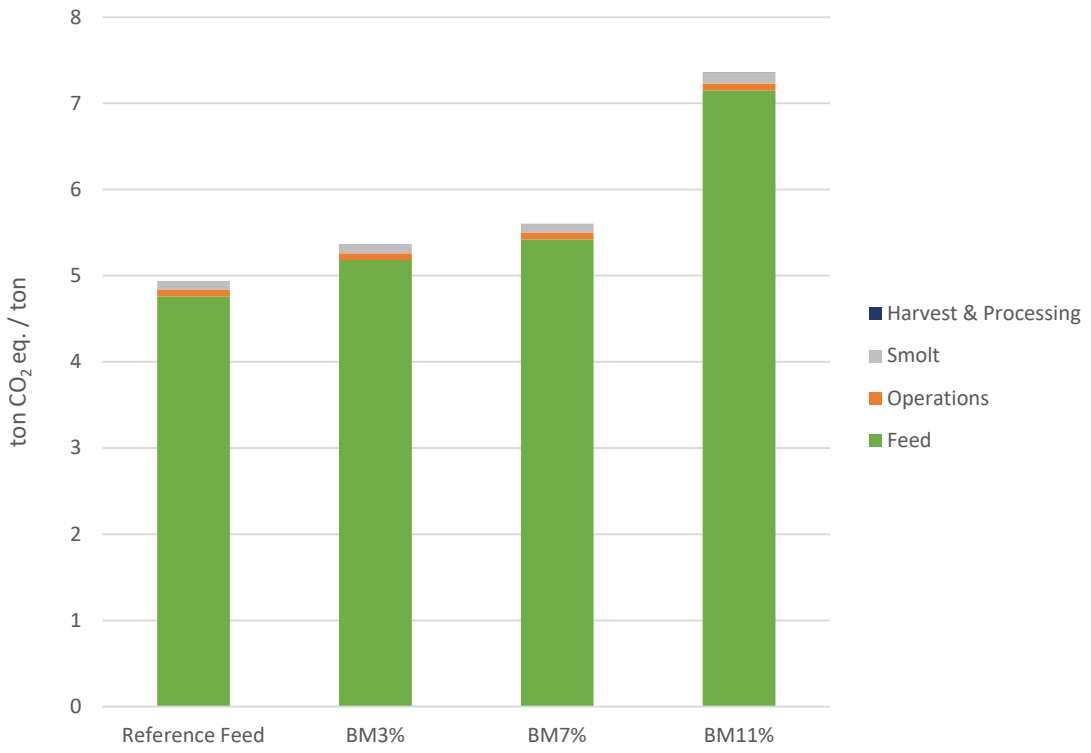

Figure 9: *Estimated greenhouse gas emissions of salmon fed with blue mussel feeds*

As described for the case of seaweed feeds, Figure 9 shows that the estimated GHG-emissions for the salmon fed with blue mussel feeds are also dominated by the emissions of the feed production. Thus, the estimated emissions for the salmon production are largely influenced by the FCR values for each feed. Overall emissions of salmon fed the blue mussel silage (and the reference feed) gradually rise by 14% from 4.9 ton CO_2 eq./ton (Ref) to 5.9tons CO_2 eq./ton (BM7). The BM11 feed then shows a much higher GHG output (6.9tons CO_2 eq./ton).

Marine eutrophication potential

Figure 10 describes the eutrophication potential of each of the tested salmon.

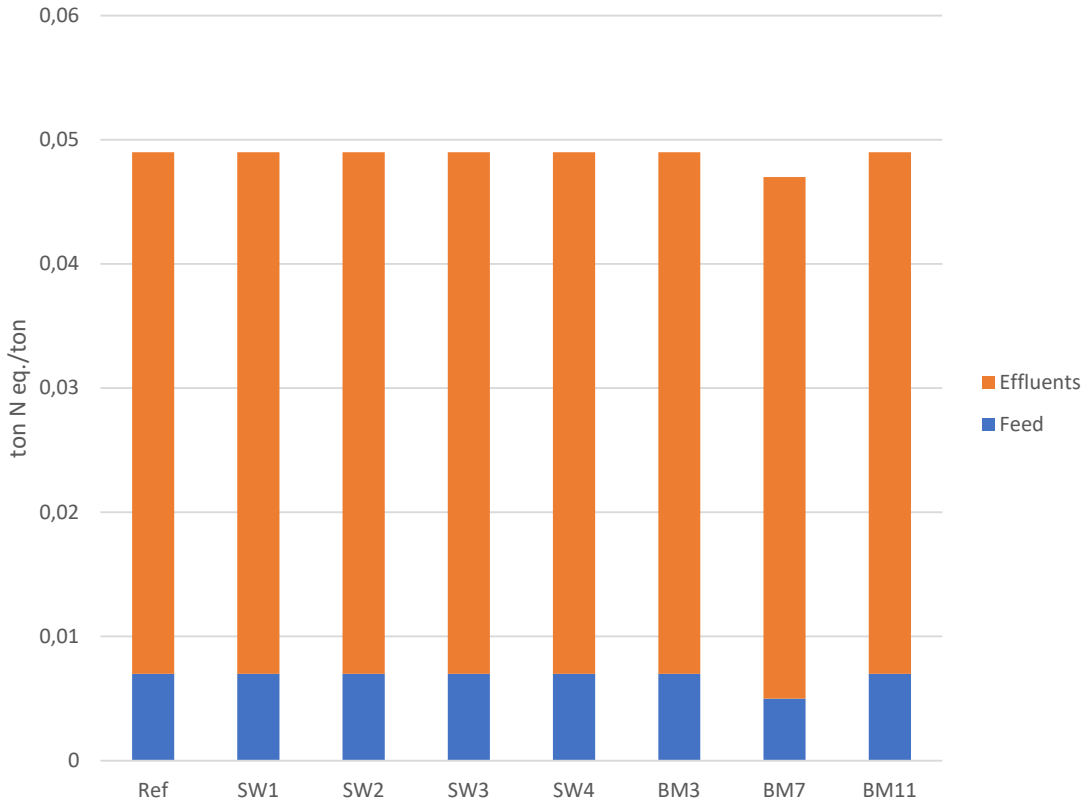

Figure 10: *Estimated marine eutrophication potential of salmon fed with the tested feeds*

Figure 10 shows that the marine eutrophication potential remains stable at 0.049 ton N eq./ton for all the tested feeds except for the BM7 feed, which shows a slightly lower estimated marine eutrophication potential of 0.047tons N eq./ton of salmon. Furthermore, the results clearly show that most of the N eq. emissions result from the effluents caused by the fish farming in open net-cages, whereas the marine eutrophication potential caused by the agricultural ingredients only account for 15% of overall emissions (10% in the case of BM7).

4.3 Sensitivity analysis

This section analyses the dependency of the results on certain key data points and assumptions. The sensitivity analysis tests if the results from this study are robust. To ensure comparability, each sensitivity analysis will be performed for the case of the reference feed. Thus, the scenarios will only be applied to the reference feed.

Formulation of micro ingredients

As seen in Figure 4, the micro ingredients give an important contribution to the feed GHG emissions (and thus also on salmon emissions). These high emissions result from a literature-based estimation of the GHG emissions that the production of the micro-ingredients, especially the pigment astaxanthin, produce. This study assumed that the greenhouse-gas emissions for the astaxanthin production are 169 ton CO_2 eq./ton. This estimation relies on a weighted average of the findings by Winther et al. (2020) and Onorato & Rösch, (2020) (see Appendix A6).

Winther et al. (2020) estimated the emissions caused by the astaxanthin production to be 89 ton CO_2 eq./ton. Inserting this value to the model of the feed, lowers the overall emissions of the reference feed by 15% from 4tons CO_2 eq./ton of feed to 3.4tons CO_2 eq./ton of feed. For the salmon at farm gate, the overall GHG-emissions for the salmon fed with the reference feed drop by 15.5% from 4.9tons CO_2 eq./ton of feed to 4.14tons CO_2 eq./ton of feed. Thus, the assumptions underlying the greenhouse gas emissions of micro ingredients and astaxanthin in particular have a large effect on the overall CO_2 eq. emissions of the products. However, the relative emissions of the feeds to one another do not change since the amount of astaxanthin remains constant over all feed formulations (see Appendix A1).

Impact assessment methods

This study uses the ReCipe Midpoint-method. However, other methods are also available, although they do not always include all used impact categories (esp. land use). They can differ in intrinsic differences of the models, which affects the results and thus the conclusions (Dekker et al., 2020). Running the model with the CML-1A-baseline method, developed by the University of Leiden, results in an output of 4.9tons CO_2 eq./ton for the salmon fed with the reference feed. That is 1.3% less than the emissions that result from the calculation with the ReCipe midpoint method. Running the same model with the ILCD-method from the European Commission, results in a climate change potential of 4.2 ton CO_2 eq./ton. This is a decrease of 15% compared to the main results from the analysis with ReCipe. The difference between the outcome of the calculation with the ReCipe Midpoint-method and the CML1A-baseline method comes from a different weighting of the ingredients, especially the agricultural ingredients. Whereas the ReCipe-calculation values greenhouse gas emissions of the ingredients more in accordance to their inclusion rate in the different recipes, the CML-baseline method values agricultural ingredients, especially Rapeseed Oil higher and gives less weight to soy protein concentrate or micro ingredients. Thus, the choice of impact assessment method can have a significant effect on the results.

FCR

As can be seen in Figures 7 & 8, the global warming potential of salmon fed with different feeds is highly dependent on the FCR values used in the calculation. A generalization of FCRs for is very difficult, because they can vary widely between different site-specific characteristics of the fish farms or other external impacts like climatic features of certain years (Nordgarden et al., 2003). Thus, the sensitivity analysis will estimate emissions of salmon farms with other FCRs that were reported from fish farms to test for the representativeness of the assumptions made in section 3.2.

Table 4 shows the estimated GHG emissions of salmon but calculated with different FCR values, each of which was reported by salmon producers to the Norwegian Directorate of Fisheries as part of their annual profitability study 2020 (Fiskedirektoratet, 2020).

Table 4: *Sensitivity analysis: Variation of feed conversion ratios*

FCR (As reported to Fiskedirektoratet for 2019)	**Global Warming Potential of salmon fed with Ref. Feed**	**Change compared to this study's results**
FCR = 1.32 (avg. for 2019)	**5.45 ton CO_2 eq./ton**	**+ 11%**
FCR = 0.89 (Reported by 9 companies)	**3.65 ton CO_2 eq./ton**	**- 25%**
FCR = 1.15 (Reported by 17 companies)	**4.77 ton CO_2 eq./ton**	**- 2.8%**
FCR = 1.35 (Reported by 14 companies)	**5.57 ton CO_2 eq./ton**	**+ 13%**
FCR = 1.61 (Reported by 15 companies)	**6.61 ton CO_2 eq./ton**	**+ 34%**

Table 4 shows how much FCR values can vary from farm to farm. Furthermore, the global warming potential of farmed salmon is highly sensitive to changes in the FCR. Coupled with the large variety of FCR values, this should always be kept in mind.

Data sources

This study uses core data from the Agrifootprint and the Ecoinvent databases. Especially the data source of the primary emissions of the agricultural ingredients are therefore highly relevant for the outcome, since they represent the majority of the emissions caused by the feed and thus also the salmon grow out. This study tests the sensitivity of the results on the data sources for agricultural goods by replacing the primary data with similar data from the World Food LCA Database, which focusses on agri-food data. The resulting greenhouse gas emissions of the reference feed are 3.72tons CO_2 eq./ton. This is 24% less than the estimated emissions of the reference feed as calculated in the main results. Thus, the choice of databases can have a significant effect on the outcome.

5. Discussion & Interpretation

5.1 Interpretation of results for feeds

Interpretation of the results for global warming potential

The results of the Life Cycle Assessment presented above show the development of the emissions caused by the feeds in comparison to each other. Both, the seaweed feeds as well as the feeds that include blue mussel silage show that the replacement of fishmeal with one of the novel feed ingredients results in slightly lower greenhouse gas emissions. This can be traced to the low greenhouse gas emissions caused by the blue mussel silage and the seaweed silage. The farming and processing of both, mussel and seaweed silage only requires very little energy and material input, so the emissions caused by the production of these ingredients are very low. Thus, the savings on emissions are caused by the reduction of the inclusion rate of mainly fishmeal, but for the case of BM11 also of soy protein concentrate and are not compensated by the inclusion of blue mussel silage, which lets the overall emissions of the feeds that include the novel ingredients drop.

For the case of the feeds that include seaweed silage, the inclusion of plant proteins and fish oil increases with the inclusion of the novel ingredient (see Table 2). This dampens the overall reduction of GHG emissions slightly since both ingredients emit more greenhouse gasses than the seaweed silage. This effect is also displayed in Figure 5, since the contribution of the

emissions caused by "other plant proteins" gets higher as the overall emissions get lower with the reduction of the fishmeal inclusion rate. The same goes for the feeds that include blue mussel silage. Here, the other plant proteins also increase in line with the inclusion of blue mussel silage, which dampens the overall reduction of GHG emissions (see Figure 6).

The results show that the inclusion of seaweed silage or blue mussel silage as a replacement for fishmeal or protein sources like soy protein concentrate can lower the greenhouse gas emissions of the feeds. However, the reduction of greenhouse gas emissions is relatively ineffective if the novel ingredients replace ingredients which already contribute relatively little to the overall. This is the case for most feeds tested in this study. Here, the recipes focus on the replacement of fishmeal with novel feed ingredients. The fishmeal itself already produces relatively low greenhouse gas emissions. For the case of the reference feed, a 25% inclusion rate results in a 14% contribution to the overall global warming potential. Thus, a 5% replacement of the fishmeal-content would only result in a 2.8% reduction if the overall emissions of CO_2 equivalent. Therefore, although the estimations show a clear reduction of greenhouse gas emissions, the effect is rather limited when focussing on the fishmeal, even though the emissions of the replacing seaweed silage and blue mussel silage is even lower.

The reduction of greenhouse gas emissions of feeds would be much more effective when concentrating on high-emission ingredients, such as the micro ingredients and the soy protein concentrate. As it can be seen in Figure 3, these two ingredients have notably higher greenhouse gas emissions than the other ingredients, whereas especially the micro ingredients stand out. For the feeds, they combined add up to more than 65% of the total emissions (see Figures 4 & 6). The effectiveness of a replacement of soy protein concentrate can be observed for the case of the feeds that include blue mussel-silage. Here, the formulation of the BM11 feed has 3.4% less soy protein concentrate than the reference, which is replaced by parts of the added blue mussel silage (see Table 2). This decrease of SPC however leads to a 10% reduction of the overall greenhouse gas emissions (see Figure 6). An even larger effect would be achieved when lowering the inclusion rate of the micro ingredients only by a little bit. They contribute only between 3.17% and 3.62% to the overall feed but are responsible for 36% - 40% of the feed's overall greenhouse gas emissions (see Figure 4 & Figure 6). Thus, only a 0.5% reduction of the inclusion of micro ingredients could lead to a 5% reduction of the feed's overall greenhouse emissions. However, the tested feed formulations show a slight increase of micro ingredients when the fishmeal-content was decreased (see Table 2).

Interpretation of the results for land use potential

As can be seen in Figure 7, the land use is mainly driven by the soy protein concentrate. Since the inclusion rate of soy protein concentrate in the feeds that include seaweed silage remains stable at 20% (see Table 2), the agricultural land use remains somewhat stable at just over 0.15 ha/ton of feed for these feeds as well. The slight differences between these feeds (a deviation of 0.004 ha/ton) can be explained with slight changes in the inclusion rate of the other plant proteins, which increase in line with the inclusion of seaweed silage (see Table 2).

At 0.158 ha/ton of feed, the BM3 feed has a relatively high estimated land use. This can be linked to a relatively high inclusion rate of other plant proteins, while the inclusion rate of soy protein concentrate is as high as it is in the reference feed. The BM7 and BM11 feeds replace parts of the soy protein concentrate with blue mussel silage, which effects the agricultural land use potential. It drops from 0.158 ha/ton (BM3) to 0.157 (BM7). At 0.154 ha/ton, the BM11 feed then has the same estimated land use as the reference feed, despite a lower SPC content.

Like for the case of greenhouse emissions, the reduction of the agricultural land use is most effective by replacing agricultural ingredients, mainly soy protein concentrate, with novel feed

ingredients. The soy protein concentrate has an agricultural land use of 0.366 ha/ton. With an inclusion rate of 20% for the case of the reference feed, this means that 0.073 ha of agricultural land are used by the production of soy protein concentrate per ton of reference feed, or 48% of the total land use of the feed. The replacement of soy protein concentrate with other plant proteins has a reductive effect on the land use. For every percent of SPC excluded from the feed, the land use decreases by 2.3%. For every percent of OPP being withdrawn from the feed, the land use decreases by 1.3%. Thus a 1:1 replacement of SPC with OPP would lead to a 1% reduction of land use.

5.2 Interpretation of the results for salmon grow-out

Interpretation of GHG-emissions of the salmon production

The greenhouse gas emissions of the salmon production are dominated by the feed. The feed contributes to more than 95% of the estimated overall emissions of the salmon farming (see Figure 8 & Figure 9). This is roughly in line with the findings from Pelletier et al. (2009). They estimate that about 93% of the overall global warming potential is due to the feed. Other publications came to different results. Winther et al. (2020) find that the feed contributes to around 85% of the overall climate change potential of farmed salmon, when excluding transport of the product after slaughtering and processing. The difference to the findings of Winther et al. (2020) can be explained with the difference in the assumptions underlying the greenhouse gas emissions caused by the production of the micro ingredients, especially Astaxanthin (see section 4.3).

The high contribution that feeds have on the estimated global warming potential of farmed salmon means that the amount of feed used in the grow out of salmon is the single most important factor that determines the industry's overall carbon footprint. This can also be observed in Figure 8 & Figure 9. Figure 8 shows clearly that the estimated emissions of the salmon fed with feeds that include seaweed silage rise with the inclusion level of seaweed silage, before dropping again when the inclusion level reaches 4%. This is contrary to the findings of Figure 4, which show that the emissions caused by the feed itself drop with the inclusion of seaweed silage. These contradicting developments can be drawn back to the development of the estimated FCR values, which rise when including seaweed silage (see Table 3). Thus, the impact that the rise of the FCR values has on the overall emissions of farmed salmon rules out the alleviating effect that the replacement of seaweed silage has on the emissions caused by the feed.

This effect is more clearly visible in Figure 9. Here, the higher the inclusion level of blue mussel silage is, the higher estimated emissions caused by the production of the salmon get, even though the emissions of the feeds get notably lower (see Figure 6). Again, this can be linked to the strongly increasing FCR values for these feeds. Thus, the extra amount of feed needed to grow a salmon with feeds that include blue mussel silage is eradicating possible reductions of through the use of feeds which have a lower GHG emissions themselves.

Norambuena et al. (2015) conclude in their study that the salmon fed with feeds that include algae products do not change the FCR rates significantly. They remain at a low level between 0.77 and 0.86. However, this study does not consider changing FCRs in a grow-out scenario since their study is based on feeding trials of smolt only. Thus, a general conclusion cannot be seen as representative. But when comparing their results to those of the feeding trials that this study bases its estimation of FCRs on, the results are comparable. The feeding trials of seaweed feeds in Smolt stage have shown FCRs between 0.68 for the reference feed and 0.74 for the SW4 feed (see Table 3). Contrary to the observations done by this study's project partners at

the Institute for Marine research, Norambuena et al. (2015) find that the observed FCR of fish fed with feed with a 5% inclusion rate of algae is slightly lower than the control feed.

Figure 11 shows the percentual change of the FCR and the percentual change of the greenhouse gas emissions, both in relation to the reference feed.

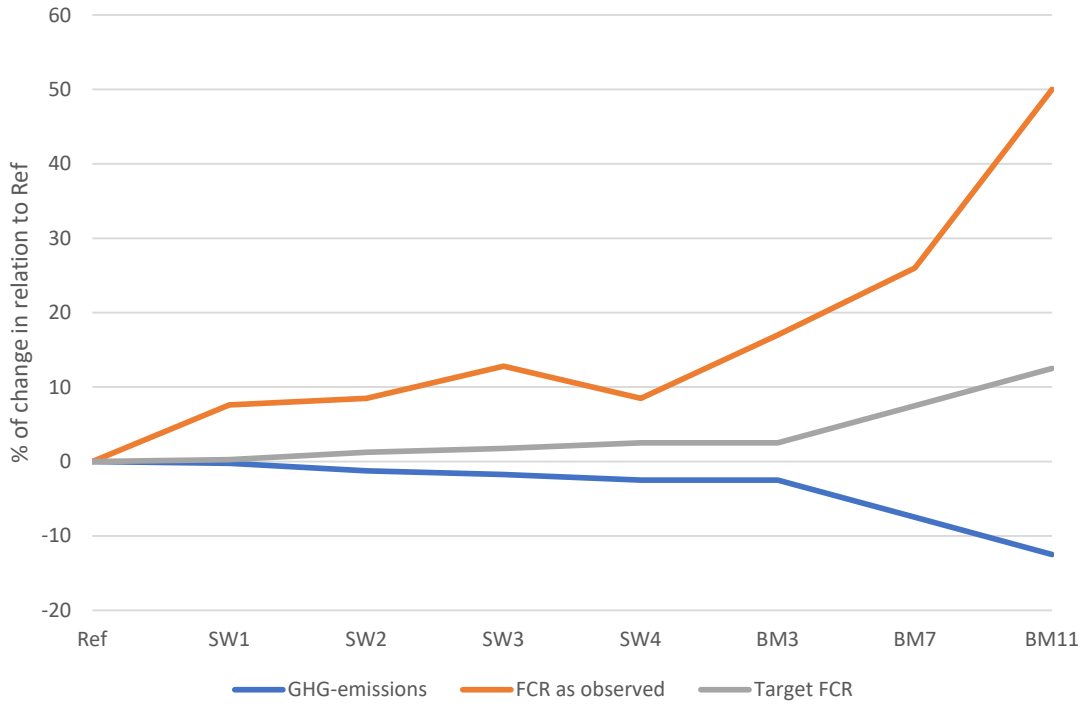

Figure 11: *Development of greenhouse gas emissions and feed conversion ratio for all feeds, related to reference feed as baseline*

Figure 11 clearly shows that the FCR as observed for the novel feeds increases much stronger than the greenhouse gas emissions of the same feeds decrease. This leads to the results displayed in Figures 8 & 9, where the overall greenhouse gas emissions of the farming increase regardless of the lower greenhouse gas emissions of the feeds. If the overall emissions should be decreased, the increase of the FCR must not outbalance the decrease of GHG emissions. So, relative to the reference value, the FCR can only increase as much as the greenhouse gas emissions decrease. In Figure 11, this hypothetical FCR is marked as the target FCR. Since the growth of the observed FCR clearly surpasses the target FCR, the overall emissions of the application of the feeds also grow along with the increasing FCR, whereas the difference between the observed FCRs and the target FCRs describes the amount of which the overall emissions of salmon farming increase.

Thus, this difference needs to be minimized to achieve lower greenhouse gas emissions in salmon farming. When applied to Figure 11, this would mean that the observed FCRs and the target FCRs need to be as close together as possible or, ideally, the observed FCR should be lower than the target FCR.

Generally, the results of the salmon grow out are speculative. As described in section 3.2, the FCR values used in this study do not come from trials which represent a realistic grow-out scenario. They are an estimation based on the feeding trials which only covered 76 days of the smolt stage and average values reported from the trial feed producer. To receive more robust

results, data on growth rate and feed conversion would need to be gathered from trials representing the grow-out in under realistic external conditions.

Interpretation of the results for eutrophication

As can be seen in Figure 9, marine eutrophication potential is dominated by the effluents caused by the fish-farming operation. However, the data underlying the nitrogen emissions from salmon farms are solely based on the estimation of average nitrogen emissions in Norwegian salmon aquaculture by Grefsrud et al. (2021) and therefore is not representing potential changes of effluences caused by the different feed formulations. It could be that the inclusion of seaweed silage or blue mussel silage changes the digestion of the feed and thus also influences the amount of faeces excreted by the fish. Such a potential coherence needs further scientific investigation.

The minor part of the marine eutrophication potential is linked to the agricultural feed ingredients used in the feeds. The eutrophication potential of these ingredients mainly results from the use of nitrogen fertilizer in agriculture (Hungria et al., 2011; Smaling et al., 2008). Figure 9 shows that the eutrophication potential caused by the production of the feed remains stable across all feed formulations, except for the BM7 feed. When comparing the results to the inclusion rates of the different feed ingredients in Table 2, one can see that the inclusion of rapeseed oil and other plant proteins in the BM7 feed is a bit lower compared to other feed formulations. This lower inclusion could lead to a lower use of fertilizer and ultimately lower marine eutrophication potential. However, these potential relations need further research.

5.3 Upscaling Scenario

In 2016, the Norwegian salmon industry has used more than 1.62 Mtons of feed (Aas et al., 2019). Assuming that this feed is roughly the composition of the reference feed used in this study, the overall annual emissions caused by the feed use alone lie at around 6.5 Mtons CO_2 eq. Due to the large amounts of feed used in the industry, even small changes in the feed formulations can have a major effect on the total greenhouse gas emissions of the industry.

Applying the amount of feed used in today's Norwegian salmon aquaculture to the greenhouse gas emissions of the tested feeds can give an estimation of the potential savings in greenhouse gas emissions. Applying the emissions caused by the SW4-feed to the total amount of feed used in Norwegian salmon production results in estimated overall greenhouse gas emissions of 6.3 Mtons CO_2 eq., which is a reduction of 3.1% or about 200.000 tons in total. This equals roughly half of the greenhouse gas emissions caused by the heating of Norwegian households (Statistics Norway, 2022). For the case of the BM11-feed, the savings of greenhouse gas emissions in the same scenario results in estimated savings of about 800.000 ton CO_2 eq. (or 12.4%).

However, the observed development of the FCR values suggests that the total amount of feed used is also increasing in line with the inclusion rate of seaweed silage and blue mussel silage (see Table 3). Thus, the total emissions of the industry would also increase accordingly.

Still, the upscaling scenario illustrates that even small changes in the feeds can have a large effect on the total emissions. This becomes increasingly important when considering the expected growth of the industry. Olafsen et al. (2012) estimated that the Norwegian aquaculture industry will produce around 5 Mton of salmon by 2050. When keeping all other variables constant, this would result in a feed use of 6.5 Mtons and greenhouse gas emissions of 26 Mton CO_2 eq. for the feed production alone. Even though the estimation of the production volume in 2050 is rather vague and the assumption that all other factors, including the FCR, remain

constant is very unlikely, this upscaling scenario highlights the importance of finding ways to decrease the environmental footprint of the industry, even if the cuts in emissions are only marginal.

Resource availability in an upscaled scenario

Whether or not the industry can grow on the basis or alternative feeds, is also highly dependent on the availability of the needed resources. The relevance that the stagnation of supply in fishmeal and fish oil had on the shift to soy-protein based feeds, serves as an example on how important the supply can be on the development of the industry (Aas et al., 2019; Naylor et al., 2021; Pelletier et al., 2018; Shepherd & Jackson, 2013). Thus, scenarios on an upscaled production of alternative feeds cannot be discussed without consideration of the supply of the respective feed ingredients.

Availability of seaweed

Marine algae already contribute around 25% of the world's overall aquaculture production. Thus, seaweeds are already one of the most abundant products on the global market for marine bioresources. However, the production of the seaweeds is highly concentrated to east Asian markets. China dominates the world's production of algae with a yearly production of 18.5 Mton. (FAO, 2020)

In Europe, the industry is nowhere near the production volume abroad. The overall production of Europe (EU plus Norway and Iceland) lies only at 250.000 ton, of which almost all is wild harvest. Only 700 tons are being produced in aquaculture every year, of which about half comes from Norwegian producers (Araujo, 2019; Araújo et al., 2021; Fiskedirektoratet, 2021). If only a tenth of the whole feed used in Norwegian salmon aquaculture would contain 2% seaweed silage, the amount of seaweed needed would be around 3200 tons. This is already far more than the European seaweed aquaculture industry can supply. Of course, seaweed from wild harvest could be used as well, but since the occurrences of suitable kelp are limited, so is the resource as such and the production's scalability is limited as well. Also, dependencies on wild harvest might make it more difficult to guarantee a steady quality and quantity due to external changes that impact wild seaweed-occurrences.

Furthermore, import of seaweed from abroad, especially Asia, could be an option to provide the aquafeed industry with ingredients, but the long transportation routes would countereffect the savings of greenhouse gas emissions caused by the replacement of conventional feed ingredients with seaweed. Besides, the import of ingredients from abroad would increase dependencies Thus, the European seaweed production would need to increase drastically to supply enough for a feasible production of alternative salmon feeds.

However, the development of a European seaweed industry is gaining in traction. The European Commission has defined the seaweed sector as a key point of the EU Blue Growth Strategy. Combined with the EU Green Deal, the sector can expect good growth opportunities over the next years (Araújo et al., 2021). It remains to be seen if this boost in production will result in a supply that is sufficient for a large-scale application in salmon feeds.

Availability of blue mussel

Contrary to the seaweed aquaculture, the farming of blue mussel is far more established in Europe. In the late 1990's, the European mussel production peaked at around 600.000tons annually. However, the production has declined to about 480.000tons in 2016. Reasons for this decline are low prices, limited space, and a very low level of atomization. (Avdelas et al., 2021)

Just like the seaweed feeds, feeds that include blue mussel silage are dependent on a steady supply of blue mussel silage in an upscaled scenario. For the case of the BM7-feed, the amount of mussel silage needed to provide 10% of the total Norwegian salmon feeds used would lie at more than 11.000 tons annually, given that all other variables, including the FCR, remain constant. Thus, the amounts that would be needed by the feed producers would be far more accessible than the seaweed. However, it must be considered that the mussel-harvest is calculated including the shell weight, whereas the mussel-silage is only the meat. Thus, the actual amount of farmed, usable mussel meat lies at around half at what is stated by Avdelas et al. (2021).

Therefore, the blue mussel cultivation in Europe also is not at a stage where it could provide enough for salmon feed on a large scale. However, there are higher production capacities available, so there is potential to expand production volumes. If the buyers can pay competitive prices for the mussels, it could encourage the expansion of production. Then, the blue mussel silage could become an accessible feed ingredient in the future.

5.4 Agricultural Land Use

Since the start of the inclusion of soy protein concentrate to replace fishmeal in salmon feeds in the late 1990's, soy has developed to be the main provider of protein in salmon feeds. As it can be seen in the feed formulations of this study, soy protein concentrate accounts for around 20% of the overall feed. Including the other plant proteins, the initial plant proteins amount up to 35% - 40% of the overall feed, depending on the formulation. This is in line with findings from Aas et al. (2019), who analyse the feed resources used in the Norwegian aquaculture industry and find that 40.3% of all feed used in Norwegian aquaculture were plant protein sources, with nearly half of it being soy protein concentrate.

The shift from marine protein sources towards plant protein sources was mainly triggered by the limited supply and thus rising prices of fishmeal and fish oil (Shepherd & Jackson, 2013). To some extent, this shift is widely considered as a decrease of pressure on the marine ecosystem, since biodiversity in the sea is threatened due to the fisheries of small pelagic fish used in the fishmeal and fish oil production. The fisheries could affect the fish stocks both directly through the extraction of biomass and indirectly through the effect that the extraction might have on predatory animals which feed on the small pelagic fish (Diana, 2009; Shannon & Waller, 2021).

However, this study argues that the quota system which is widely used to manage fish stocks results in a situation in which the fish gets fished anyway, since quotas are usually maxed out. Thus, whether used in salmon feeds or somewhere else, the potential effect of pelagic fisheries on the ecosystem remains the same.

Modern soybean production however also comes with a wide variety of environmental challenges, most of which can be linked to the large-scale deforestation happening to expand cultivable land for soy production (Barona et al., 2010; Gollnow et al., 2018). The deforestation is a direct cause of a severe loss of biodiversity in Brazilian cultivation areas, since the primal forest is habitat to an extremely high density of flora and fauna, which is severely affected by the habitat-loss through deforestation (Paiva et al., 2020; Vieira et al., 2008). Besides the effect on biodiversity, the deforestation can also be linked to global warming, since the intact forest has shown to be a relevant carbon sink (Hubau et al., 2020; Phillips et al., 2017).

The SPC which is used in the feeds underlying the feeding trials and thus also in the LCA originates in Brazil. According to personal communication with our project partner, this is in

line with the origin of the vast majority of SPC used in Norwegian aquaculture. This is in line with Winther et al. (2020).

According to the Observatory of Economic Complexity, Norway imported 113mio. USD worth of soy from Brazil in 2018. In the same year, the average world market price for soy was 342 USD/ton. When applying the world market price to the trade volume of soy, the resulting total mass of soy that Norway imported from Brazil was approximately 330.000ton. According to Aas et al. (2019), the Norwegian salmon aquaculture feed industry processed 309.000ton of SPC in 2016. Thus, the amount of soy that Norwegian firms imported from Brazil roughly matches the amount that was used in salmon aquafeed production.

Due to the major environmental issues that expansion of agriculture causes in Brazil especially, the aquafeed industry should be motivated to reduce the use of agricultural inputs from this region. Reducing the content of SPC in salmon feeds is the most efficient way of achieving this. Thus, novel ingredients for the replacement of SPC should be researched with increased emphasis.

5.5 Ecosystem services of low trophic species

Despite the nutritional advantages of blue mussel and seaweed that are briefly introduced in section 1 of this study, both bioresources are considered as underutilized in Europe, especially given the relatively low negative and potential positive impact their cultivation can have on the ecosystem (Visch et al., 2020). Seaweed farming can provide ecosystem services, benefitting the local benthos and mobile fauna. Besides, seaweed can also sequester nitrogen and phosphorous, both of which are major causes for eutrophication (Hasselström et al., 2018; Visch et al., 2020). Similarly positive ecosystem services can be provided by the cultivation of blue mussels. As filter-feeders, blue mussels can significantly improve the water quality by removing nitrogen and phosphorus from the water (Carlsson et al., 2012; Kraufvelin & Díaz, 2015). Kotta et al. (2020) find that these characteristics of blue mussel-cultivation could even help to mitigate the Baltic sea's severe eutrophication problem.

Petersen & Loo, (2004) find that one ton of blue mussel takes up between 27,7kg and 44,7kg of Carbon and between 6,4kg and 10,2 kg of Nitrogen, most of which is stored in the meat. These values can put into perspective by looking at the amounts of Nitrogen produced by salmon. The uptake of C and N of blue mussel but also seaweeds have triggered an increasing interest on so called integrated multi trophic aquaculture systems (IMTA-systems). These systems try to sequester the Nitrogen and Carbon emissions caused by fish farms directly on site by farming mussels and seaweed on the same site. (Chopin, 2010)

If the sequestered nitrogen and carbon that is stored in the mussel meat is being processed to silage and then into feed, it would eventually get back into the ecosystem and would not be extracted from it. This would not be target-orientated if the aim is the reduction of nitrogen and carbon levels in the water. In the best case, the IMTA-system could trap some of the nitrogen and carbon in a partially circular system, since parts of the emissions by the fish farm operations eventually gets reused as feed. Besides, the effectiveness of such systems when upscaled can be questioned. As described in Figure 10, the Norwegian salmon production emits about 50kg of nitrogen per ton of salmon. Combined with the findings by Petersen & Loo, (2004), this would mean that for each ton of salmon, a minimum of 5 tons of mussels would need to be cultivated near the salmon farms when aiming at a sequestration of the emissions.

Theuerkauf et al. (2022) highlight in their literature study that the aquaculture of seaweed and bivalves can also provide valuable ecosystem services through offering habitats for a variety of

fish and mobile invertebrates. They show that seaweed- and bivalve cultivation sites show a higher abundance in marine fauna than reference sites. Though the effect is dependent on a variety of site-specific characteristics, this effect is particularly high in the case of bivalve production, especially oysters and mussels. However, some seaweed farms also show a significant increase of fauna when being compared to reference sites nearby (Radulovich et al., 2015; Theuerkauf et al., 2022).

However, the cultivation of low trophic species could also have negative effects on the ecosystem. For instance, a seaweed farm absorbs parts the kinetic energy contained in waves and currents. This can affect the nutrient availability and native species which are used to stronger currents (Shi et al., 2011). Furthermore, the absorption of light caused by a seaweed farm can influence the benthic environment below the farm (Campbell et al., 2019).

Despite some problems, the beneficial ecosystem services add to the reasons why an increasing use of low trophic species is widely considered as beneficial and in increased production in aquaculture systems is politically motivated (Araújo et al., 2021).

5.6 Limitations

The present study does come with a variety of limitation, some of which are due to the assumptions that were made and the chosen data. The most prominent of these limitations are already analysed in detail in the sensitivity analysis (see section 4.3). However, this section will briefly introduce further limitations, especially regarding the LCA methodology.

Lifetime

As described in section 3.1, the study has defined a maximum lifetime of the equipment to be included in this LCA. This naturally excludes some emissions which are also impacting the emissions of the observed product but are too difficult to break down to the functional unit. Examples for these emissions are the emissions caused by the construction of the boats used in fish-, seaweed- or mussel farming or the construction of the buildings used for the processing and / or management of the facilities. This ultimately leads to incomplete data, which distorts the results to some extent.

Allocation

Like the assumption of the lifetime, the allocation problem leads to the exclusion of some emissions that have influence the final product. This is the case when it becomes too complex to estimate the share that a certain part of the value chain has on the product at focus of the LCA. For the case of the present study, an example could be the emissions caused by the construction of the roads or ports used for the transport.

Though both, the problem of lifespan and allocation problem distort the results and make them a bit lower than they actually are, the effect is very likely to so minor that it can be neglected.

Limited feeding trials

As stated in section 3.2 of this research, the relative changes of the FCR values that are associated with the different feeds rely on the data gathered during the feeding trials at the Institute for Marine Research in Bergen. These feeding trials were under controlled conditions and the sample group of fish was relatively small. Furthermore, the trials were only 76 days long and thus only spanned a short period of the salmon's life cycle. This means that conclusions to the effects that the feeding of the different feed formulations have on the FCR in different life stages are very difficult and should be treated with caution. This limits the

findings on the estimated emissions of the salmon production. The alternative FCRs used in the sensitivity analysis highlight the importance that this' study's assumptions regarding the FCRs have with regard to the results.

Besides, in a real-world-scenario, the FCR would also include the uneaten feed. This is then the so-called economic feed conversion ratio (eFCR). As described in equation (1), the feed conversion ratios that were observed in the feeding trials exclude the leftover feed, since it was removed from the tank and the amount was then subtracted from the feed input. This practice is usually chosen in feeding trials, because the fish get way more feed than they need to assure that every single fish has eaten enough. Therefore, the leftover feed in trials exceeds the leftover feeds in a real-world production notably which would make an eFCR incomparable. Even though it is assumed that the high feed costs motivate salmon producers to keep feed waste in a real salmon production at an absolute minimum, they are not zero as they are in equation (1). This distorts the observed FCR slightly.

6. Conclusions & Outlook

Conclusions

The discussion of the results, the results themselves as well as limitations of this study allow for a set of conclusions that can be drawn from the present study. The main concluding remarks are listed below.

- The application of novel feeds from low trophic species in salmon feeds did not lead to lower greenhouse gas emissions. The results of this study show that the emissions instead leads towards higher emissions than the application of the conventional reference feed. This development can be traced down to the FCRs, which increase as the inclusion rate of the novel feed ingredients increased. However, the importance of the FCR indicates that thorough conclusions on the environmental performance of salmon feeds can only be drawn when based on comprehensive data on FCRs for each feed when fed over the whole life cycle of the salmon.

- As shown in this study, the replacement of common feed ingredients with ingredients from low trophic species can lower the emissions of the salmon feed production. However, the effect is only marginal. When aiming at the reduction of the emissions caused by the feed-production, it's more effective to replace ingredients which have very high emissions as raw materials already. Figure 3 shows that the soy protein concentrate and especially the micro ingredients have very high greenhouse gas emissions. Thus, the focus should lie on the replacement of these two ingredients since only a slight reduction of their content lowers the overall emissions caused by the feed notably (see section 5.1). However, the change of feed formulations must be accompanied by a thorough test of their characteristics when fed to the fish. Otherwise, it could be that the replacement of certain ingredients with novel ingredients lets the FCR increase to an extent, where the reduction of emissions caused by the feed production itself are outbalanced. This effect can be clearly seen for the case of the BM11 feed (see Figure 6 & Figure 9). When aiming at the reduction of the agricultural land use potential, the focus should primarily be set on the replacement of soy protein concentrate, since this raw material has very high associated ecosystem costs (see section 5.4).

- Previous LCA-studies that discuss the environmental impact of farmed salmon have established that feed is the most important contributor to the overall emissions, especially when looking at greenhouse gases. This finding is supported by this study. Thus, the amount of feed used in the farming process is crucial for the overall emissions of the industry. When aiming at the reduction of the overall emissions while keeping production volumes stable, the focus should lie on the reduction of the feed use through lower Feed Conversion Ratios. As it can be seen in section 4.3, lower FCRs have a very high effect on the overall emissions.

Outlook

The development of salmon feeds does not stop and will continue to remain a main focus of research within the field of salmon aquaculture. Based on the findings of this study, the author specifically suggests that future research should pay specific attention to the following topics:

- Since the FCRs are so crucial to the environmental performance of the salmon production, this study suggests that trials with promising feeds should be evaluated based on feeding trials that represent a more realistic scenario. Ideally, the feeding trials should include whole life cycle of the salmon. Thus, both the smolt stage in tanks and the grow out in open net-pens should be respected in the trials. This way, trials could determine FCR values for each of the tested feeds that represent a real grow out scenario. Such FCR values could be at the basis of a founded and robust estimation of the real environmental impact of novel salmon feeds compared to conventional feeds when applied in salmon farming. Furthermore, reliable data derived from such trials could make it easier for the industry to decide to fund further trials on their expenses, for example in different climatic conditions. This could well be the case if thorough data from large scale trials that represent the whole life cycle are promising.

- Future research focussing on the reduction of emissions caused by the feed production should focus on the reduction of high-emitting feed ingredients. Here, already small changes in the feed formulations can have a large effect on the overall emissions caused by the feed production. Based in the findings of this study, especially the reduction of the SPC- and micro ingredients could have a large effect on the reduction of the emissions caused by the feed production. This is especially he case for agricultural land use and GHG-emissions.

- When changing feed formulations for the sake of reduction of emissions, the development of the FCR should remain under close supervision. Even when reducing high-emission ingredients as encouraged above, the replacement could still cause higher emissions in salmon farming if the FCR rises. Thus, future research should closely monitor the effects of changed feed formulations on FCRs and then try finding an optimum in which reduced emissions caused by the feed and low FCR produce the lowest possible feed-related emissions of salmon farming. As described in section 5.2 of this research, the growth of the FCR should never surpass the threshold set by the decrease of the greenhouse gas emissions or vice versa. However, such an optimum can only be found with a large set of reliable data regarding the emissions and especially the FCRs. This dependency on data again highlights the need for comprehensive feeding trials.

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Literature References

Aas, T. S., Ytrestøyl, T., & Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2016. *Aquaculture Reports*, *15*, 100216.

Araujo, R. (2019). Brief on algae biomass production. *Publications of the European Union*.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I. C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., & Ullmann, J. (2021). Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. *Frontiers in Marine Science*, *7*, 1247.

Asche, F., & Roll, K. H. (2013). Determinants of inefficiency in Norwegian salmon aquaculture, *Aquaculture Economics & Management* 17.3 (2013): 300-21.

Avdelas, L., Avdic-Mravlje, E., Borges Marques, A. C., Cano, S., Capelle, J. J., Carvalho, N., Cozzolino, M., Dennis, J., Ellis, T., Fernández Polanco, J. M., Guillen, J., Lasner, T., le Bihan, V., Llorente, I., Mol, A., Nicheva, S., Nielsen, R., van Oostenbrugge, H., Villasante, S., … Asche, F. (2021). The decline of mussel aquaculture in the European Union: causes, economic impacts and opportunities. *Reviews in Aquaculture*, *13*(1), 91–118.

Bannister, R. J., Valdemarsen, T., Hansen, P. K., Holmer, M., & Ervik, A. (2014). Changes in benthic sediment conditions under an atlantic salmon farm at a deep, well-flushed coastal site. *Aquaculture Environment Interactions*, *5*(1), 29–47.

Barona, E., Ramankutty, N., Hyman, G., & Coomes, O. T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, *5*(2).

Barroso, F. G., de Haro, C., Sánchez-Muros, M.-J., Venegas, E., Martínez-Sánchez, A., & Pérez-Bañón, C. (2013). *The potential of various insect species for use as food for fish*.

Baumann, H., & Tillman, A.-M. (2004). The Hitchhiker's Guide to LCA : An Orientation in Life Cycle Assessment Methodology and Application*, Studentlitteratur, Lund, Sweden (2004)*

Becker, E. W. (2007). Micro-algae as a source of protein. *Biotechnology Advances*, *25*(2), 207–210.

Belghit, I., Liland, N. S., Waagbø, R., Biancarosa, I., Pelusio, N., Li, Y., Krogdahl, Å., & Lock, E. J. (2018). Potential of insect-based diets for Atlantic salmon (Salmo salar). *Aquaculture*, *491*, 72–81.

Berardy, A., Costello, C., & Seager, T. P. (2015). Life Cycle Assessment of Soy Protein Isolate Microgrid Design and Controls View project Sustainable Intelligence View project, *Proceedings of the International Symposium on Sustainable Systems and Technologies* (Vol. 3)

Boesch, Df., & Brinsfield, Rb. (2000). Coastal Eutrophication and Agriculture: Contributions and Solutions. *Biological Resource Management Connecting Science and Policy*, 93–115.

Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., Hughes, A. D., & Stanley, M. (2019). The environmental risks associated with the development of seaweed farming in Europe - prioritizing key knowledge gaps. *Frontiers in Marine Science*, *(6)*, 107.

Carlsson, M. S., Engström, P., Lindahl, O., Ljungqvist, L., Petersen, J. K., Svanberg, L., & Holmer, M. (2012). Effects of mussel farms on the benthic nitrogen cycle on the swedish west Coast. *Aquaculture Environment Interactions*, *2*(2), 177–191.

Chopin, T. (2010). Integrated Multi-Trophic Aquaculture. *Advancing the Aquaculture Agenda*, 195–217.

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*, *1*(5), 301–308.

Curran, M., Hellweg, S., & Beck, J. (2014). Is there any empirical support for biodiversity offset policy? *Ecological Applications*, *24*(4), 617–632.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., & Pengue, W. A. (2007). LCA of soybean meal. *The International Journal of Life Cycle Assessment 2008 13:3*, *13*(3), 240–254.

de Baan, L., Alkemade, R., & Koellner, T. (2013). Land use impacts on biodiversity in LCA: A global approach. *International Journal of Life Cycle Assessment*, *18*(6), 1216–1230.

Dekker, E., Zijp, M. C., van de Kamp, M. E., Temme, E. H. M., & van Zelm, R. (2020). A taste of the new ReCiPe for life cycle assessment: consequences of the updated impact assessment method on food product LCAs. *The International Journal of Life Cycle Assessment*, *25*, 2315–2324.

Diana, J. S. (2009). Aquaculture Production and Biodiversity Conservation. *BioScience*, *59*(1), 27–38.

FAO. (2020). The State of World Fisheries and Aquaculture 2020. *Sustainability in Action*.

Fisher, H. J., Collins, S. A., Hanson, C., Mason, B., Colombo, S. M., & Anderson, D. M. (2020). Black soldier fly larvae meal as a protein source in low fish meal diets for Atlantic salmon (Salmo salar). *Aquaculture*, *521*.

Gollnow, F., Hissa, L. de B. V., Rufin, P., & Lakes, T. (2018). Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. *Land Use Policy*, *78*, 377–385.

Hasselström, L., Visch, W., Gröndahl, F., Nylund, G. M., & Pavia, H. (2018). The impact of seaweed cultivation on ecosystem services - a case study from the west coast of Sweden. *Marine Pollution Bulletin*, *133*, 53–64.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2017). Life Cycle Assessment: Theory and Practice. *Life Cycle Assessment: Theory and Practice*, 1–1216.

Henriksson, L., Ståhle, J., Sundberg, C., & Svensson, N. (n.d.). *Using Blue Mussels as a Tool for Mitigating Eutrophication in the Baltic Sea*. Retrieved December 10, 2021, from www.liu.se

Hognes, E., & Skaar, C. (2017). *Avfallshåndtering fra sjøbasert havbruk (FHF prosjekt 901352) SINTEF rapport OC2017 A-218*.

Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., … Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature 2020 579:7797*, *579*(7797), 80–87.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, *22*(2), 138–147.

Hungria, M., Franchini, J. C., Campo, R. J., Crispino, C. C., Moraes, J. Z., Sibaldelli, R. N. R., Mendes, I. C., & Arihara, J. (2011). Nitrogen nutrition of soybean in Brazil: Contributions of biological N2 fixation and N fertilizer to grain yield. *Canadian Journal of Plant Science, 86*(4), 927–939.

IPCC. (2019). IPCC Climate Change and Land An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

ISO. (2006a). ISO 14040. Environmental Management – Life Cycle Assessment – Principles and Framework. *International Standards Organization*.

ISO. (2006b). ISO 14044. Environmental Management – Life Cycle Assessment – Requirements and Management. *International Standards Organization*.

Jönsson, L., Elwinger, K., Jo¨nsson, L., Jo¨nsson, J., & Elwinger, & K. (2009). Mussel meal as a replacement for fish meal in feeds for organic poultry – a pilot short-term study. Acta Agriculturae Scand Section A*, 59*(1), 22–27.

Joos, F., Roth, R., Fuglestvedt, J. S., Peters, G. P., Enting, I. G., von Bloh, W., Brovkin, V., Burke, E. J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B., Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., … Weaver, A. J. (2013). Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmospheric Chemistry and Physics*, *13*(5), 2793–2825.

Kamunde, C., Sappal, R., & Melegy, T. M. (2019). Brown Seaweed (AquaArom) Supplementation Increases Food Intake and Improves Growth, Antioxidant Status and Resistance to Temperature Stress in Atlantic Salmon, Salmo Salar. *PloS One* 14.7 (2019)

Kiron, V., Phromkunthong, W., Huntley, M., Archibald, I., & de Scheemaker, G. (2012). Marine microalgae from biorefinery as a potential feed protein source for Atlantic salmon, common carp and whiteleg shrimp. *Aquaculture Nutrition*, *18*(5), 521–531.

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P. R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M. M., Mühl, M., … Virtanen, E. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. *Science of The Total Environment*, *709*, 136144.

Kraufvelin, P., & Díaz, E. R. (2015). Sediment macrofauna communities at a small mussel farm in the northern Baltic proper. *Boreal Environment Research*, *20*(3), 378–390.

Langeland, M., Vidakovic, A., Vielma, J., Lindberg, J. E., Kiessling, A., & Lundh, T. (2016). Digestibility of microbial and mussel meal for Arctic charr (Salvelinus alpinus) and Eurasian perch (Perca fluviatilis). *Aquaculture Nutrition*, *22*(2), 485–495.

Liland, N. S., Biancarosa, I., Araujo, P., Biemans, D., Bruckner, C. G., Waagbø, R., Torstensen, B. E., & Lock, E. J. (2017). Modulation of nutrient composition of black soldier fly (Hermetia illucens) larvae by feeding seaweed-enriched media. *PloS One*, *12*(8), e0183188–e0183188.

Liu, Y., Rosten, T. W., Henriksen, K., Hognes, E. S., Summerfelt, S., & Vinci, B. (2016). Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater. *Aquacultural Engineering*, *71*, 1–12.

Marinussen, M. (2010). *Environmental impacts of synthetic amino acid production preliminary results*.

Mente, E., Pierce, A. G. J., Santos, A. M. B., Neofitou, C., Mente, A. E., Santos, M. B., Mente, E., Graham, A. E., Ae, J. P., Begoñ, M., Ae, S., & Neofitou, C. (2006). Effect of feed and feeding in the culture of salmonids on the marine aquatic environment: a synthesis for European aquaculture. *Aquaculture International 2006 14:5*, *14*(5), 499–522.

Morrisey, D. J., Gibbs, M. M., Pickmere, S. E., & Cole, R. G. (2000). Predicting impacts and recovery of marine-farm sites in Stewart Island, New Zealand, from the Findlay-Watling model. *Aquaculture*, *185*(3–4), 257–271.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021). A 20-year retrospective review of global aquaculture. In *Nature* (Vol. 591, Issue 7851, pp. 551–563). Nature Research.

Nixon, S. W. (1995) Coastal marine eutrophication: A definition, social causes, and future concerns, *Ophelia*, 41:1, 199-219

Norambuena, F., Hermon, K., Skrzypczyk, V., Emery, J. A., Sharon, Y., Beard, A., & Turchini, G. M. (2015). Algae in Fish Feed: Performances and Fatty Acid Metabolism in Juvenile Atlantic Salmon. *PLOS ONE*, *10*(4)

Nordgarden, U., Oppedal, F., Taranger, G. L., Hemre, G.-I., Hansen, & T., & Nordgarden, U. (2003). Seasonally changing metabolism in Atlantic salmon (Salmo salar L.) I-Growth and feed conversion ratio. *Aquaculture Nutrition* 9.5 (2003): 287-93

Olafsen, T., Winther, U., Olsen, Y., & Sjermo, J. (2012). Value created from productive oceans in 2050 . *Sintef Report A23299*.

Onorato, C., & Rösch, C. (2020). *Comparative life cycle assessment of astaxanthin production with Haematococcus pluvialis in different photobioreactor technologies*.

Paiva, P., de Lourdes Pinheiro Ruivo, M., da Silva Júnior, O., de Nazaré Martins Maciel, M., Braga, T., de Andrade, M., dos Santos Junior, P., da Rocha, E., de Freitas, T., da Silva Leite, T., Gama, L., de Sousa Santos, L., da Silva, M., Silva, E., & Ferreira, B. (2020). Deforestation in protect areas in the Amazon: a threat to biodiversity. *Biodiversity and Conservation*, *29*(1), 19–38.

Pelletier, N., Klinger, D. H., Sims, N. A., Yoshioka, J.-R., & Kittinger, J. N. (2018). Nutritional Attributes, Substitutability, Scalability, and Environmental Intensity of an Illustrative Subset of Current and Future Protein Sources for Aquaculture Feeds: Joint Consideration of Potential Synergies and Trade-offs. *Environmental Science & Technology* 52.10 (2018): 5532-544

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., & Silverman, H. (2009). Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems. *Environmental Science and Technology*, *43*(23), 8730–8736.

Petersen, J. K., & Loo, L.-O. (2004). *Miljøkonsekvenser af dyrkning af blåmuslinger. Rapport til Interreg-projekterne "Gränslöst samarbete" og "Forum Skagerrak II"*.

Peterson, B. C., Burr, G. S., Barrows, F. T., Block, S., Bowzer, J., & Buentello, A. (2019). Growth Performance of Atlantic Salmon Smolts Fed Diets Containing Heterotrophic Algal Biomass as Replacement of Fish Oil. *North American Journal of Aquaculture*, *81*(4), 364–371.

Philis, G., Gracey, E. O., Gansel, L. C., Fet, A. M., & Rebours, E. (2018). Comparing the primary energy and phosphorus consumption of soybean and seaweed-based aquafeed proteins e A material and substance flow analysis. *Journal of Cleaner Production* 200 (2018): 1142-153

Philis, G., Ziegler, F., Gansel, L. C., Jansen, M. D., Gracey, E. O., & Stene, A. (2019). Comparing Life Cycle Assessment (LCA) of Salmonid Aquaculture Production Systems: Status and Perspectives. *Sustainability 2019, Vol. 11, Page 2517*, *11*(9), 2517.

Phillips, O. L., Brienen, R. J. W., Gloor, E., Baker, T. R., Lloyd, J., Lopez-Gonzalez, G., Monteagudo-Mendoza, A., Malhi, Y., Lewis, S. L., Vásquez Martinez, R., Alexiades, M., Álvarez Dávila, E., Alvarez-Loayza, P., Andrade, A., Aragão, L. E. O. C., Araujo-Murakami, A., Arets, E. J. M. M., Arroyo, L., Aymard, G. A., … Ricardo, J. (2017). Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions. *Carbon Balance and Management*, *12*(1), 1–9.

Radulovich, R., Umanzor, S., Cabrera, R., & Mata, R. (2015). Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture*, *436*, 40–46.

Rosas, V. T., Poersch, L. H., Romano, L. A., & Tesser, M. B. (2019). Feasibility of the use of Spirulina in aquaculture diets. *Reviews in Aquaculture*, *11*(4), 1367–1378.

Seghetta, M., Hou, X., Bastianoni, S., Bjerre, A. B., & Thomsen, M. (2016). Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers – A step towards a regenerative bioeconomy. *Journal of Cleaner Production*, *137*, 1158–1169.

Shah, M. R., Lutzu, G. A., Alam, A., Sarker, P., Kabir Chowdhury, M. A., Parsaeimehr, A., Liang, Y., & Daroch, M. (2017). Microalgae in aquafeeds for a sustainable aquaculture industry. *Journal of Applied Phycology 2017 30:1*, *30*(1), 197–213.

Shannon, L., & Waller, L. (2021). A Cursory Look at the Fishmeal/Oil Industry From an Ecosystem Perspective. *Frontiers in Ecology and Evolution*, *9*.

Shepherd, C. J., & Jackson, A. J. (2013). Global fishmeal and fish-oil supply: inputs, outputs and markets. *Journal of Fish Biology*, *83*(4), 1046–1066.

Shi, J., Wei, H., Zhao, L., Yuan, Y., Fang, J., & Zhang, J. (2011). A physical–biological coupled aquaculture model for a suspended aquaculture area of China. *Aquaculture*, *318*(3–4), 412–424.

Smaling, E. M. A., Roscoe, R., Lesschen, J. P., Bouwman, A. F., & Comunello, E. (2008). From forest to waste: Assessment of the Brazilian soybean chain, using nitrogen as a marker. *Agriculture, Ecosystems & Environment*, *128*(3), 185–197.

Sofie Grefsrud, E., Karlsen, Ø., Olav Kvamme, B., Glover, K., Husa, V., Kupka Hansen, P., Einar Grøsvik, B., Samuelsen, O., Sandlund, N., & Helge, L. (2019). *Risikorapport Norsk fiskeoppdreit 2021 - Risikovurdering*

Sørensen, M., Marit Berge, G., Reitan, K. I., & Ruyter, B. (2016). Microalga Phaeodactylum tricornutum in feed for Atlantic salmon (Salmo salar)-Effect on nutrient digestibility, growth and utilization of feed. *Aquaculture* 460 (2016): 116-23

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., Kvamme, B. O., Boxaspen, K. K., Bjørn, P. A., Finstad, B., Madhun, A. S., Morton, H. C., & Svåsand, T. (2015). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science*, *72*(3), 997–1021.

Theuerkauf, S. J., Barrett, L. T., Alleway, H. K., Costa-Pierce, B. A., st. Gelais, A., & Jones, R. C. (2022). Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Reviews in Aquaculture* (Vol. 14, Issue 1, pp. 54–72). John Wiley and Sons Inc.

Thomas, J. B. E., Sinha, R., Strand, Å., Söderqvist, T., Stadmark, J., Franzén, F., Ingmansson, I., Gröndahl, F., & Hasselström, L. (2021). Marine biomass for a circular blue-green bioeconomy?: A life cycle perspective on closing nitrogen and phosphorus land-marine loops. *Journal of Industrial Ecology*.

Ulén, B., Bechmann, M., Fölster, J., Jarvie, H. P., & Tunney, H. (2007). Agriculture as a phosphorus source for eutrophication in the north-west European countries, Norway, Sweden, United Kingdom and Ireland: a review. *Soil Use and Management*, *23*, 5–15.

van Oirschot, R., Thomas, J. B. E., Gröndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J. (2017). Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. *Algal Research*, *27*, 43–54.

Vidakovic, A., Langeland, M., Sundh, H., Sundell, K., Olstorpe, M., Vielma, J., Kiessling, A., & Lundh, T. (2016). Evaluation of growth performance and intestinal barrier function in Arctic Charr (Salvelinus alpinus) fed yeast (Saccharomyces cerevisiae), fungi (Rhizopus oryzae) and blue mussel (Mytilus edulis). *Aquaculture Nutrition*, *22*(6), 1348–1360.

Vieira, I., Toledo, P. M., Silva, J., & Higuchi. (2008). Deforestation and threats to the biodiversity of Amazonia. *Braz. J. Biol*, *68*(4), 949–956. www.geoma.lncc.br

Visch, W., Kononets, M., Hall, P. O. J., Nylund, G. M., & Pavia, H. (2020). Environmental impact of kelp (Saccharina latissima) aquaculture. *Marine Pollution Bulletin*, *155*, 110962.

Weinhold, D., Killick, E., & Reis, E. J. (2013). Soybeans, poverty and inequality in the Brazilian Amazon. *World Development*, *52*, 132–143.

Wilke, T., Faulkner, S., Murphy, L., Kealy, L., Kraan, S., & Brouns, F. (2015). Seaweed enrichment of feed supplied to farm-raised Atlantic salmon (Salmo salar) is associated with higher total fatty acid and LC n-3 PUFA concentrations in fish flesh. *European Journal of Lipid Science and Technology*, *117*(6), 767–772.

Winter, L., Lehmann, A., Finogenova, N., & Finkbeiner, M. (2017). Including biodiversity in life cycle assessment – State of the art, gaps and research needs. *Environmental Impact Assessment Review*, *67*, 88–100.

Winther, U., Skontorp Hognes, E., Jafarzadeh, S., & Ziegler, F. (2020). Greenhouse gas emissions of Norwegian seafood products in 2017.

Appendix

A1: Composition of micro ingredients

	Ref. Feed	Seaweed Feeds				Blue Mussel Feeds		
Code / Ingredient	**Ref.**	**SW1%**	**SW2%**	**SW3%**	**SW4%**	**BM3%**	**BM7%**	**BM11%**
Phosphate	25	25.5	26	26.25	26.55	25.5	26.13	26.75
Minerals & Vitamins	25	25.5	26	26.25	26.55	25.5	26.13	26.75
Pigments (excl. Astaxanthin)	22.5	21.6	20.7	20.25	19.53	21.6	20.5	19.35
Astaxanthin	2.5	2.4	2.3	2.25	2.17	2.4	2.28	2.15
Amino Acids	25	25	25	25	25	25	25	25
Total	100	100	100	100	100	100	100	100

The composition of the micro-ingredients is based on and Winther et al. (2020) personal communication with the project partners and Markus Langeland. It was assumed that the absolute mass of astaxanthin in the micro-ingredient remains constant across all different feeds. This assumption is based in personal communication with Markus Langeland. Thus, the relative amount of astaxanthin in the micro-ingredient mix changes with the change of the inclusion rate of astaxanthin in the respective feed-formulation (see Table 1).

A2: Inventory data for agricultural ingredients

Ingredient / Input factor	**Process in Agribalyse / EcoInvent**	**Amount (ton per ton of feed)**
Rapeseed Oil	Rape oil, crude {Europe without Switzerland}| rape oil mill operation | Cut-off, S	Depending on formulation, see Table 2
Other Plant Protein	Broad bean, at farm/DE Mass Maize gluten feed, dried, consumption mix, at feed compound plant/NL Mass Pea, protein-concentrate, at plant/RER Mass	Depending on formulation, see Table 2
Raw Wheat	Wheat gluten feed, from wheat starch extraction, at plant/FR U	Depending on formulation, see Table 2
Soy Protein Concentrate	Soybean protein concentrate, from crushing (solvent, for protein concentrate), at plant/BR Mass	Depending on formulation, see Table 2

A3: Emission data for fishmeal and fish oil

Ingredient	Emission	Source	Amount (kg/kg finished product)
Herring	2.8kg CO_2 eq. / kg	Winther et al. (2020)	2/9kg
Sandeel	2.0kg CO_2 eq. / kg	Winther et al. (2020)	2/9kg
Sprat	1.9kg CO_2 eq. / kg	Winther et al. (2020)	2/9kg
Blue Whiting	2.3kg CO_2 eq. / kg	Winther et al. (2020)	1/3kg

As stated in the table above, the emission data for the fishmeal and fish oil production from the different fish species come from Winther et al. (2020). The composition of the fishmeal and fish oil is an estimation based on personal communication with Cargill Norway Inc. and the most commonly used species in the Norwegian fishmeal and -oil production. However, the composition does not represent the most common composition used in the market. They solely represent the mix used in the feeding trials. A more realistic composition of fishmeal and fish oil would include trimmings from the capture fisheries as well as foreign fish, such as Peruvian anchovies.

A4: Emission data for blue mussel silage

Ingredient / Input factor	Process in EcoInvent (if applicable)	Amount (per ton of feed)
Production of Mussels	Drawn from Thomas et al. (2021)	63,2kg CO_2 eq. 0.152kg P eq.
Fermentation	Fermentation activator, bacterial, at plant/RER U (ACYVIA)	0.01kg

The emissions for the mussel production are drawn from the findings by Thomas et al. (2021). Primary data was not available.

A5: Inventory data for seaweed silage

Group	Equipment	System process	Amount (per ton of mussel)
Permanent Infrastructure	Anchor	Steel, chromium steel 18/8 {GLO}| market for | APOS, U Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S	0.0037ton
	Anchoring Chain	Steel, chromium steel 18/8 {GLO}| market for | APOS, U Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S	0.5kg
	Boys	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Cut-off, S Blow moulding {RER}| blow moulding | Cut-off, U	0.042kg
	Yarn Ring	Polyethylene, high density, granulate {GLO}| market for | Cut-off, U Blow moulding {RER}| blow moulding | Cut-off, U	0.018 piece
	Clips	Chromium steel pipe {GLO}| market for | Cut-off, U Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, S	0.018 piece
	Boat Use	Diesel {Europe without Switzerland}| market for | APOS, U	0.98kg
	Ropes	Fleece, polypropylene {RoW}| production | Cut-off, U	0.27 kg
Spore Collecting / Hatchery	Energy use in Hatchery	Electricity, medium voltage {NO}| market for | APOS, S	1030 kWh
	Boat use	Diesel {Europe without Switzerland}| market for | APOS, U	2.01kg
Growout / Maintenance	Ropes	Fleece, polypropylene {RoW}| production | Cut-off, U	7.33kg
	Threads	Yarn, cotton {GLO}| market for yarn, cotton | APOS, S	0.04kg
	Boat use	Diesel {Europe without Switzerland}| market for | APOS, U	5.47kg
Harvesting / Processing	Boat Use	Diesel {Europe without Switzerland}| market for | APOS, U	39,4kg
	Generator Use	Machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators {GLO}| machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | APOS, S	0,16hr
	Fermentation	Fermentation activator, bacterial, at plant/RER U (ACYVIA)	0.01kg
	IBC Container (1 piece per ton)	Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U Metal working, average for metal product manufacturing {RER}| processing | Cut-off, U Polyethylene, high density, granulate {Europe without Switzerland}| polyethylene, high density, granulate, recycled to generic market for high density PE granulate | Cut-off, U Blow moulding {RER}| blow moulding | Cut-off, U	57kg 8.8kg

The inventory data for the production of the seaweed silage was gathered from a seaweed farm on the Norwegian west coast. This farm also produced the seaweeds which was used in the feeding trials. The farm hat a yearly production of 150ton. All equipment used as permanent

infrastructure was assumed to have a lifetime of ten years. This life time is already incorporated in the amount per ton specification.

A6: Emission data for micro-ingredients

Ingredient	Process in EcoInvent (if applicable)	Emissions
Amino Acids		10.2kg CO_2 eq./kg 28.6kg SO_2 eq./kg 10.7kg P eq./kg
Minerals & Vitamins		1.33kg CO_2 eq./kg
Phosphate	Triple superphosphate {ROW}, market for, Cut-Off, S	See Appendix A1
Pigments & Astaxanthin		169.4kg CO_2 eq./kg

The composition of the micro ingredients is based on the expertise of project partners. The emissions caused by the different ingredients are derived from different sources. The emissions of phosphate come from the EcoInvent database deposited in SimaPro. The greenhouse gas emissions from the Minerals & Vitamin come from Winther et al. (2020). The Sulphur Dioxide emissions and phosphorus emissions from the Amino Acids were drawn from Marinussen (2010).

The greenhouse gas emissions of the Pigments are dominated by the Astaxanthin, which is very energy intensive in the production. Winther et al. (2020) estimate the greenhouse gas emissions caused by the production of Astaxanthin are 888kg CO_2 eq./kg. Onorato & Rösch, (2020) find that the greenhouse gas emissions of Astaxanthin are somewhere between 1000kg CO_2 eq./kg and 4000kg CO_2 eq./kg, depending on the energy mix at the production site and other location-specific characteristics. Thus, the mean value of the greenhouse gas emissions as estimated by Onorato & Rösch, (2020) is 2500kg CO_2 eq./kg.

To represent the underlying literature and the respective findings best, this study uses the mean value of the estimations from Onorato & Rösch, (2020) and Winther et al. (2020). This mean value is 1694kg CO_2 eq./kg ((2500+888)/2 =1694).

Following the approach by Winther et al., (2020), the greenhouse gas emission of the astaxanthin is then divided by ten, because the Astaxanthin usually is diluted in the ratio of 1:10. Any potential emissions caused by the solution-liquid are not respected. The resulting greenhouse gas emissions for the Pigments & Astaxanthin then is 169.4kg CO_2 eq./kg.

A7: Data for aquafeed-production

Ingredient / Input factor	Process in EcoInvent	Amount (per ton of feed)
Production of pellets	Diesel, low-sulfur {Europe without Switzerland}| market for | Cut-off, U Liquefied petroleum gas {Europe without Switzerland}| market for liquefied petroleum gas | Cut-off, S Electricity, medium voltage {NO}| market for | Cut-off, S Heat, district or industrial, natural gas {NO}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, S	0.42kg 2.76kg 0.53GJ 0.29GJ

A8: Data for smolt production

Ingredient / Input factor	Process in EcoInvent	Amount (per ton of smolt)
Feed	Depending on formulation (see Table 2)	0,9ton
Energy used in smolt production plant	Electricity, medium voltage {NO}| market for | Cut-off, S Diesel {Europe without Switzerland}| market for | Cut-off, S	1000kWh 26.4kg

A9: Transport

Ingredient / Input factor	Process in EcoInvent	Distance (in ton km)
Rapeseed Oil	Transport, freight, lorry >32 metric ton, euro4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, S Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-off, U	1440tkm 135tkm
Other Plant Protein	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | Cut-off, S Transport, freight, lorry >32 metric ton, euro4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, S	350tkm 1200tkm
Raw Wheat	Transport, freight, sea, bulk carrier for dry goods {GLO}| market for Transport, freight, lorry >32 metric ton, euro4 {RoW}| market for transport, freight, lorry >32 metric ton, EURO4 | Cut-off, S	1617tkm 500tkm
Soy protein Concentrate	Transport, freight, sea, bulk carrier for dry goods {GLO}| market for transport, freight, sea, bulk carrier for dry goods | Cut-off, U Transport, freight, lorry 16-32 metric ton, euro3 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO3 | Cut-off, S	13200tkm 500tkm
Fishmeal	Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	650tkm
Fish Oil	Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	650tkm
Seaweed Silage	Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	650tkm
Blue Mussel Silage	Transport, freight, lorry 16-32 metric ton, euro4 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	650tkm
Feed Pellets to farming site	transport, freight, sea, bulk carrier for dry goods | Cut-off, S	650tkm

The estimation of distances for all agricultural ingredients were drawn from Winther et al. (2020). The estimation of distances the marine ingredients travelled is based on personal communication with Cargill Norway Inc. This has shown that there are three major feed production facilities in Norway. One in the south, one in the middle and one further up north. When taking the whole length of Norway into account, the production facilities are roughly 1100km apart from each other, so the nearest factory is never further away than 1100/2=650km. The same goes for the transport of the feed to the farming site.