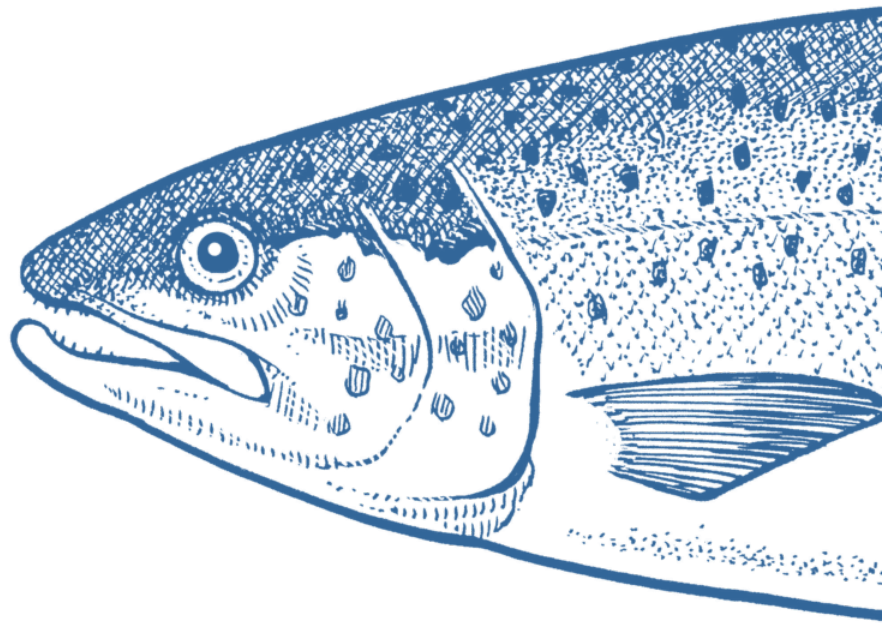




UNIVERSITY OF
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DEPARTMENT OF MARINE SCIENCES

Environmental performance of organic and conventional salmon production in Norway



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Picture source:

<https://goodfish.org.au/wp-content/uploads/atlantic-salmon-jpeg.png>

Abstract

Globally, aquaculture production of seafood has been rising steadily, surpassing capture fisheries in volumes in 2011. Atlantic salmon is one of the economically more valuable farmed species. They require external feed input and are commonly farmed in net pens in colder coastal waters, predominantly in sheltered Norwegian fjords. With rise in production volume, environmental problems with parasites and diseases, escaping fish, feed sourcing and effluents have increased. Organic aquaculture is seen as a potential mitigation to these problems, but no comparative studies have been done for Norwegian salmon. In this study, life cycle assessment (LCA) was used to quantify emissions associated with organic and conventional salmon feed production. This was complemented with a qualitative comparison of production standards to include potential environmental differences which are hard to quantify using LCA methods. The results show that organic feed has lower greenhouse gas- and phosphorus emissions than conventional feed but higher impact in regard to emissions contributing to acidification and marine/terrestrial eutrophication. These differences were primarily driven by the high inclusion of marine ingredients and fishery by-products in the organic and use of emission intensive micro ingredients in the conventional feed. The standards comparison found organic production to offer improvements for some problems but also identified trade-offs in production efficiency. Determining whether organic production of salmon offers a mitigation to the current environmental problems in Norwegian production, where strong regulatory framework already exists, is a matter of perspective. It also requires further investigation of pressures not included and potential differences in the grow out phase.

Popular scientific summary

Can organic salmon save Norwegian fjords?

Atlantic salmon is one of the most consumed fish species in the western world and the demand today is primarily provided by fish farmed in net pens anchored in coastal waters. Norway is the world's biggest salmon producer and over the last years problems with diseases, salmon feed, fish escaping, eutrophication and other pollutants entering the environment have been rising. In my thesis I investigated whether organic regulations could help mitigating the emerging problems. I used a method called life cycle assessment (LCA) to investigate if organic feed has a lower environmental impact than the currently used feed. LCA adds up all emissions connected to the materials and processes used in the production of a product, salmon feed in this case. Since the LCA method is incomplete in addressing environmental problems like e.g. escapee numbers and treatments, I also compared conventional and organic regulations to determine how these issues were addressed. The LCA showed that the production of organic feed has a lower influence on global warming but higher acidifying and nitrate emissions than conventional feed. This is largely the result of including more fish and fish by-products into the organic feed. Conventional salmon is already heavily regulated in Norway. Whether organic standards offer mitigations to environmental problems with Norwegian salmon production depends on the perspective. It also requires further investigations related to potential differences in the farming phase and methods to robustly include issues that could not be included, such as toxicity and ecological effects of escaping fish.

1. Introduction

The world population is projected to reach 10 billion by 2050 (UN DESAPD 2019). Providing everyone with a healthy and sustainable diet will be one of the biggest challenges of the near future (Grafton et al. 2015). Today land-based animal protein production is associated with high environmental cost and global meat consumption is rising (Foley et al. 2011). Seafood from aquaculture or capture fisheries offers a more efficient protein alternative which provides essential nutrients for the human diet and has a lower environmental footprint (Béné et al. 2015; Nijdam et al. 2012). However, globally most fish stocks are being exploited at or over their maximum capacity (FAO 2018). Since 1990 global fisheries yield has plateaued while fishing effort is rising (Anticamara et al. 2011; FAO 2018). Therefore, the limit of annual amount of marine protein available in the current capture fishery is almost reached. Aquaculture production has meanwhile been increasing exponentially from under 20% of total fish production in 1990 to surpassing capture fisheries yields in 2011 (Fig. 1). Based on the benefits described above, seafood from aquaculture has thus been proposed as a key component in sustainable future diets (Foley et al. 2011).

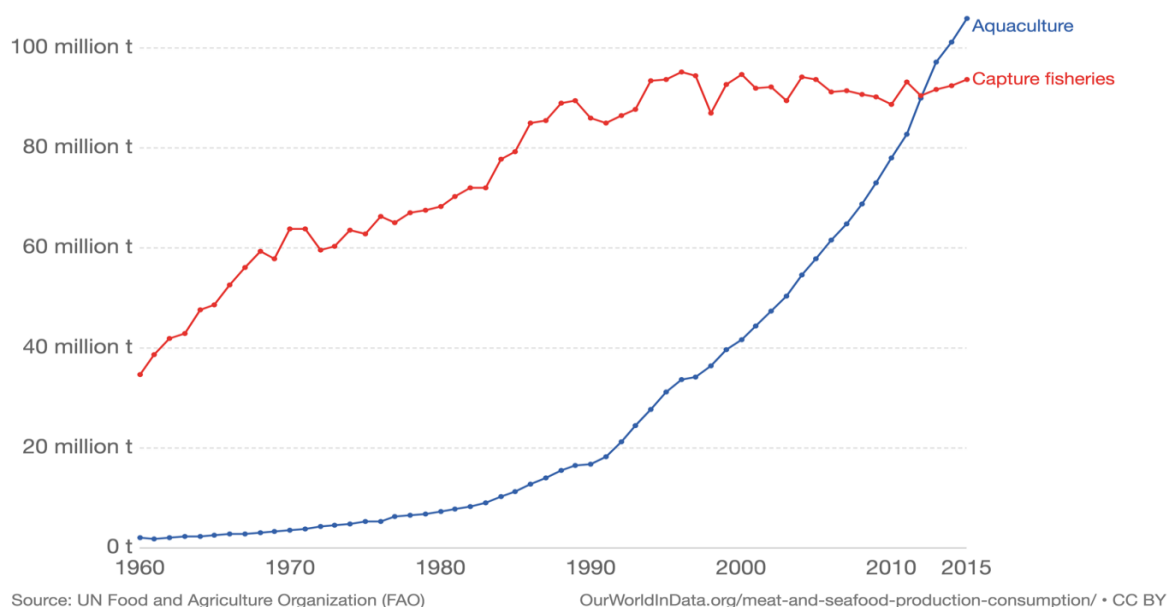


Figure 1. Development of global capture fisheries and aquaculture. Vertical axis represents the yearly global yields.

Europe has seen a rise in seafood consumption per capita over the last 20 years, while landings of wild-caught fish have declined, thus European countries have become increasingly dependent on imports. Marine aquaculture differs from this declining production trend with growing production volumes for both cold and warm water species (EUMOFA 2018). Atlantic salmon (*Salmo salar*) is one of the most consumed fish species in Europe alongside wild-caught Atlantic cod (*Gadus morhua*) and different tuna species (EUMOFA 2018). Atlantic salmon production has changed from predominately being wild-caught fish in 1970 to over 90% of demand being provided by aquaculture today.

Norway is the world's leading producer of Atlantic salmon, with 52% of global production volume in 2017, followed by Chile (26%) and Scotland (8%) (FAO Fisheries and Aquaculture Department 2020). Norwegian aquaculture production has seen massive growth, tripling production volume between years 2000 and 2017 from 400 ktons to 1 236 ktons (FAO Fisheries and Aquaculture Department 2020). Aquaculture operations and associated industry (e.g. fish processing, well boat operation) accounted for 225 billion NOK in revenue in 2017 and is Norway's second biggest export industry after oil (EY 2018). The Norwegian government has proposed plans to increase salmon production volume up to 5-fold by 2050, but in recent years, problems with infection from the parasitic sea lice (*Lepeophtheirus salmonis* and *Caligus elongatus*) and other parasites and diseases have remained constant. These problems today result in 12 - 15% of total fish dying during one production cycle (Norsk Fiskeridirektoratet 2019). Therefore the Norwegian legislation has imposed a halt on further expansion of the industry until effective countermeasures are found to protect fish health, wild stocks and the environment (Aarø 2017).

The environmental challenges associated with current Norwegian salmon aquaculture can be summarized into four overarching topics:

Feed. The feed composition has undergone continuous change and inclusion of marine ingredients has been decreasing over time. In today's feed, fish oil and meal make up around 30% of feed composition in general. Plant-based proteins, mainly soy, are filling in the gap. Most fish used for the production of salmon feed have been found to also be fit for direct human consumption (Cashion et al. 2017), even if trimmings from processing are increasingly utilized (FAO 2018). Here the aquaculture industry competes with other livestock agriculture (e.g. primarily poultry) over a limited feed resource (Froehlich et al. 2018). Use of terrestrial protein production for feed implies similar competition (Troell et al. 2014), but comes with their own set of environmental costs. Soybeans are often associated with a high use of pesticides, water use and depletion of top soil as well as deforestation, in areas with high biodiversity like Brazil (Fearnside 2001). Soybeans have also been criticized for promoting social inequality in rural areas and suppressing small scale farming (Weinhold et al. 2013). Just like the forage fish, most crops utilized would be suitable for direct human consumption as well and adding the intermediate step of using them for feed lowers the efficiency of the food system (Herrero et al. 2013; Shepon et al. 2018). Today's large-scale agriculture monocultures also depend heavily on the use of pesticides and fertilizer to enable high output production. These practices are associated to biodiversity loss, which is one of the biggest problems of the near future and currently happening at high rates (Chaudhary et al. 2016). Especially insects, including important pollinators, have been shown to be negatively affected by high pesticide use (Ndakidemi et al. 2016).

Disease and parasites. The dominating method to raise salmon in aquaculture are net pens anchored close to shore for the grow-out stage. Fish are kept at densities

of up to 25 kg/m³ which would not occur in the wild. This aggregation facilitates the rapid spread of diseases and parasites. Sea lice are crustacean exo-parasites living on blood and skin cells and have become a major problem for Norwegian farms again after developing resistance to earlier treatments (Aaen et al. 2015). High sea lice infestation levels can lead to lower fitness or even death of fish (Abolofia et al. 2017). Two viral diseases, with no direct treatment available, have also become common in farmed salmon over the last years, the pancreas disease and infectious salmon anaemia. Both diseases can lead to increased mortality and spread easier in southern Norway due to warmer water temperatures (Robertsen 2011). Because the fish are only separated from the ocean by a net, both lice and disease can be transferred to wild salmon populations (Bjørn et al. 2001). The same applies for treatments used on fish as some chemical treatments are directly applied in the net pen and can spread into the surrounding ecosystem be harmful to local fauna (Burridge et al. 2010; Overton et al. 2019). In addition, high antibiotic use is a big problem associated with aquaculture worldwide (Romero et al. 2012), but has been reduced to minimal levels in Norway due to the widespread use of vaccination at the salmon's smolt stage (Love et al. 2020).

Escapees. Over time, the net pen infrastructure can wear out or have large amounts of fouling species attached to it. If this is combined with unusual bad weather, material failure can happen and let farmed fish escape into the open ocean. In 2018, 122 000 salmon escaped from Norwegian farms (Norsk Fiskeridirektoratet 2019). These fish go on to compete for the same resources as the natural salmon population and have been shown to interbreed with wild fish. This can weaken the natural gene pool, as farmed fish have been bred for controlled farm conditions, whereas wild fish are adapted to a different environment (Bolstad et al. 2017).

Effluents. Fjords are abundant in Norway and provide a sheltered location for net pens. Many fjords do not have an active water exchange with the open ocean. New farms are only allowed in locations which have suitable environmental conditions for salmon farming. The nutrient release for the farms can contribute to local eutrophication and result in low oxygen conditions in deeper water levels (Strain 2005). By law, there are regular inspections of the surrounding seafloor for environmental status. If deteriorated seafloor conditions are found, this can in severe cases lead to farm closure, reduced biomass or extended periods of fallowing. Little is known about the effects from increased nutrient discharge from aquaculture at a regional scale (Johansen et al. 2018).

The environmental issues described above, together with concerns about potential health issues associated with toxic substances in the fish, have damaged the public image of salmon farmed in net pens (Olsen and Osmundsen 2017). Eco-certification (hereafter called organic and defined as the EU standard¹) is seen as an opportunity to regain consumer trust and mitigate some of the current problems. Organic salmon is a premium product at higher price and should therefore arguably imply reduced impacts compared to conventional production. Another widely used certification is the Aquaculture Stewardship Council (ASC) which, opposed to the EU organic standard which has the same requirements for all species, has species-specific guidelines (Aquaculture Stewardship Council 2017). However, there is no study comparing the actual environmental performance of organic versus conventional salmon production.

Life Cycle Assessment (LCA) is a standardized, ISO certified, tool to quantify resource use and environmental impact of goods and processes, including salmon

¹ Aquaculture production following Council Regulation (EC) 834/2007 and Commission Regulation (EC) 710/2009

production (Philis et al. 2019). Previous studies have shown that the feed contributes the biggest share to many environmental issues e.g. 60-80% of carbon emissions associated with salmon production (Liu et al. 2016; Philis et al. 2019; Winther et al. 2020). So far, however, these product-based evaluations have been scarce in terms of analysing whether organic salmon production offers environmental benefits compared to conventional production. Only one Canadian study from 2007 showed a reduced impact for organic salmon feed compared to feed following national legislation (Pelletier and Tyedmers 2007). The feed industry has changed considerably since then (Shepherd et al. 2017), and no comparative study has been made of Norwegian salmon production. Furthermore, many of the ecological concerns associated with salmon farming in net pens are difficult to assess with existing LCA methodology (Ford et al. 2012). Potential differences between conventional and organic salmon are thus difficult to fully evaluate with LCA. Other studies related to organic versus conventional salmon, such as Luthman et al. (2019), have compared the actual differences in production guidelines between the ASC standard and conventional regulations in different countries. This is lacking for conventional Norwegian regulations and organic standards and may provide further insights on differences in environmental performance.

Aim

In this study, the objective was to compare organic and conventional salmon production in Norway with the overall aim to evaluate current environmental performance and identify improvement potentials. This work intended to utilize LCA to quantitatively evaluate the environmental implications of differences in feed production following EU organic and Norwegian conventional salmon production guidelines. Furthermore, due to limitations of the LCA method, it intended to qualitatively compare potential differences in primarily the salmon grow-out stage

in relation to the four areas of concern listed above through comparison of the actual differences in production guidelines. The specific research questions were:

1. Would a switch from current conventional feed to organic feed result in a lower environmental impact of feed production?
2. Do organic standards offer solutions to the problems prevalent in Norway's salmon aquaculture industry?

2. Material and method

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) was used to quantify and compare the environmental impact of organic and conventional salmon feed. It is a tool designed to be able to include pressures from all processes contributing to the value chain of a product, from the acquisition of raw materials to disposal of final product, the so called "cradle to grave" approach (Ness et al. 2007). An LCA consists of different successive steps, starting with the Goal and Scope. Here the fundamental framing of the study is done (study object, impacts included, data used, intended audience, etc.). The next step is collecting data for all relevant in-and outputs for the different steps in the products lifecycle, the so-called Life Cycle Inventory. The third step is the Life Cycle Impact Assessment, where all environmental burdens associated with the different processes in the products lifecycle get quantified and summarized into impact categories related to different areas of environmental concerns. In the final step of the assessment, the Interpretation, the results from the Life Cycle Impact Assessment are evaluated in relation to the goals defined earlier to reach conclusions. In this step the results can also be tested for their robustness, e.g. with a sensitivity analysis. An LCA is an iterative process, meaning that some choices made early in the process might have to be altered later on to best answer the intended objective of the assessment.

2.1.1 Goal and scope

Goal of this Life Cycle Assessment

The goal of this LCA was to compare feed for Norwegian farmed salmon produced in accordance with national legislation or EU organic guidelines. The intended audience was the salmon aquaculture industry and feed producers. Focus was laid on areas where production processes mainly differ based on previous LCAs, i.e. feed composition, sourcing of ingredients and ingredient refinement practices.

System boundaries

The scope of this assessment covered the salmon feed production system following the cradle-to-feed mill gate principle. Since no reliable data on feed conversion ratios (FCR) for organic salmon could be obtained, ending the comparison at the feed mill gate, opposed to the farm gate, had to be chosen. Geographically this study was limited to activities related to salmon feed production in Norway and associated processes. This includes agricultural production of crops, fishing of marine species for feed production as well as refining of raw ingredients and transport to Norway (Fig. 2). Construction and maintenance of infrastructure and equipment in feed production and transport were not considered.

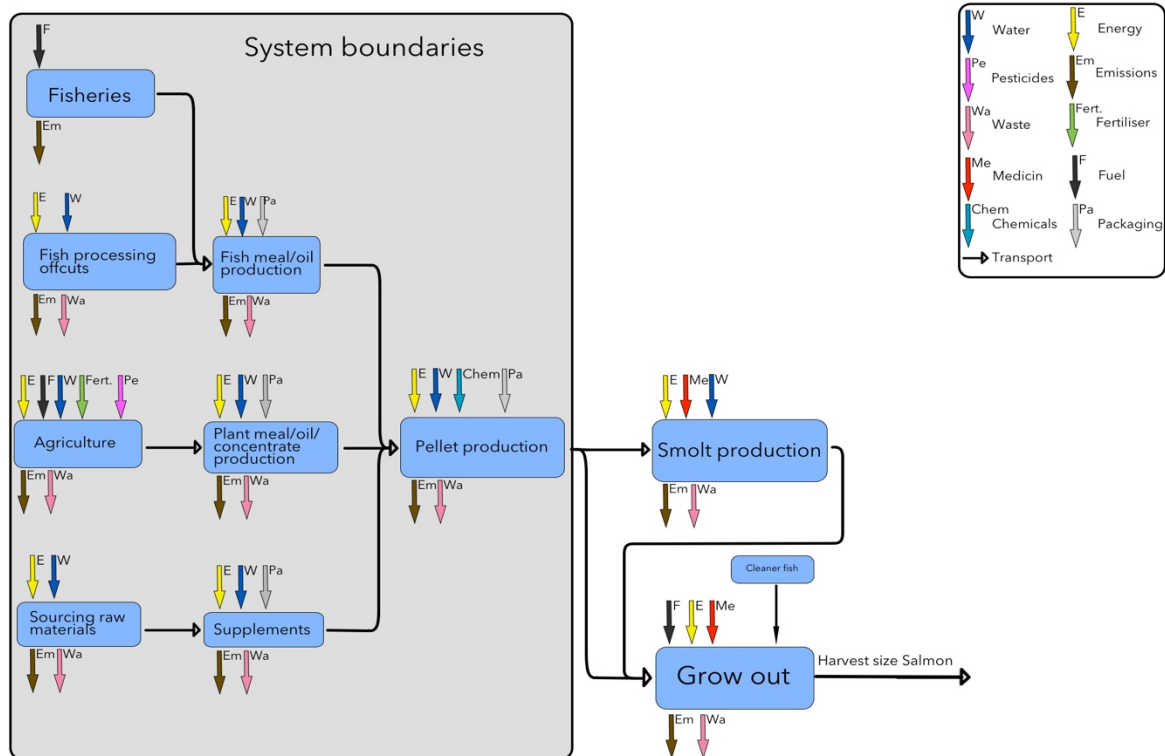


Figure 2. Processes within the salmon production system with in-and outputs

Functional unit

The functional unit is the object of study to which inputs and outputs from all processes relate to. In this assessment the functional unit was 1 kg salmon pellet feed at factory gate.

Allocation

Allocation deals with the problem that one production process can produce multiple products and environmental burdens may need to be split between co-products. Many raw materials undergo refining steps before being converted into feed. This produces co-products, or the used product is a co-product itself (e.g. fish oil/fishmeal from fish cut offs). Allocation was dealt with based on mass since temporal stability of product prices is unstable and the ISO standard for LCA (14040:2006) recommends mass- over economic allocation (ISO 2006a, 2006b).

Impact categories

In LCAs the impacts of a product are characterized into so-called impact categories, representing the potential impact the product has on different environmental issues. Based on the inventory results, all emissions and resources associated to the modelled product are summed up through use of equivalents (e.g. CO₂-equivalents for the total Global warming potential) to provide a single score value per impact category. The impact categories included in this study were Global warming potential, Eutrophication potential, Acidification potential and Cumulative Energy Demand (fossil fuel) (Table 1). This selection was made because these impact categories cover most environmental impacts and have been previously used in aquafeed LCAs (Philis et al. 2019). Analysing results for toxicity was seen as important, but the lack of appropriate impact assessment methods and inventory data led to exclusion of this impact category. The calculation method used for Acidification- and Eutrophication potential was ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting. The Cumulative Energy Demand (CED) was calculated using the CED V1.11 method. Global warming potential (GWP) was calculated using the IPCC 2013 100a method (land use change was included).

Table 1. Impact categories included and LCA methods.

Impact category	Abbreviation	Description	Characterisation factor
Global warming potential	GWP	Contribution to radiative forcing in the atmosphere	Kg CO ₂ -equivalents (eq.)
Eutrophication potential (marine/freshwater/terrestrial)		Contribution to biological oxygen consumption	Marine: kg N-eq. Freshwater: kg P-eq. Terrestrial: molc N-eq.
Acidification potential		Contribution to acid deposition	molc H ⁺ eq.
Cumulative energy demand (fossil fuel)	CED	Sum of all fossil energy spend producing the final product	MJ

2.1.2 Life cycle Inventory

Data sources and processing

SimaPro (version 9.0.0.48) was used to access process data from the Ecoinvent (version 3.5) and Agrifootprint (version 4.0) data libraries. Information and data needed for the modelling was acquired from industry contacts, aquaculture and feed company reports as well as peer-reviewed papers (Appendix 1). In this study two commercial feeds currently used in Norwegian aquaculture were compared. The feed compliant with EU guidelines for organic production, hereafter referred to as organic, is produced by Cargill Aqua Nutrition in the United Kingdom and has an annual production volume of approximately 10 000 tonnes. The feed based on guidelines by Norwegian legislation, hereafter referred to as conventional, is a weighted average of three major aquaculture companies based in Norway (Winther et al. 2020). To assure comparability, the organic feed production was modelled to be situated in Norway opposed to its real production location. Since the feed comprises of many sources, the modelled processes were grouped by characteristic for easier analyses. All fish-based ingredients were summarised as "Marine ingredients", ingredients from agricultural production as "Agricultural ingredients" and additives given in small quantities were called "Micro ingredients". All transports of ingredients to the feed mill were summarised under "Transport". Remaining processes such as e.g. energy use in the feed mill, were summed up as "Other".

Uncertainty analyses

To determine the uncertainty of results, a Monte Carlo analysis (1000 runs) was used on both feeds. The calculated uncertainty is presented as standard deviation.

Representativeness, assumptions and limitations

The organic feed composition was based on the recipe provided by a single company and therefore cannot represent the whole organic salmon feed sector. The conventional feed composition was based on the recipes of three Norwegian companies with a high market share and is consequently an accurate representation. A detailed list of assumptions made in modelling of the feeds can be found in Appendix 1. This list includes data on assumed transport modes and distances, fishmeal/fish oil yield, energy consumption during production as well as a detailed list of processes used to model both feeds.

2.2 Qualitative comparison

Since many areas in the production certification standards (e.g. medical treatments, predator control) were difficult to assess quantitatively through LCA, a complementary qualitative comparison was chosen to be able to discuss non-measurable differences. Limiting factors for a complete quantitative comparison were the lack of robust LCA method which takes local ecological pressures into account (Ford et al. 2012), lack of characterization factors (equivalents) for all relevant substances, and lack of inventory data on organic aquaculture practices (e.g. FCR, pesticide use). For this qualitative comparison, the conventional and organic regulations were categorised in relation to the problem areas described earlier. Comparable categorisation has been used previously in similar studies to describe problems in salmon aquaculture (Olaussen 2018). The basis of the conventional production guidelines in this study are multiple bills (the so called "Norwegian standards") released by Norwegian legislation (Fiskeridepartementet 2011; Nærings- og fiskeridepartementet 2008, 2009, 2015; Standards Norway 2009). The organic production guidelines are laid out in multiple regulations released by the European Council (European Commission 2007, 2009).

3.Results

3.1 Inventory results

The two feeds compared in this study showed different contribution patterns between the ingredient groups (Tables 2-3). While the marine ingredients make up more than 60% of the organic feed, they make up less than 30% of the conventional feed. The reverse pattern was seen for the agricultural ingredients which make up about 35% in the organic feed and double that for the conventional one (70%). The inclusion of micro ingredients is similar for both feeds.

Table 2. Composition of the organic feed studied (EU organic guidelines)

Group	Ingredient	Proportion (%)	Origin
Micro ingredients	Vitamins and Mineral mix	2.01	EU
Crop oils	Organic Soy oil	7.76	China
Crop proteins/carbohydrates	Organic Wheat	6.13	UK
	Organic Peas	12.00	UK
	Organic Soy Expeller	9.62	China
Fish meal- reduction fisheries	Organic fishmeal (Blue Whiting/Sprat)	21.84	Norway/ Iceland/ Denmark
Fish meal - By-products	Organic fishmeal (Whitefish)	21.22	UK
Fish oil - By-products	Organic fish oil (Mackerel/Herring)	19.36	UK

Table 3. Composition of the conventional feed studied (Norwegian guidelines)

Group	Ingredient	Proportion (%)	Origin
Micro ingredients	Amino Acids	0.35	EU
	undefined micro ingredients	1.30	EU
	Phosphate	0.51	EU
	Pigments	0.14	EU
	Vitamins and minerals	0.33	EU
Crop oils	Rapeseed oil	20.00	EU
Crop proteins	Fababeans	3.00	EU
	Guar	0.92	Brazil
	Horsebeans	0.21	EU
	Legume	2.80	Brazil
	Maize	1.10	EU
	Pea	1.00	EU
	Soy	20.50	Brazil
	Sunflower	1.40	EU
	Wheat	9.10	EU
Crop carbs	Pea	0.90	EU
	Wheat	9.00	EU
Fish meal- reduction	Blue Whiting <i>Micromesistius poutassou</i>	5.70	Norway
	Capelin <i>Mallotus villosus</i>	0.50	Norway
	Herring <i>Clupea harengus</i>	0.40	Norway
	Krill <i>Euphasiacea sp.</i>	0.90	Norway
	Peruvian Anchovy <i>Engraulis ringens</i>	1.13	South America
	Gulf Menhaden <i>Brevoortia patronus</i>	0.10	South America
	Norway pout <i>Trisopterus esmarkii</i>	0.40	Norway
	Mackerel <i>Scomber scombrus</i>	0.10	Norway
	Sandeel <i>Ammodytes sp.</i>	1.60	EU
	Sprat <i>Sprattus sprattus</i>	0.70	EU
Fish meal - By-products	Capelin <i>Mallotus villosus</i>	0.30	Norway
	Undefined	0.35	Norway
	Herring <i>Clupea harengus</i>	2.50	Norway
	Mackerel <i>Scomber scombrus</i>	0.60	Norway
	Whitefish (e.g. Cod) <i>Gadus morhua</i>	0.90	Norway
Fish oil - By-products	Capelin <i>Mallotus villosus</i>	0.20	Norway
	Undefined species	0.40	Norway
	Herring <i>Clupea harengus</i>	1.50	Norway

	Mackerel <i>Scomber scombrus</i>	0.70	Norway
	Salmon <i>Salmo salar</i>	0.50	Norway
	Whitefish <i>Gadus morhua</i>	0.20	Norway
Fish oil - reduction fisheries	Blue Whiting <i>Micromesistius poutassou</i>	0.70	Norway
	Capelin <i>Mallotus villosus</i>	0.50	Norway
	Herring <i>Clupea harengus</i>	0.50	Norway
	Mackerel <i>Scomber scombrus</i>	0.10	Norway
	Menhaden <i>Brevoortia patronus</i>	2.00	South America
	Peruvian Anchovy <i>Engraulis ringens</i>	1.30	South America
	Norway pout <i>Trisopterus esmarkii</i>	0.20	Norway
	Sandeel <i>Ammodytes sp</i>	0.80	EU
	Sardine <i>Sardina pilchardus</i>	0.30	EU
	Sprat <i>Sprattus sprattus</i>	1.40	EU

3.2 Impact Assessment results

Overall the organic feed had a lower impact on Global Warming and Freshwater Eutrophication than conventional feed. In Acidification, Marine- and Terrestrial Eutrophication and fossil fuel CED the conventional feed showed lower impact values.

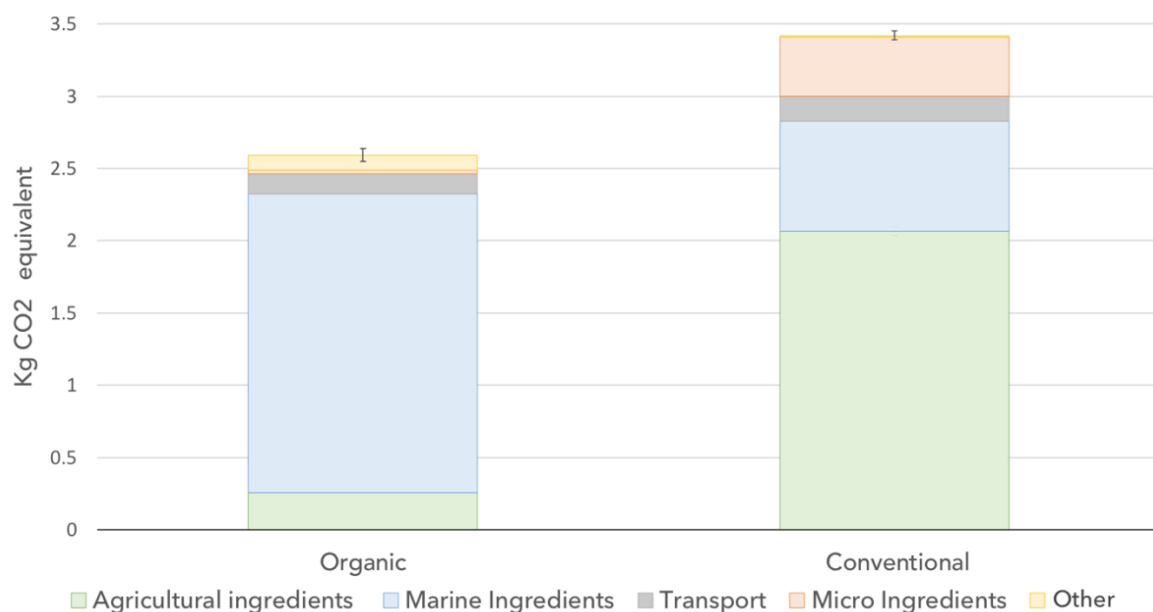


Figure 3. Contribution of different feed ingredient groups to CO₂ eq. emissions of 1 kg organic or conventional salmon feed. The error bars represent standard deviation.

In absolute values, the Global Warming potential of organic salmon feed was 2.59 kg CO₂ eq./kg feed whereas the conventional feeds CO₂ eq. emissions summed up to 3.42 kg CO₂ eq./kg feed (Fig 3). The main contribution to the organic feeds GWP were the marine ingredients (80%). These emissions were dominated by fuel burned during fishing operations. With 10%, the agricultural ingredients were the second biggest contributor followed by transport with 5%. The micro ingredients contributed with marginal amounts (1%). For conventional feed, the agricultural ingredients were the biggest contributor (54%) with almost half of emissions deriving from Brazilian soybeans. Marine ingredients and micro ingredients both contributed similar amounts with 20% and 21% respectively. The higher contribution of micro ingredients in conventional feed was connected to the pigment and amino acid additives, these had high GWP/kg impact and are not included in the organic recipe. Transport had the lowest contribution (5%).

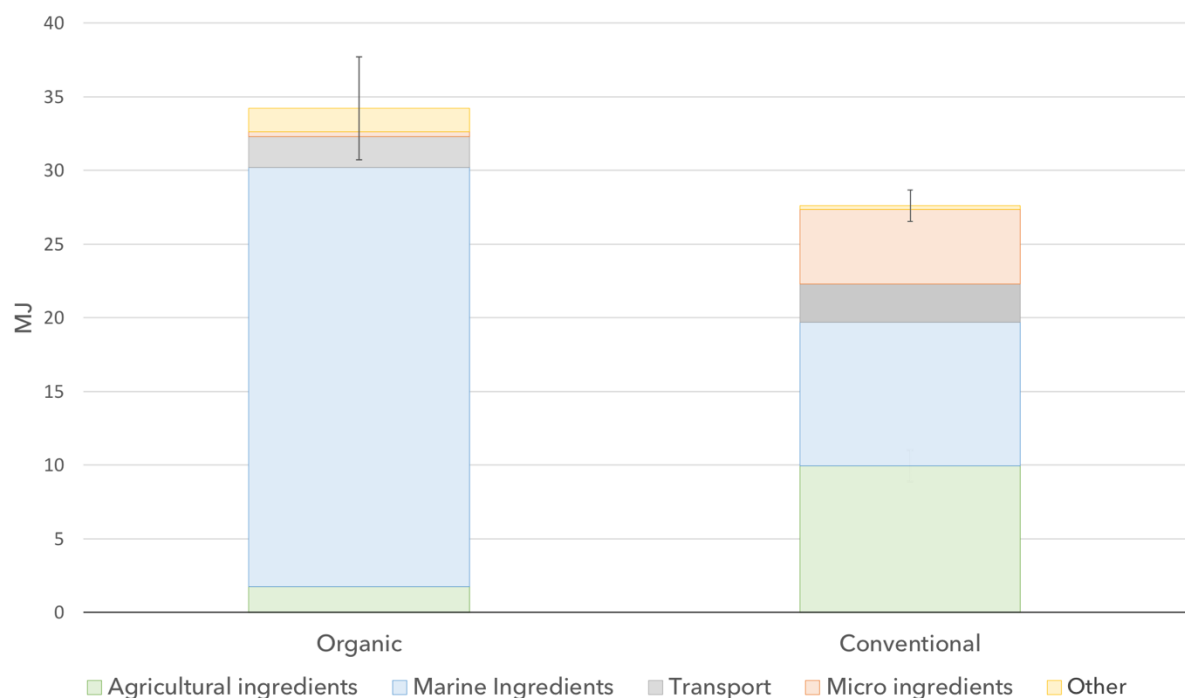


Figure 4. Contribution of feed ingredient groups to the Cumulative Energy Demand (fossil fuel) of 1 kg organic or conventional feed. The error bars represent standard deviation.

Overall, with 34 MJ, the organic feed had a higher fossil fuel CED than the conventional feed with 28 MJ (Fig. 4). The main contributor to the organic feeds

fossil fuel CED were the marine ingredients with 83%. The fuel used in fishing vessels was the biggest contributor. Agricultural ingredients (5%) and transport (6%) contributed with similar amounts of fossil fuel-based energy. In the organic feed, the micro ingredients share of fossil fuel CED was 1%. Marine and agricultural ingredients contributed on a similar level to the conventional feed's fossil fuel CED with 35% and 36% respectively. The second biggest contributor were the micro ingredients with 18% followed by transport with 9.5%. Within the micro ingredients, the energy use during pigment production had the highest contribution.

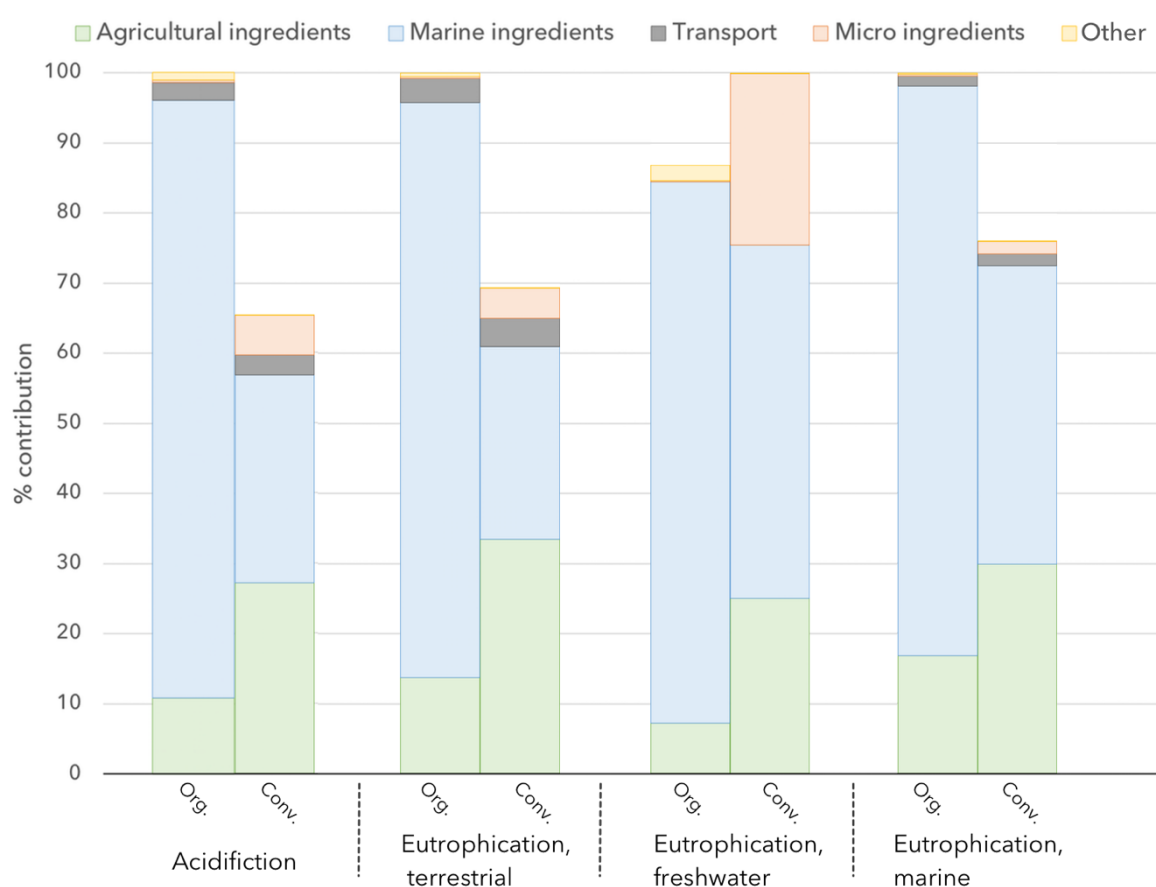


Figure 5. Comparison of Acidification potential and terrestrial/freshwater/marine Eutrophication potential between organic and conventional feed.

Organic feed showed a higher Acidification potential than conventional feed due to its higher inclusion rate of marine ingredients compared to conventional feed (Fig. 5). For both feeds, the fuel use of fishing vessels contributed the most to the acidifying emissions. The organic feed showed higher emissions in both terrestrial

and marine Eutrophication. In these impact categories marine ingredients were the biggest contributor with about two thirds of the nitrogen emissions being caused by wastewater treatment during fish processing, followed by fuel use of fishing vessels.

Conventional feed showed a higher Eutrophication potential for freshwater than organic feed. This was based on the high contribution of pigment production to phosphate emissions within the micro ingredients.

In all impact categories, the organic feed exhibited a higher standard deviation than the conventional feed, i.e. is associated to larger uncertainties. This related back to the higher uncertainty in the values of the processes used in modelling of the organic feed. A table with total contributions of the different ingredient groups to all impact categories can be found in Appendix 1.

Table 4. Comparison in percentages of inclusion- to contribution rate of ingredient groups to different impact categories.

	Ingredient group	Share in feed	Global Warming	Acidification	Terrestrial Eutrophication	Freshwater Eutrophication	Marine Eutrophication	CED, fossil fuel
Organic	Agricultural ingredients	35.5	10	11	13.7	8.2	16.8	5
	Marine ingredients	62.4	80	85.1	82.1	89.0	81.3	83
	Micro ingredients	2	1	<1	<1	<1	<1	1
Conventional	Agricultural ingredients	69.9	60.5	41.6	48.3	25	39.3	36.0
	Marine ingredients	27.5	22.2	45.2	39.6	50.4	56.1	35.3
	Micro ingredients	2.6	12	8.6	6.1	24.4	2.3	18.3

Comparing the inclusion rates of the feed ingredient groups with their contribution to the different impact categories highlighted ingredient groups with disproportionally high or low impacts (Table 4). The agricultural ingredients in both

feeds contributed less to all impact categories than their share in weight. While making up about a third of the feed, the organic agricultural ingredients contributed under one fifth or less in all impact categories. The agricultural ingredients made up over two thirds of the conventional feed but at most contributed between 40% and 55% of emissions. For freshwater Eutrophication these only accounted for approximately 25% of missions. The marine ingredients in organic feed consistently contributed more than their inclusion rate to the different impact categories. With the exception of Global warming potential, the same pattern was seen for the conventional feed. Especially the marine Eutrophication stood out with the marine ingredients contributing more than double their inclusion rate to the impact category. The micro ingredients in organic feed contributed marginally to the impact categories, in line with their low inclusion rate. For the conventional feed, however, the micro ingredients contributed considerably to the Global warming-, Acidification-, CED (fossil fuel) and freshwater Eutrophication potential. Especially the freshwater Eutrophication potential stood out with the contribution rate being almost ten times higher than the inclusion rate.

3.3 Qualitative comparison

There are several differences in the guidelines between conventional and organic farming related to the four environmental issues described in the introduction. The feed requirements have been quantitatively evaluated through LCA, but other aspects of the organic standard such as stocking density and use of chemicals during the grow-out phase may affect the outcome of an LCA comparison if data was made available (Table 5). A full version of all the organic and conventional guidelines regulations can be found in Appendix 1, including minor guidelines of less relevance to the four environmental issues (e.g. daily feeding)

Table 5. Comparison of conventional and organic production guidelines regarding the current problems of Norwegian salmon aquaculture. A full list for both guidelines, as well as the ASC standard, can be found in Appendix 1.

Category	Sub category	Conventional	Organic
Feed	Agricultural ingredients	-	-No GMO ¹ crops -Organically certified ingredients -Max 60% inclusion
	Marine ingredients	-	From sustainable fisheries or aquaculture
	Feed additives	-	No artificial amino acids or growth promoters
Diseases and parasites	Lice treatments	-Local impact assessment of lice treatments -No chemical treatments close to shrimp grounds	-Use of cleaner fish preferred -Max 2 treatments per year (except vaccinations)
	Disease treatment	-Veterinarian 4 – 12 times a year depending on farm size -Daily collection and keeping of dead fish for further inspection -No preventive treatments -No relocation if illness is suspected -Food safety inspection on farm opening	-Veterinarian min 1/year -Max 2 allopathic treatments per year -Treatment hierarchy (homeopathic to allopathic) -No preventive treatments
Escapees	Documentation	Detailed documentation of all incidents	Detailed documentation of all incidents
	Recapture	Catchment of all salmon within 500m	Recapture when possible
	Stock density	-Max. 25 kg fish/m ³ -Max. 200 000 fish per production unit	Max. 10 kg fish/m ³
	Stock	Only native species	Only native species No artificial genetic traits
	Enclosure	-Inspection after heavy weather -Only use of certified hardware	
Effluents	Fallow between production cycles	2 months	4 months
	Chemicals	-	No copper antifouling

			Only certified organic cleaning agents
	Waste levels	-Waste levels based on Norwegian Standard 9410 -Regular survey of surrounding seabed -Bad environmental status leads to biomass reduction or farm closure	- Environmental assessment to minimise impact -Shall be located in suitable location to minimise impact

¹Genetically modified organisms

4.Discussion

4.1 Life cycle assessment of conventional and organic feed

This study has shown that a switch from conventional to organic feed results in a reduction of Global warming potential and freshwater Eutrophication potential but increase environmental pressures in regard to fossil fuel-based Cumulative energy demand, Acidification potential and marine and terrestrial Eutrophication potential. The sourcing of marine ingredients is connected to high investments of energy and emissions throughout raw material acquisition and further processing (Hall 2018; Winther et al. 2020). It is therefore not surprising that for most impact categories the contribution rate surpasses the inclusion rate of marine ingredients in both feeds. The only exception was the contribution below their inclusion rate of conventional marine ingredients to the GWP. This connects back to the conventional ingredients use of highly efficient forage fish fisheries and low inclusion of fish oil (Parker and Tyedmers 2015). The organic marine ingredients contrast this by using mostly by-product derived fishmeal and oil, which has added emissions from i) the fish processing plant on top of initial filleting emissions; ii) the by-products used as raw material partly stem from less fuel-efficient fisheries compared to forage fisheries; and iii) the oil and meal yield is lower for some species (Cashion et al. 2016). The high diesel use in organic marine ingredients also drives the high acidifying and nitrogen emission and is the reason behind organic feed having a higher fossil energy demand. Fish processing drives the high contribution of marine ingredients

to marine and freshwater Eutrophication potential. However, the high utilization of fish by-products in the organic feed addresses a problem connected to the growing resource use of salmon aquaculture. With limited production volumes of forage fisheries, the use of alternative raw materials, like fish processing by-product, is motivated (Alder et al. 2008; Froehlich et al. 2018). The increasing use of offcuts from fish destined for human consumption for feed increases the efficiency in the use of an already limited resource (FAO 2018; Olsen et al. 2014). This study has shown that there are trade-offs to this practise.

Organic and conventional agriculture follow two different sets of principles in terms of land management, pesticide use and fertilising. In this study organic crop derived ingredients were found to have a drastically lower inclusion to contribution rate than conventional ones for all impact categories. A strong driver for this discrepancy in this study is the high level of emissions associated with land use change in conventional Brazilian soybean production. The high importance of land use change in GWP calculation was also found in Winther et al. (2020). These results imply that organic agricultural ingredients deliver a better performance in all impact categories considered in this study. Previous studies comparing organic and conventional crop production have found varying results on this (Van Stappen et al. 2015; Williams et al. 2006) but also the accuracy of organic agriculture emissions in LCAs are under continuous investigation. As an example, one study by Meier et al. (2015) identified shortcomings in the nitrogen flux calculations regarding organic agriculture which influence the accuracy of Acidification-, Eutrophication- and Global warming potential calculations. Their findings suggest that organic fertiliser is not accurately accounted for and improvement of the LCA method is needed in this area.

Micro ingredients have earlier been found to have a major contribution in relation to their inclusion rate in conventional feed (Winther et al. 2020). Especially the pigment production is responsible for a big share of emissions in all impact categories. High phosphorus emissions resulted in the conventional feed having a higher freshwater Eutrophication potential than the organic feed. While being allowed to include the same algae-based pigments as the conventional feed, the organic micro ingredients consisted exclusively of a vitamins and mineral mix. Therefore, the results in this study (low emissions) cannot be representative of all organic salmon feed production. Furthermore, it is uncertain if the lack of pigment in organic feed involves use of an additional pigment supplement added to the feed later, or if the fish is free of pigment. While the micro ingredients are source to significant emissions they are seldom included in salmon feed LCAs (Philis et al. 2019) and further studies would contribute to more accurate representation of salmon feed emissions.

The only prior study comparing organic and conventional salmon feeds using LCA methods was done for Canadian production in 2007 (Pelletier and Tyedmers 2007). While feed formulations and regulatory framework behind this study and the Canadian differ due to development over time, some similar findings were obtained. In line with this study, the organic feed was associated with higher acidifying emissions than the conventional one and also required a higher input of energy in its production. With regard to GWP and freshwater Eutrophication potential, Pelletier and Tyedmers (2007) obtained different results since the organic feed was found having higher CO₂ eq. and phosphate emissions than the conventional one. This was due to the exclusive use of by-product derived fishmeal and fish oil in organic feed (which was also the case in this study), but also due to not considering the influence of land use change for agricultural ingredients. A study on feed for another commonly farmed salmonid species, Rainbow trout

(*Oncorhynchus mykiss*), resulted in a considerably lower GWP at a comparable feed composition with 1.41 kg CO₂ eq./kg feed (Papatriphon et al. 2004). The same study also found almost three times higher phosphate eq. emissions than associated with the organic feed studied. Due to a lack of disclosed details about the feed modelling in this study no definitive driver of differences to the organic feeds impacts could be obtained. Another study evaluating the environmental impact of closed Chinook salmon (*Oncorhynchus tshawytscha*) aquaculture analysed a feed with high marine inclusion rates (80% marine ingredients) which had a GWP of 3.38 kg CO₂ / kg feed (McGrath et al. 2015). There is also one more LCA comparing conventional and organic aquaculture but for a completely different system and species, Vietnamese shrimp aquaculture, which found lower CO₂ eq. emissions for organically produced shrimp compared to conventional practises (Jonell and Henriksson 2015). The lower CO₂ eq. emissions were caused by lower land use change in the organic system.

The findings of this comparison are limited in terms of being able to generalize more broadly since only one organic feed recipe could be obtained and the representativeness is unknown. With the reported production volume of 10 000t organic feed roughly 7700t of organic salmon could be produced (assuming an FCR of 1.3). Although this would represent nearly half (45%) of Norway's organic salmon production in 2017 (EUMOFA 2020), the feed is distributed to different markets with unknown volume destined for Norway. Furthermore, absolute values of different LCAs should always be interpreted with caution since there are many factors that influences results. One factor is the choice of allocation method. While mass allocation is recommended above economic, and was chosen for this assessment, economic allocation would affect the outcome considerably for some ingredients. When applying mass allocation, there is no difference in emissions associated per kg filets or off cuts (i.e. by-products). It could be argued that the fillets are the main

products whereas the offcuts are side streams of much lower economic value. Using economic allocation would place larger burdens on the main product, and by this decrease the impacts of by-products.

4.2 Qualitative comparison

When comparing guidelines, it becomes clear that both conventional and organic standards are associated with environmental benefits in some areas and lack in others. Which standard offers better performance depends on the perspective chosen. In general terms, the conventional, Norwegian regulations compared to EU organic standard differ in their distinctiveness to Norwegian salmon aquaculture. The Norwegian regulations are specifically tailored to the local conditions and can set distinct requirements for e.g. effluent levels. The EU organic guidelines must be applicable to European aquaculture of multiple species and locations and are therefore more generic in their statements or refers to local authorities and regulations. It is also important to keep in mind that all conventional regulations still apply to organic production since these are a requirement to run any salmon farm in Norway and therefore organic production regulations are add-ons.

Feed. The improvement potential organic feed guidelines offer in relation to feed issues of today's aquaculture depends on what is being compared. Looking at marine ingredients, the organic guidelines focus on sustainable sourcing of ingredients with preferred use of by-product and sustainable fisheries-derived marine ingredients. This promotes more efficient resource utilisation by utilising an already fished resource. The maximum inclusion rate of 60% for agricultural ingredients for organic feed in turn requires an inclusion of at least 30-40% marine ingredients, higher than found in conventional feed, which limits the potential for reducing future marine resource use. The organic guidelines require all agricultural ingredients to be certified organic (EU standard). While organic agriculture is not

necessarily more efficient than conventional per kilo product in terms of directly measurable impacts such as emissions causing e.g. climate change and acidification (Van Stappen et al. 2015; Williams et al. 2006), the restriction on pesticides and fertiliser use promotes local biodiversity (Bengtsson et al. 2005). While there are no regulations related to conventional feed, the industry has undergone significant changes over the years. Many feed producers are part of initiatives promoting responsible feed ingredient sourcing for both agricultural (e.g. Proterra, European Feed Manufacturers' Federation (FEFAC) soy sourcing guideline) and marine (e.g. Marine Stewardship Council (MASC), International Forrage Fish organisation (IFFO)) ingredients (Biomar 2019; Cargill 2019; Skretting 2018). The ban on amino acid additives under the organic guideline are positive from an environmental perspective as these are associated with high environmental impacts (Marinussen and Kool 2010). However, no data was obtained on possible effect on growth rate, which if negative, would influence resource use. Based on communication with an organic salmon farmer, feed conversion efficiency does not differ significantly between conventional and organic salmon.

Diseases and Parasites. In conventional production, minimum requirements of treatment type and frequency are set by regulators. The organic guidelines also dictate maximum treatment numbers and treatment hierarchies. Both regulations require detailed reporting of treatments, daily collection of dead fish and forbid preventive treatments (excluding cleaner fish and vaccinations). Under organic guidelines, the use of non-allopathic lice treatment methods like cleaner fish and freshwater/temperature baths are the only ones permitted but increases energy inputs and causes impacts elsewhere connected with cleaner fish sourcing. When used, they reduce the potential impact of chemical treatments to the surrounding ecosystem. Lice treatments under conventional guidelines are generally restricted in Norway in that they are not to be used close to shrimp fishing grounds. Shrimps

and other crustaceans are especially affected by treatment runoff because most allopathic treatments are arthropod specific insecticides (Baillie 1985; Miller and Adams 1982). Organic guidelines restrict stocking densities of less than half of conventional levels. While this practise is based on the assumption that it helps to prevent the spread of diseases and parasites and increases fish wellbeing the opposite might hold true. A study by Samsing and colleagues showed that lice infection levels per fish were higher at lower stocking densities due to a higher lice per fish ratio compared to higher stocking densities (Samsing et al. 2014). This potentially affects growth rates which in turn requires more feed and prolonged infrastructure use for organic salmon. An attempt was made to statistically evaluate the influence of lice infestation levels and region on salmon FCR on a Norwegian scale but had to be excluded due to technical issues and data resolution. Furthermore, other studies on commonly farmed salmonid fish found that higher stocking densities correlate with better growth rate and less aggressive fish behaviour (Adams et al. 2007; Brown et al. 1992). Finally, while antibiotic use is low in today's salmon aquaculture in Norway (Burridge et al. 2010; Love et al. 2020), neither organic nor conventional guidelines restrict the use of antibiotics.

Escapees. The regulations regarding escapees are generally stricter in conventional regulations than their organic counterpart. Both guidelines prohibit the farming of foreign species and require enclosures appropriate for local conditions. Conventional guidelines add to this as here the cleaner fish also have to be native species, a point not specified in organic guidelines. No restrictions are given on origin of the cleaner fish while imported wrasse have been shown to hybridize with native populations (Faust et al. 2018). The required lower stocking density in organic aquaculture is beneficial in escape events as the total number of fishes per net pen is lower compared to conventional aquaculture, but from an LCA perspective and combined with the twice as long fallow period, more infrastructure

is required per ton produced. Norway has declared a number of fjords with important wild salmon populations as “National Salmon Fjords”. No new farm licenses are being issued in the fjords and surrounding areas to protect native salmon runs, regardless of being conventional or organic.

Effluents. Both production guidelines require the net pens to be located so that their impact on the local environment due to effluents is minimised. The conventional guidelines prescribe regular checks of the surrounding seafloor for environmental status but don’t address antifouling or cleaning agents. Organic production is not allowed to use copper antifouling which has been found to be the most efficient antifouling option for net pens (Swain and Shinjo 2014). Concerns over elevated copper levels in the surrounding ecosystem, or salmon themselves, due to copper antifouling have been studied before and no significant influence was found (Solberg et al. 2002). While long term accumulation studies are lacking and could conclude different results there is no current advantage to this organic practise. The limitation on cleaner agents used and preference for mechanical removal of fouling species under organic regulations results in lower release levels of chemicals in the surrounding environment.

4.3 Perspectives for the future

Salmon aquaculture is a highly innovative industry and new production methods and efficiency measures are implemented constantly. Organic standards may sometimes hinder development that potentially offers environmental improvements. One example is that under organic guidelines, the use of closed systems like land-based recirculating aquaculture systems (RAS) or solid wall marine containment systems (sea bags) are prohibited. These technologies offer the potential to solve issues related to effluents, escapees and lice infestation as they are separated from the natural environment and allow for higher control of

environmental parameters. Use of genetically modified organisms is also prohibited under organic guidelines but offers possibilities in novel feed ingredient sourcing. Small quantities of omega 3/6 rich oils derived from genetically modified algae are already included in some feeds (Biomar 2019). Allowing this could limit the dependency on wild-caught fish while ensuring the nutritional quality of the final product.

An alternative to the EU organic certification is the Aquaculture Stewardship Council (ASC). This certification serves an intermediate step between conventional and organic production standards and addresses all areas included in both production guidelines as well as taking more holistic approach through requiring community engagement and workers' rights (Table 7, Appendix 1). In term of feed, the ASC regulations stands in contrast to organic guidelines by limiting the marine ingredient inclusion through forage fish dependency ratios (by-products are not included in calculation). Both standards agree in their requirements for sustainably sourced feed ingredients. In terms of effluents, the ASC standard dictates stricter measures than the organic counterpart. Similar to the conventional standard, ASC requires regular assessments of the surrounding seafloor and the PO_4 level in the water is limited. By requiring marginal levels of fine particles in the feed mix, the direct nutrient emission through feeding is minimised as well. Furthermore, the ASC standard set maximum escapee numbers per production cycle in order to be certified, which is not done for conventional or organic production. ASC also limits the number of animal fatalities related to predator control allowed per production cycle as well as prohibiting the use of acoustic deterrent devices. The ASC standard has more strict regulations than organic and conventional standards related to diseases and parasites, as it requires treatment bioassays and rotation, as well as prohibits use of antibiotics essential for human health. Being a species-specific standard allows the ASC guidelines to set stricter limits on environmental issues

related to salmon aquaculture. The organic guidelines have to encompass multiple species and aquaculture systems and are therefore forced to remain general in their regulations.

5. Conclusions

This study aimed to evaluate current environmental performance and identify improvement potentials of conventional and organic salmon production in Norway. An Life Cycle Assessment (LCA) of feeds used did not lead to a definitive answer on which feed has better environmental performance but rather demonstrated that this depends on the impact category analysed. Use of micro ingredients were found to be important to follow up upon, as well as potential differences in growth rate, as these factors contribute heavily to the environmental impact of feed and overall LCA performance of salmon. There are also limits of LCA for comparing organic and conventional production systems, and results are not comprehensive. Differences in toxicity between feeds could not be investigated due to lack of data and methods.

Other potential differences like animal health, sustainable ingredient sourcing and effects of interbreeding between escapees and native salmon are difficult to quantify. A complementary qualitative comparison of production standards showed, again, the importance of perspective in deciding which standard offers improvements for current challenges seen in salmon aquaculture. The organic standard is an add-on to existing conventional regulations and focuses on limiting disease and parasite treatments and reducing the influence of non-organic substances on the environment, whereas the conventional standard stays as requiring frequent monitoring of environmental impact and fish health and directs problem solving to experts. Finally, the ASC standard was assessed as a certification alternative and found to offer concrete solutions based on stricter than conventional, but looser than organic regulations. Expanding the organic

guidelines with more salmon-specific regulations would allow better addressing of the environmental issues in salmon aquaculture while keeping the organic status of the final product.

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Appendix 1

Fish species information

Table 1. Additional information about the included fish species

	Species	Scientific name	Fishery type	Filleting efficiency (fillet/offcut) ¹	% Yield Fish oil/ Fishmeal ²
Reduction fisheries	Blue Whiting	<i>Micromesistius poutassou</i>	pelagic	/	19.70/1.90
	Capelin	<i>Mallotus villosus</i>	pelagic	/	16.50/7.70
	Herring	<i>Clupea harengus</i>	pelagic	/	20.00/11.00
	Krill	<i>Euphasiacea sp.</i>	pelagic	/	16.00/0.08
	Peruvian Anchovy	<i>Engraulis ringens</i>	pelagic	/	24.00/5.00
	Gulf Menhaden	<i>Brevoortia patronus</i>	pelagic	/	21.00/16.00
	Norway pout	<i>Trisopterus esmarkii</i>	pelagic	/	20.40/11.50
	Mackerel	<i>Scomber scombrus</i>	pelagic	/	19.40/18.60
	Sandeel	<i>Ammodytes sp.</i>	pelagic	/	19.70/4.24
	Sprat	<i>Sprattus sprattus</i>	pelagic	/	18.80/7.80
Fish meal - by-products	Capelin	<i>Mallotus villosus</i>	pelagic	As Herring	9.30/11.00
	Herring	<i>Clupea harengus</i>	pelagic	53/47	9.30/11.00
	Mackerel	<i>Scomber scombrus</i>	pelagic	38/62	18.70/18.60
	Whitefish (Cod)	<i>Gardus morhua</i>	demersal	37/63	0.17/17.00

¹ (Norsk Fiskeridirektoratet 2018) Fish processing in/outputs are based on Hall (2018).

²(Aidos 2002; Cashion et al. 2016; Winther et al. 2020)

Table 2. Data used to model reduction of marine ingredients into meal and oil (from Winther et al. 2020).

Activity and in-/outputs	Value
Electricity input (kWh/ton into reduction)	26
Heat from natural gas (MJ/ton into reduction)	1.910
Polypropylene (kg/ton into reduction)	0.594
Extrusion, plastic film	0.594
Treatment of plastic waste in municipal incineration	1.19

The fuel use required to land fish for further processing was modelled by sorting fish into two categories, demersal and pelagic fisheries. Demersal fisheries were modelled after Cod fisheries with 0.36 l diesel/kg LW catch burned in a fishing vessel. For pelagic fisheries a fuel use of 0.1 l diesel/kg LW fish was used (Winther et al. 2020).

Transport

Table 3. Assumed distances and modes of transport for different ingredients from their source to the feed mill

Ingredient	Transport Land	Transport sea
Vegetable Europe	1440 km	135 km
Vegetable China	22 626 km	500 km
Vegetable Brazil	9 260 km	500 km
Marine ingredients Europe	1617 km	500 km
Marine ingredients South America	13 425 km	500 km
Marine ingredients North America	8 906 km	500 km
Marine ingredients Norway	-	500 km
Micro ingredients	1440 km	13 425 km

Micro ingredients

Pigment production was modelled following a study on the production of carotenoid astaxanthin from algae by (Panis and Carreon 2016). A 10 % inclusion of pure astaxanthin in the pigment feed additive was assumed (Winther et al. 2020). Amino acid production was modelled following a study on L-Threonine production by (Marinussen and Kool 2010). The mineral and vitamin additive was modelled using the process "Total minerals, additives, vitamins, at plant/RER Mass S" by the Global Feed LCA initiative databank.

Processes used for feed modelling

Table 4. Processes used to model the conventional feed recipe

Group	Ingredient	Datasource (Ecoinvent databank)	Comment
Micro ingredients	Amino Acids	Modelled after L-Threonine production (Marinussen and Kool 2010)	
	undefined micro ingredients	filled in with weighted average of other micro ingredients	
	phosphate	Triple superphosphate, as 80% $\text{Ca}(\text{H}_2\text{PO}_4)_2$ (NPK 0-48-0), at regional storehouse/RER Mass	
	Pigments	Modelled after astaxanthin production (Panis and Carreon 2016)	Only energy use is considered
	Vitamin and minerals	Total minerals, additives, vitamins at plant/ RER Mass	
Crop oils	Rapeseed oil	crude rapeseed oil, from crushing (pressing), at plant/DE Mass	
Crop proteins	Faba beans	Broad bean meal, at plant /NL Mass	
	Guar	included in Legumes	
	Horsebeans	included into Faba beans	
	Legume	Soybeans at farm /IN Mass	
	Maize	Maize gluten feed, dried, consumption mix, at feed compound plant/NL Mass	
	Pea	Pea, protein-concentrate, at plant RER	
	Soy	Soybean protein concentrate, from crushing (solvent, for protein concentrate), at plant/BR Mass	
	Sunflower	Sunflower seed meal, from crushing (solvent), at plant/NL Mass	
	Wheat	Wheat gluten meal, consumption mix, at feed compound plant/NL Mass	
Crop carbohydrate	Pea	Pea. starch (from protein-concentrate). at plant/RER Mass Crude	
	Wheat	Wheat starch, dried, consumption mix, at feed compound plant/NL Mass	
Reduction fisheries	Blue Whiting	Norwegian purse seine fisheries (fuel use in appendix)	
	Capelin	Norwegian purse seine fisheries (fuel use in appendix)	
	Herring	Norwegian Herring (fuel use in appendix)	
	Krill	Fuel use: 0.141 l/kg krill	
	Peruvian Anchovy	Fishmeal, 63-65% protein, from anchovy {GLO} market for fishmeal, 63-65% protein, from anchovy Cut-off, S	

		Fish oil, from anchovy {PE} fishmeal and fish oil production, protein Cut-off, S	
	Gulf Menhaden	Fuel use: 0.037 l/kg	
	Norway pout	Modelled with data for pelagic trawled fish (fuel use in appendix)	
	Mackerel	Norwegian mackerel (fuel use in appendix)	
	Sandeel	Modelled as 55% pelagic trawl/45% purse seine fisheries (fuel use in appendix)	
	Spratt	Norwegian purse seine fisheries (fuel use in appendix)	
Fish meal - by-products	Capelin	as Herring	
	undefined	/	
	Herring	Norwegian Herring (fuel use and fileting efficiencies in appendix)	
	Mackerel	Norwegian Mackerel (fuel use and fileting efficiencies in appendix)	
	Whitefish	Norwegian Cod (fuel use and fileting efficiencies in appendix)	

Table 5. Processes used to model the organic feed recipe

Group	Ingredient	Datasource (Ecoinvent/Agrifootprint databank)	Comment
Micro ingredients	Vitamin and minerals	Total minerals, additives, vitamins at plant/RER Mass	
Crop oils	Organic soy oil	Crude soybean oil, organic, from crushing (pressing), at plant {RoW} Mass	
Crop proteins and carbs	Organic Wheat	Wheat grain, organic, {GLO} market for Cut-off, U	
	Organic protein pea	Protein pea, organic {GLO} market for Cut-off, U	
	Organic soy expeller	Soybean expeller, organic, from crushing (pressing), at plant {RoW} Mass	
Reduction fisheries	Organic fishmeal	Fish meal, from fish meal and oil production, at plant/ X*Mass	*1/3 Norway (NO) 1/3 Denmark (DK) 1/3 Iceland (no Iceland data so NO as proxy)
Fish meal - by-products	Organic fishmeal	Norwegian Cod (fuel use and fileting efficiencies in appendix)	

	Organic fish oil	Norwegian Mackerel (fuel use and fileting efficiencies in appendix) Norwegian Herring (fuel use and fileting efficiencies in appendix)	½ Mackerel trimmings ½ Herring trimmings
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Contribution of feed ingredients to the different impact categories

Table 6: Impact contribution of ingredient groups to of 1kg organic or conventional feeds total impact

	Impact category	Unit	Total	Agricultural ingredients	Marine ingredients	Transport	Micro ingredients	Other
Organic	Climate Change	kg CO ₂ eq.	2.59	0.26	2.07	0.14	0.02	0.11
	Acidification	molc H ⁺ eq.	0.0510	0.0056	0.0435	0.0013	0.0002	0.0005
	Terrestrial Eutrophication	molc N eq	0.1733	0.0237	0.1423	0.0060	0.0004	0.0009
	Freshwater Eutrophication	kg P eq.	0.0013	0.0001	0.0011	<0.0000	<0.0000	<0.0000
	Marine Eutrophication	kg N eq.	0.0380	0.0064	0.0309	0.0005	0.0001	0.0001
	CED, fossil fuel	MJ	34.22	1.74	28.49	2.07	0.32	1.61
Conventional	Climate Change	kg CO ₂ eq.	3.42	2.07	0.76	0.18	0.41	0.01
	Acidification	molc H ⁺ eq.	0.0334	0.0139	0.0151	0.0015	0.0029	<0.0000
	Terrestrial Eutrophication	molc N eq	0.1201	0.0580	0.0476	0.0071	0.0073	0.0001
	Freshwater Eutrophication	kg P eq.	0.0015	0.0004	0.0007	0.0000	0.0004	<0.0000
	Marine Eutrophication	kg N eq.	0.0289	0.0113	0.0162	0.0006	0.0007	<0.0000
	CED, fossil fuel	MJ	27.59	9.94	9.75	2.62	5.05	0.23

Comparison of production standards for Norwegian salmon aquaculture

Table 7: Comparison of the Norwegian standard for salmon production with rules set by the ASC and EU guidelines for organic production (Aquaculture Stewardship Council 2017; European Commission 2007, 2009; Fiskeridepartementet 2011; Nærings- og fiskeridepartementet 2008, 2009)

	Conventional	ASC	EU organic
Feed	<ul style="list-style-type: none"> * daily feeding 	<ul style="list-style-type: none"> * <1% fines in feed (3 month test interval) * FFDRmeal¹ of <1.2 * FFDRoil of <2.52 OR <30g/kg EPA+DHA from marine sources * traceability for all feed ingredients with more than 1% proportion * no fishmeal/oil from red list species * responsibly sourced plant ingredients * disclosure to buyer if more than 1% is GMO² crop 	<ul style="list-style-type: none"> * no GMO² ingredients * fish based ingredients from sustainable fisheries (common fisheries policy) or sust. Aquaculture * no growth promoters or artificial amino acids * no use of salmon cut off etc. in feed * max 60% plant based * crops must be organic certified
Enclosure	<ul style="list-style-type: none"> * inspection of gear after heavy weather * monitoring of environmental data (°C, O₂...) Stock density: <ul style="list-style-type: none"> * max 25kg/m³ * max 200k fish per production unit * max 6 days in slaughter cages * only use of certified hardware * mooring analyses prior to installation * 2 months fallow of site between cycles 	<ul style="list-style-type: none"> * No acoustic deterrent devices * proper disposal or recycling of material (incl. nets) * no copper net cleaning in situ/only with effluent measures on land * only use of EU/US/AUS permitted antifouling 	<ul style="list-style-type: none"> * clear separation of eco and conv. Salmon * cleaning/ disinfecting agents have to be certified for organic production * No RAS³ (except for brood stock) * AC has to be located in area free of influence of non organic substances * net cleaning by hand/physical means (except. may be used for better results "Annex 7.2") * no copper antifouling Stock density: <ul style="list-style-type: none"> * freshwater 20kg/m³ * Saltwater 10kg/m³ * 4 month fallow between production cycles
Lice treatments	<ul style="list-style-type: none"> * assessment on local impact of lice treatment * chemical lice treatments not to be used close to shrimp grounds * cleaner fish can be used in multiple salmon production cycles 	<ul style="list-style-type: none"> -max. 0.1 female lice/salmon during sensitive periods for wild salmonids -Publicly available sea lice test results -monthly test (weekly during sensitive times) -no use of non-native cleaner fish species 	<ul style="list-style-type: none"> * use of cleaner fish preferred * max. 2 lice treatments/year
Disease treatment	<ul style="list-style-type: none"> * food safety authority inspection when opening farm * disinfection of all gear before using it somewhere else * keeping of dead fish for inspection by veterinarian * daily collection of dead fish * no preventive treatment with hormones/drugs 	<ul style="list-style-type: none"> * veterinarian 4/year * fish health manager/monthly * <10% disease related mortality per production cycle * no antibiotics critical for human health * detailed public documentation of treatments * integrated management plans on reducing use of therapeutants 	<ul style="list-style-type: none"> * veterinarian min. 1/year * treatment hierarchy (homeopathic, plant derived meds, immunostimulants/ probiotics) * allopathic treatments 2/year (except vaccinations) * daily collection of dead fish

	* 4 –12 health checks per year depending on farm size	* resistance bioassay if 2 treatments are ineffective * rotating treatments to prevent resistance	
Environmental impact	Waste: * Levels based on Norwegian standard NS 9410 * Environmental survey of marine fish farms"-> location dependent * bad environmental status of seabed can result in farm closure or biomass reduction	Benthic: * Good status out/inside area of effect based on biotic + abiotic markers (B+C assessment) Water: * >70% pO ₂ in weekly average with 95% of samples over 2mg/l	* environmental assessment to minimize impact * shall be located where condition allow for minimal impact on seafloor and surrounding water
Escapees	* Risk assessment when opening farm * Catchment of all fish within 500m of farm after escape * only native salmon species * immediate report of (suspected) escape	* max.300 per production cycle * escape prevention measures * public record of escapees	* only farming of native species * recapture when possible * documentation of incidents
Predator control	* appropriate measure must be taken	* 0 death of red list mammals/birds * <9 lethal incidents/2y (2 mammal max)	* must be in accordance with habitats directive (Council directive 94/43/EEC)
General	* no relocation if illness is suspected * fish must be anesthetized before killing * daily measurement of stock, biomass, loss and feed consumption -> detailed reports kept on farm * monthly reports on biomass, in/output, feed consumption... * no new farms in national salmon fjords (5km distance)	* Area based management plan (treatment, stocking etc.) with 80% of farm in area participating * no GMO salmon * record of GHG ³ emitted during production cycle (incl. feed) * worker's rights + community engagement	* no GMO * artificial induction of genetic traits (monosex, polyploidy, cloning...) forbidden * no artificial induction of reproduction through hormones * annual sustainable management plan * preferably use of renewable energy sources * detailed records on stock, health, feed etc. * wild caught animals may be used for breeding purposes

¹Forage Fish Dependency Ratio ²Genetically Modified Organisms ³Green House Gases

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