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Life cycle environmental impacts of different fish farming alternatives in the Baltic Sea

Juha Grönroos, Frans Silvenius, Markus Kankainen, Kimmo Silvo, Timo Mäkinen

Abstract

Life cycle assessment method (LCA) was used to evaluate climate and eutrophication impacts, and primary energy consumption of the total product system of Rainbow trout farmed in the Archipelago Sea area of the Baltic Sea. The results are expressed as per 1000 kg of ungutted Rainbow trout at the landing site.

The product system studied included all relevant life cycle phases needed in a product system of farmed fish. Besides the farming activity itself, manufacturing of fish feed, production of fish feed raw materials and other inputs, such as electricity generation and all transportation related to fish, fish feed and feed raw materials were included. The emissions and energy consumption data in each phase were collected. Based on this inventory data, impacts on climate change and eutrophication were assessed, and total primary energy consumption estimated.

First, the environmental consequences of the current average production model were assessed. Subsequently, the same was performed for the following three alternative options:

1. Net loading option, where low-valued fish is caught from the Baltic Sea to enable nutrient removal in order to compensate for the nutrient emissions from the fish farming;
2. Nutrient recirculation, where fish meal and oil used as raw materials for fish feed are produced from fish originating from the Baltic Sea instead of from fish caught from oceans, and
3. Rationalised fish farm location plan (spatial planning) option, where fish farming is based on fewer and bigger farms, located in more offshore areas.

In order to decrease the environmental burden of farmed fish production, it is necessary to pay attention to the total product system. Production of fish feed and feed raw materials have a major role in the environmental impacts of the total system. Feed manufacturers and fish farmers should be interested in how and where the raw materials are produced. It is important to pay further attention to practical and technical methods which reduce nutrient load from fish farming. In farming as well as in other phases of the product system, it is environmentally sound to introduce the use of renewable energy sources, e.g. biodiesel and wind energy, in order to reduce dependence on non-renewable natural resources and to decrease fossil carbon emissions to the atmosphere, and to enhance energy use efficiency. Additionally, it is meaningful to utilise the contents of organic matter and nutrients in organic wastes and by-products as effectively as possible.

Keywords: the Baltic Sea, Rainbow trout, fish farming, life cycle assessment, spatial planning

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Introduction

The Baltic Sea is one of the largest brackish-water basins in the world with the following geographical characteristics: drainage area 1,720,270 km^2 (with 85 million people), marine area 415,000 km^2, volume 21,760 km^3, maximum depth 459 m and average depth 52 m. Rivers bring annually around 2% of the volume into the sea as runoff. The Baltic Sea is connected to the world's oceans only by the narrow and shallow Danish Straits which limits the entrance of saline water from the North Sea. Moreover, the further transport of deep saline water into the sea is restricted by the presence of submarine sills separating the sub-basins of the Baltic Sea.

The effects of nutrient enrichment, eutrophication, is perhaps the most significant threat to the marine environment of the Baltic Sea. Owing to the shallow and strongly stratified basin and the long residence time of water, the Baltic Sea is highly sensitive to eutrophication. Moreover, the gradual pollution of the Baltic marine environment by hazardous substances has caused significant harm to the environment.

The amount of food fish cultivated in Finland was about 11.8 million kilograms in 2010. This represented a decrease of about 1.8 million kilograms since 2009, although the value of food fish production (44.0 million €) decreased only slightly (by 0.4 million €). The food fish supply consisted of 11.0 million kilograms of Rainbow trout, about 0.7 million kilograms of whitefish and just under 0.1 million kilograms of other food fish species. Altogether 341 fish farming enterprises were in operation in 2010. Of cultivated Rainbow trout, ca 84% was reared in the sea areas. In 2011, the consumption of domestic fish for human food in Finland totalled to ca 43 million kilograms (as whole fish).

This study is a part of EU funded Coexist project (www.coexistproject.eu) in which the competing activities and interactions in European coastal areas will be evaluated. The ultimate goal of the project is to provide a roadmap for better integration, sustainability and synergies across the diverse activities taking place in the European coastal zone. The ultimate project outcomes will be a) characterisation of relevant European coastal marine ecosystems, their current utilisation and spatial management, and b) evaluation of spatial management tools for combining coastal fisheries, aquaculture and other uses, both now and in the future.

The aim of this sub-study was to analyse the environmental impacts of the total life cycle of Rainbow trout production, farmed in the Finnish Archipelago area of the Baltic Sea. Special attention was given to climate change, eutrophication of the waters and primary energy consumption. Three alternative production options were compared to the current average production model.

Materials and methods

Life cycle assessment method (LCA; see e.g. EC 2010, Finnveden et al. 2009) was used to evaluate climate and eutrophication impacts as well as primary energy consumption of the total product system of Rainbow trout farmed in the Baltic Sea Archipelago Sea area.

LCA is a tool which was originally developed to evaluate the environmental implications of manufactured products or services during their entire life cycle. It has also been applied to studying the environmental performance of alternative production systems (e.g. conventional vs. organic food: Grönroos et al. 2006a) or management systems (e.g. technically different fish farming alternatives: Grönroos et al. 2006b). Besides the direct environmental impacts arising from the activity under consideration, LCA helps to recognise the indirect environmental consequences caused by the activity and the possible side-effects in other product systems or areas (e.g. Kløverpris et al. 2007). The idea of using the consequential – i.e. change-oriented - life cycle assessment (CLCA; see e.g. Ekvall and Weidema 2004, Finnveden et al. 2009) is to recognise the most important direct and indirect implications due to possible changes in the studied system, and to take all those consequences into account when an assessment of the changes in environmental and other impacts is made. In this study, the CLCA method was applied.

According to the international standards of LCA (ISO 2006a and ISO 2006b), there are four phases in an LCA study:

1. goal and scope definition. It provides the initial plan for conducting the life cycle inventory phase;
2. life cycle inventory analysis (LCI), where the input/output data (e.g. energy and material inputs, products and co-products, wastes and emissions to air, water and soil) are collected for each unit process included in the product system studied;
3. life cycle impact assessment (LCIA), where the LCI results are converted to environmental impacts to better understand their environmental significance;
4. interpretation, where the results of LCI and LCIA are summarised and discussed as a basis for conclusions, recommendations and decision making in accordance with the goal and scope definition.

In this study, inventory analysis data were obtained directly from the manufacturing industry (fish feed, electricity, fuels), from local actors (fishermen, fish farmers etc.) and from scientific studies (e.g. emissions and impacts of aquaculture). Additionally, the results and materials of other LCA studies as well as different national and international databases were available as data sources (e.g. Silvenius et al. 2012, Ecoinvent database). In LCIA, the values for environmental interventions (emissions, resource extractions) were transformed into impact category indicator results by characterisation factors, making the aggregation of interventions possible within each impact category.

The product system studied included all relevant life cycle phases needed in a fish farming system. Besides the farming activity itself, manufacturing of fish feed and production of fish feed raw materials and other inputs, such as electricity generation and all transportations related to fish, fish feed and raw materials were included (see Fig. 1). The data for the emissions and energy consumption in each phase were collected. Based on this inventory data, potential environmental impacts were assessed. In LCIA, the values for environmental interventions (emissions, resource extractions) were transformed into impact category indicator results by characterisation factors (Table 1), making the aggregation of interventions possible within each impact category.

First, the environmental impacts of the Current production model, i.e. the present average product system of Rainbow trout were assessed. Subsequently, the same was performed for three alternative options:

1. Net loading option, where low-valued fish (LVF) is caught from the Baltic Sea to enable nutrient removal in order to compensate for the nutrient emissions from the fish farming;
2. Nutrient recirculation (BS-feed option), where fish meal and oil used as raw materials for fish feed are produced from fish originating from the Baltic Sea instead of from fish caught from oceans, and
3. Rationalised fish farm location plan (spatial planning) option – or Offshore option, where fish farming is based on fewer and bigger farms, located in more offshore areas.

In all of the alternatives, the functional unit - i.e. the reference unit to which the inputs and outputs are related - was 1000 kg of ungutted Rainbow trout at the landing site after catching.

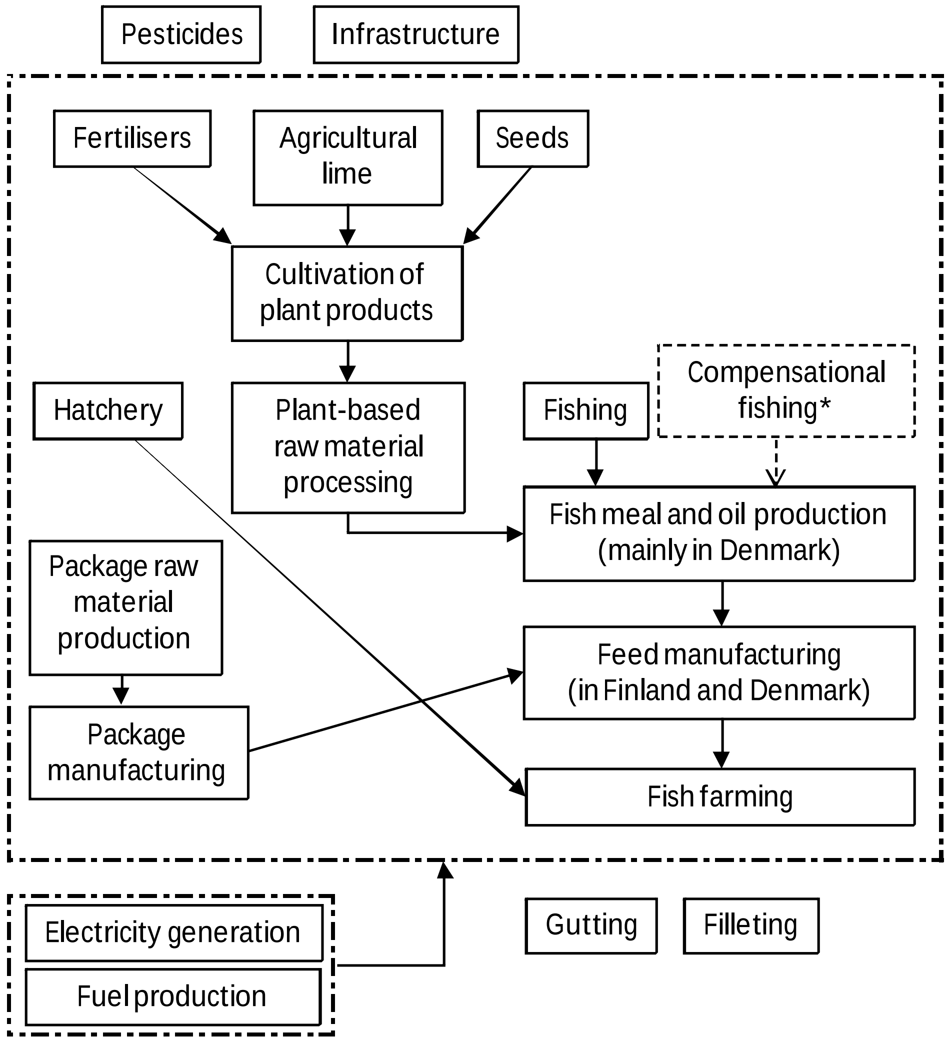

Figure 1. System boundaries (dotted line) and material and energy flows of the Rainbow trout product system studied. Compensational fishing (marked with *) is considered only in one option and is not included in the Current production model (see text).

Table 1. Characterization factors for the emissions to the atmosphere (a) and waters (w) within the impact categories climate change and aquatic eutrophication.

Variable	Characterization factor	
	Climate change (CO_2 eq kg^{-1})	Aquatic eutrophication (PO_4 eq kg^{-1})
CO_2(a)	1	
CH_4(a)	25	
N_2O(a)	298	
NH_3(a)		0.04
NO_x(a)		0.015
N(w)		0.348*
P(w)		1.102**
Source:	Solomon et al. 2007	Seppälä *et al.* 2004

* Equivalency factor 0.42, transport factor 0.92, effect factor 0.9

** Equivalency factor 3.06, transport factor 1.0, effect factor 0.36

Results and discussion

Current production model

Life cycle primary energy consumption of producing 1000 kg of Rainbow trout (ungutted, at landing site) in Finland totalled to 18.7 GJ (Fig. 2) and only one percent (1%) of this originated from renewable energy sources. The most energy-intensive phases in the product system were fish meal and oil production (53% of total primary energy consumption), production of soy products (13%), fish farming (11%), manufacturing of fish feed (10%) and transportation (7%). Package manufacturing, production of other plant-based feed raw materials, and hatchery were jointly responsible for 6% of the total energy consumption.

The climate impact – or carbon footprint – of the 1000 kg of landed Rainbow trout totalled to 1,745 kg CO_2-equivalents (Fig. 3). The most important phases in terms of GHG emissions were soy cultivation, fish meal and oil production and fish feed manufacturing.

The emissions of eutrophying substances in the 1000 kg of landed Rainbow trout equaled to 23 kg PO_4-equivalents and originated mainly from fish farming (Fig. 4).

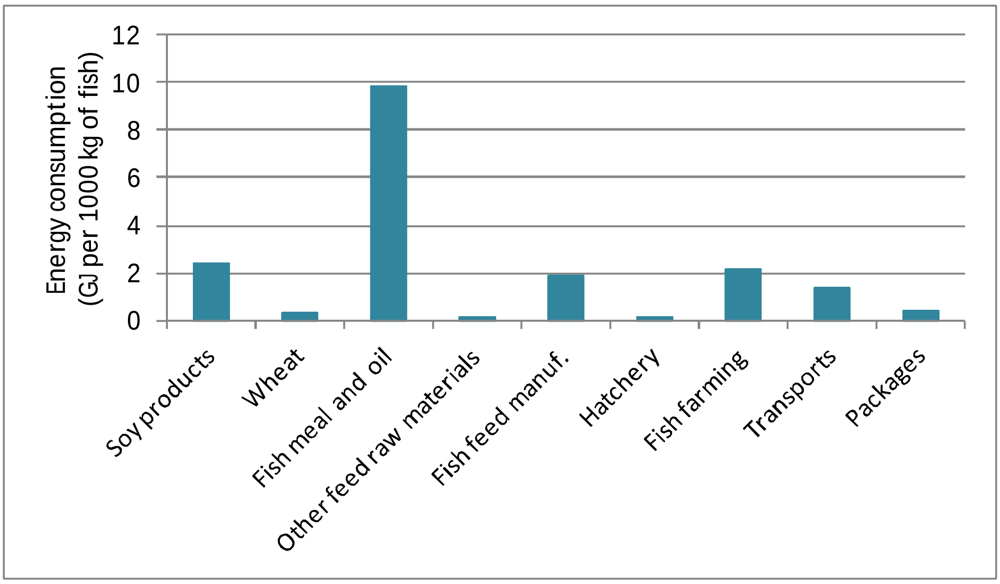

Figure 2. Primary energy consumption (GJ) of 1000 kg of Rainbow trout divided between life cycle phases in the case of the Current production model.

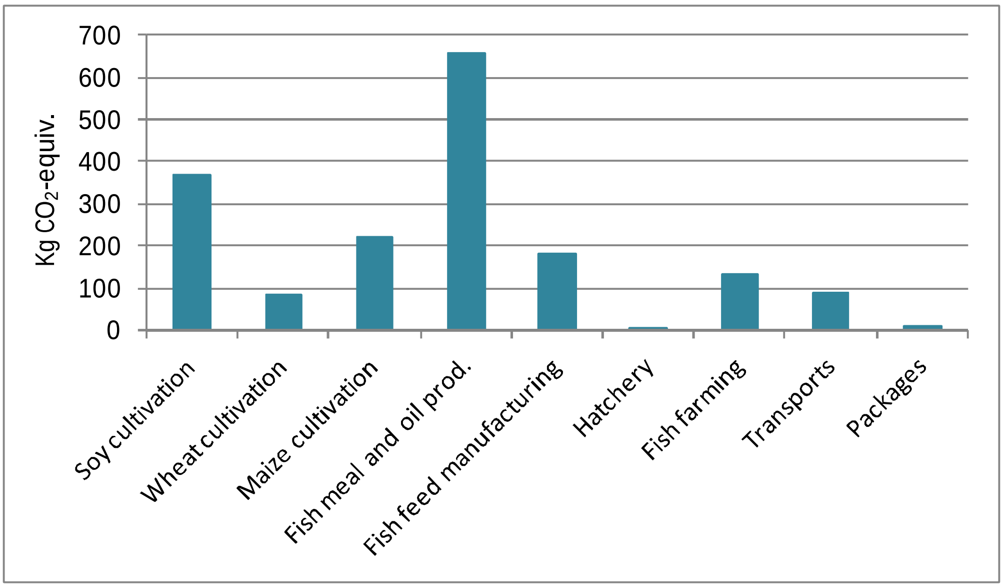

Figure 3. Climate impact (kg of CO_2-equiv.) of 1000 kg of Rainbow trout divided between life cycle phases in the case of the Current production model.

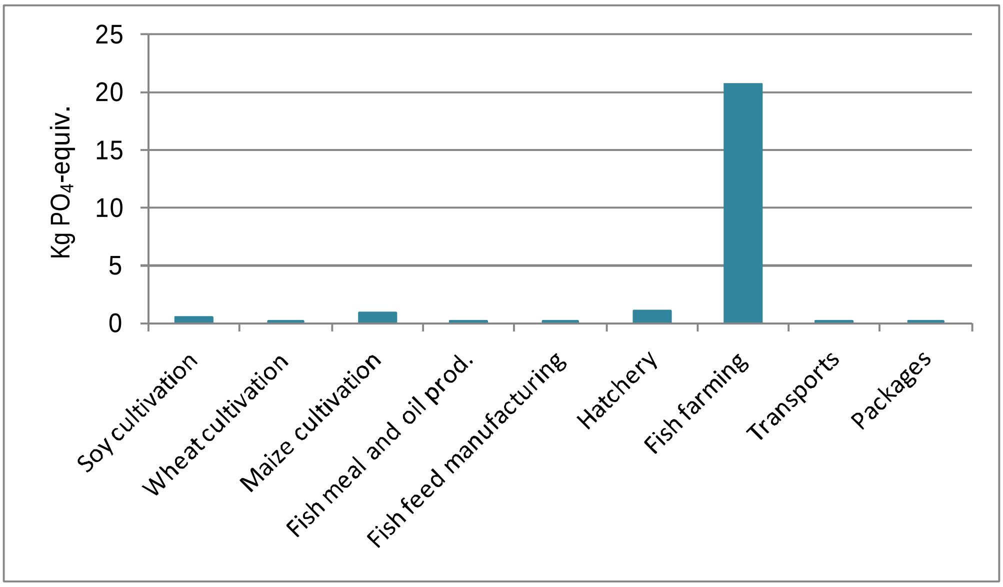

Figure 4. Eutrophying emissions (kg of PO_4-equiv.) of 1000 kg of Rainbow trout divided between life cycle phases in the case of the Current production model.

Comparisons between current and alternative fish farming management options

Regarding energy consumption, the result of the Net loading option depends strongly on what is done with the caught LVF and what it replaces: is it processed and used e.g. as a fuel and fertilisers, or is it used as fodder of fur animals. It was assumed that LVF is used as fodder for fur animals but with no replacement of currently used feed raw materials (Baltic herring or slaughter waste). If replacement occurs, the net effect of this option is smaller or even negative compared to the Current production model. In the Offshore option, the only difference to the Current production model is the slightly lower fuel use in farming phase. Therefore, in the final energy consumption results of the total life cycle its impact is somewhat small. In the BS-feed option, lower fuel use of fishing (fish from the Baltic Sea) due to shorter transport distances of feed raw materials result in the lowest energy consumption among the studied options. Regarding climate impacts, the relative differences between the options can be explained with the differences in energy consumption, as explained above.

In the Current production model and Offshore option, eutrophying emissions (N and P to the waters) are equal because the only difference is the location of the fish farms. In the Current production model, farms are located in inner and middle Archipelago areas, whereas in Offshore option, in outer Archipelago area. Even though nutrient emissions are similar, the eutrophication impacts may be different because of the local circumstances. In the inner and middle Archipelago area, it is most likely that eutrophication is manifested not only as an increase in planctic algae biomass but also as an increase in periphyton (e.g. green algae) on shorelines and solid surfaces. In the outer Archipelago areas, eutrophication is also manifested as an increase in planctic algae. This increase is usually small but can be appear over large sea areas. Additionally, deep-sea bottoms in the Archipelago area may easily suffer from hypoxia with recurrent internal loading of nutrients.

In the Net loading option, emissions from fish farming are compensated with LVF fishing if LVF does not replace anything currently captured fish from the Baltic Sea (see energy consumption results above). In BS-feed option fishing of feed raw materials from the Baltic Sea compensates for emissions from fish farming.

Uncertainties

In LCA, uncertainties are commonly grouped into 1) parameter uncertainty, which can be caused by uncertainty related to emissions and other inventory data variables, and uncertainty related to various factors that are necessary if one is to obtain input or output variables or impact assessment results (e.g., emission factors); 2) scenario uncertainty, i.e., the uncertainty caused by normative choices in LCA such as selection of system boundaries; and 3) model uncertainty, which is related to selection or formulation of the impact assessment models (e.g., Lloyd and Ries 2007; Mattila et al. 2012).

Concerning farmed fish LCA, one of the most important parameter uncertainties is related to the feed factor. In this study, however, the feed factor was equal in all management options (1.11 kg of feed per 1 kg of fish farmed) and did not affect the final conclusions. Still, the feed factor has a very important role when LCA results of farmed fish are compared to other food products.

Feed composition data and feed raw material LCA data – especially CO_2 emissions from soil and combustion of fossil fuels, were suggested to have the most important effect on the carbon footprint result. From the eutrophication point of view, emission data of N and P to the waters as well as volumes of nutrients removed from the waters as a result of fishing of LVF are the most crucial ones.

Scenario uncertainty arises from the decisions related to the system boundaries: which unit processes or life cycle phases are included, and which are excluded. We excluded infrastructure (e.g. roads) and constructions (fish farm, harbour etc) from the system, as in many other LCA studies. Additionally, we know from other studies that constructions do not have a significant role in carbon footprint results of aquaculture systems (Ayer and Tyedmers 2009, Silvenius et al. 2012).

Model uncertainty is related to the methods to convert emission values into impact indicator values. For primary energy consumption, different energy units or fuel masses or volumes were converted into mega joules using the international conversion units. For carbon footprint – or climate impact – results, the IPPC equivalency factors of CO_2, CH_4 and N_2O for 100 years were used. For eutrophication impact assessment, method of Seppälä et al. (2004) was used. There, the equivalency factors (PO_4-equivalents) of nitrogen and phosphorus were applied. The factors used – which are based on N:P ratio of phytoplankton (Redfield et al. 1963) – were 0.42 for nitrogen and 3.06 for phosphorus. The problem is, however, how to define the share of *effective* N and P of the *total* N and P emissions, and what part of emitted N or P reaches the waters where it affects photosynthesis. We used the default factors given by Seppälä et al. (2004) and Ekholm and Vielma (2000, pers. comm.).

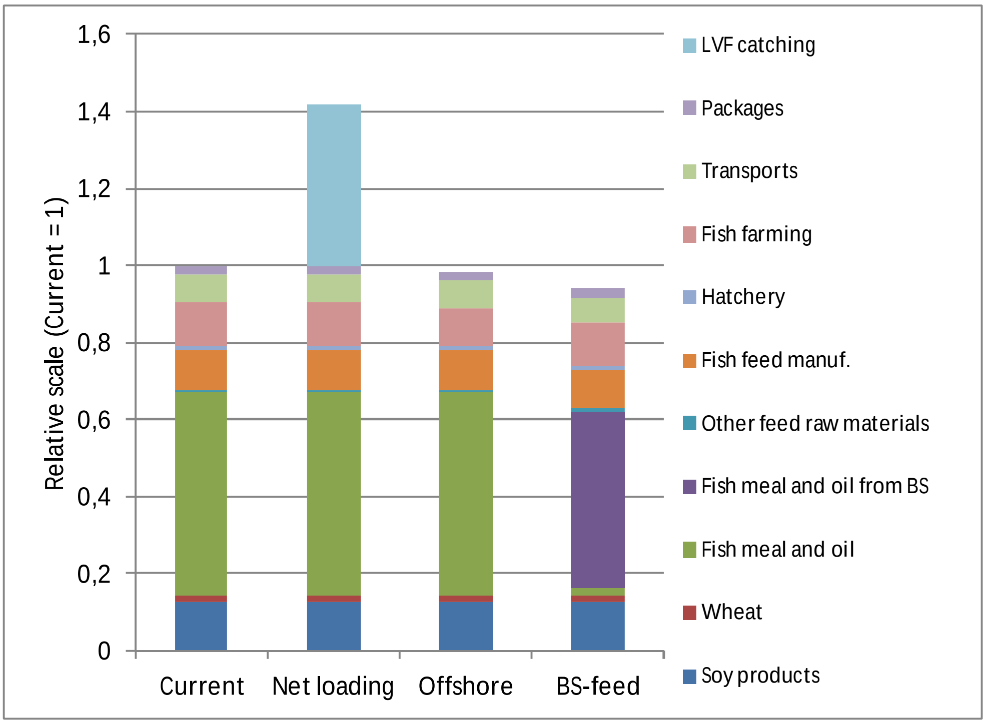

Figure 5. Relative (Current = 1) energy consumption of 1000 kg of Rainbow trout produced according to the different management options: Current production model (Current), Fisheries of low-valued fish for nutrient removal in order to justify aquaculture licenses (Net loading), Rationalised farming site location strategy (Offshore), and Localised value chain (BS-feed).

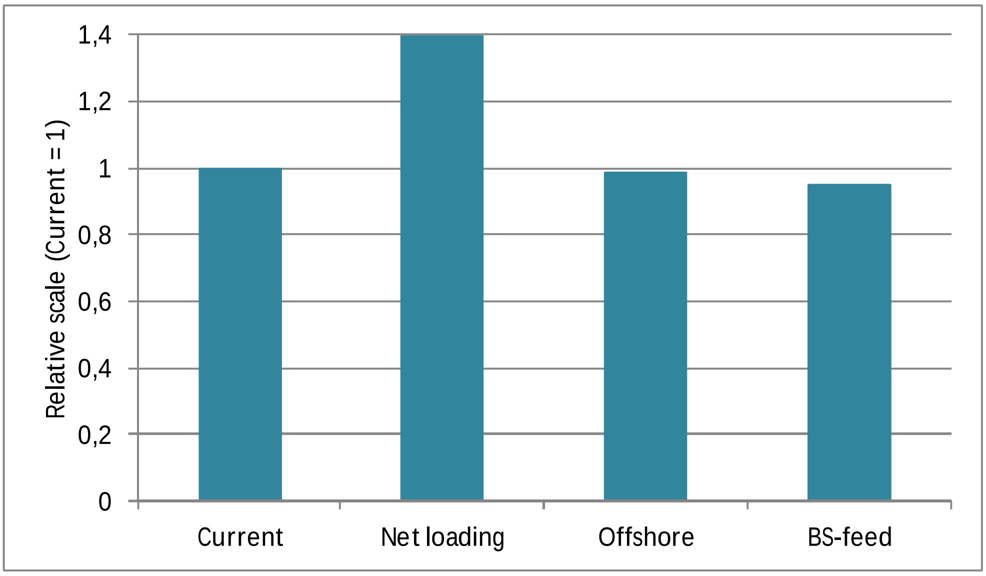

Figure 10. Relative (Current = 1) climate impact of 1000 kg of Rainbow trout produced according to the different management options: Current production model (Current), Fisheries of low-valued fish for nutrient removal in order to justify aquaculture licenses (Net loading), Rationalised farming site location strategy (Offshore), and Localised value chain (BS-feed).

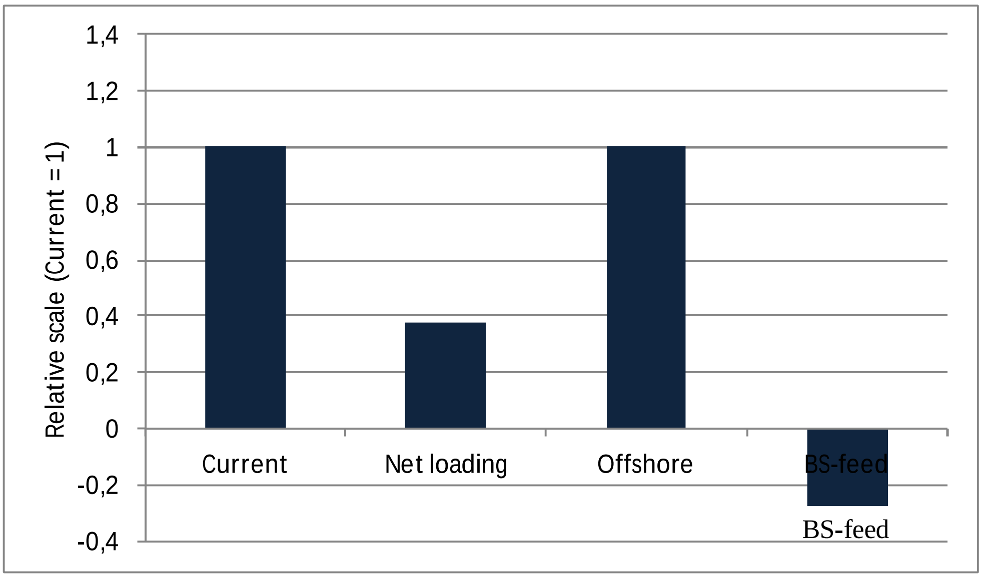

Figure 11. Relative (Current = 1) eutrophying emissions of 1000 kg of Rainbow trout produced according to the different management options: Current production model (Current), Fisheries of low-valued fish for nutrient removal in order to justify aquaculture licenses (Net loading), Rationalised farming site location strategy (Offshore), and Localised value chain (BS-feed).

Conclusions

In the present Rainbow trout product system in Finland, it is necessary to pay more attention to the practical and technical methods which reduce nutrient load from fish farming to the sea per kilogram of produced fish. In fish farming itself and other phases of product system, it is environmentally sound to introduce the use of renewable energy sources, e.g. biodiesel and wind energy, in order to reduce dependence on non-renewable natural resources and to decrease fossil carbon emissions to the atmosphere, and also to enhance energy use efficiency. Additionally, it is meaningful to utilise the organic matter and nutrient content of organic wastes and by-products of the system as effectively as possible, in order to facilitate decreased use of non-renewable natural resources and avoidance of harmful emissions from organic materials to the environment.

Because production of fish feed raw materials may have significant impacts to the environment, it is important that feed manufacturers and also fish farmers pay special attention to the environmental burdens which arise from different or differently produced raw materials. This is recommended in order to a) advice the producers that it is an important issue for both feed industry and fish farming, and b) have a better understanding of the life cycle environmental impacts of feed and farmed fish, and subsequently be able to give reliable information for instance to the clients.

In the Net loading option, the result is very sensible for the end use of low-valued fish. If LVF is used as raw material of feed for fur animals, it replaces fish (from the Baltic Sea) currently used in fur animal feeding. If this amount of fish needed for fur animal feeding is not caught for other purposes but left in the sea, in this case surprisingly, the net effect would be zero, from the point of view of eutrophication of the Baltic Sea. If the fish is used to produce energy and fertilisers (e.g. in a biogas plant), the environmental benefit, regarding the carbon foot print, would be notable. Regardless of what is the end use of captured fish, paying attention to fuel use efficiency in fishing and, if possible, replacing fossil fuel with non-fossil is sensible.

Offshore option is fairly similar to the Current production model. In addition to the lower eutrophying impact due to the different location, the only difference is the lower fuel consumption in the farming phase per one kg of farmed fish. Accordingly, the potential improvement options are the same as in the case of the Current production model.

In the Baltic Sea feed option, it also is sensible to pay special attention to fuel use efficiency of fishing the feed raw materials. However, this option is fairly new and that is why there is no exact information on the eventual feed composition available. Changes in feed composition may have significant effects on the final LCA results of this option.

LCA is a good method to point out those unit processes or life cycle phases in which most of the environmental burdens arise. However, showing environmental impacts of the total life cycle of a product may hide the environmental benefits achieved in one unit process or production phase, especially if the role of that unit or phase is small in the final LCA results. This may give the actors a wrong signal of the importance of that unit or phase from the point of view of decreasing environmental impacts.

The results call for a general examination of weighing the environmental policy regarding the Baltic Sea and the Scandinavian environment. How should the carbon footprint be weighted in relation to the nutrient emissions causing eutrophication in the Baltic Sea? This kind of examination should include all industrial and primary production branches and the weighting should have wide acceptance by the coastal countries around the Baltic Sea. Otherwise there is a danger of making solutions by unfair means making the achievements of one country empty by the actions in another country.

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