AE 2020 – Online Event April 2021

aquaculture europe

VOL. 46 (1) MARCH 2021

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1st Semester 2021
Afgiftekantoor: 8400 Oostende Mail

Evaluating the environmental and social impacts of selected food supply chains of the VALUMICS project

VALUMICS
Food System Dynamics

THIS ARTICLE HAS BEEN EDITED BY EAS STAFF FROM THE ORIGINAL DELIVERABLE 4.4 OF THE PROJECT, AUTHORED BY VALUMICS PARTNERS **WENHAO CHEN** AND **NICHOLAS M. HOLDEN** (UNIVERSITY COLLEGE DUBLIN), **SHRADDHA MEHTA** AND **MAITRI THAKUR** (SINTEF OCEAN) AND **GUDRUN OLAFSDOTTIR** (UNIVERSITY OF ICELAND).

NOTE: ONLY THE DETAILED RESULTS OF THE SALMON CASE STUDY ARE PRESENTED HERE. HOWEVER, COMPARISONS WITH THE OTHER TWO CASE STUDIES ARE MADE IN THE HOTSPOT ANALYSIS AND THE CONCLUDING COMMENTS.

VALUMICS is using a holistic systematic approach to enhance the resilience, integrity and sustainability of food value chains. Life cycle assessment (LCA) is a widely used method to identify the environmental and social hotspots in food supply chains. Such information can be used to provide strategic and operational advice for managemental strategies and agri-food policies.

Environmental LCA and social LCA are adopted as key tools for sustainability evaluation in the overall project work. The LCA models are highly integrated and trans-disciplinary drawing on the expertise from different backgrounds. **LCA models were developed for the three case studies of the VALUMICS project - butter (representing dairy sector), salmon fillet (representing aquaculture sector) and beef steak (representing animal production sector).**

There have been many studies that consider hotspots for each sector (red meat, dairy, fish) using average data, some that have modelled the complete life cycle of each sector from cradle to grave, but very few that have attempted to model specific supply chains while trying to identify commonality and differences between raw materials (milk, red meat and fish). For this reason, the work focused on specific case studies (butter, salmon fillet and beef steak) for which data were industry sourced and sufficient to reliably model environmental and social impact indicators with similar quality data for the whole system.

The LCA models for VALUMICS case studies used activity data taken from specific spatial resources (as the identified country of origin in selected food supply chain cases) and representing processing unit (e.g. actual data from companies). The investigated environmental impact assessment focused on key impacts governed by EU legislation / policy such as: greenhouse gas emissions (European Climate Change Programme), freshwater eutrophication (Water and Nitrate Framework Directives), acidification (Air Quality Directive, Ammonia regulations). The social impacts focused on quantitative social indicators (Chen and Holden, 2016).

The interpretation focussed on identifying hotspots within the food supply chains. These hotspots are associated with different stakeholders at each stage in the chain. In order to improve the sustainability performance of selected food supply chains, recommendation and future scenarios are provided.

The system boundaries of LCA models in VALUMICS project adopted the 'cradle to grave' approach. It covers off-farm raw materials extraction, primary production on farm, post-harvest storage and distribution, processing at food factory, distribution and retail, consumption and final waste management (e.g., recycle /reuse and disposal).

Figure 1. Example of comprehensive LCA model for agri-food system with 'cradle to grave'

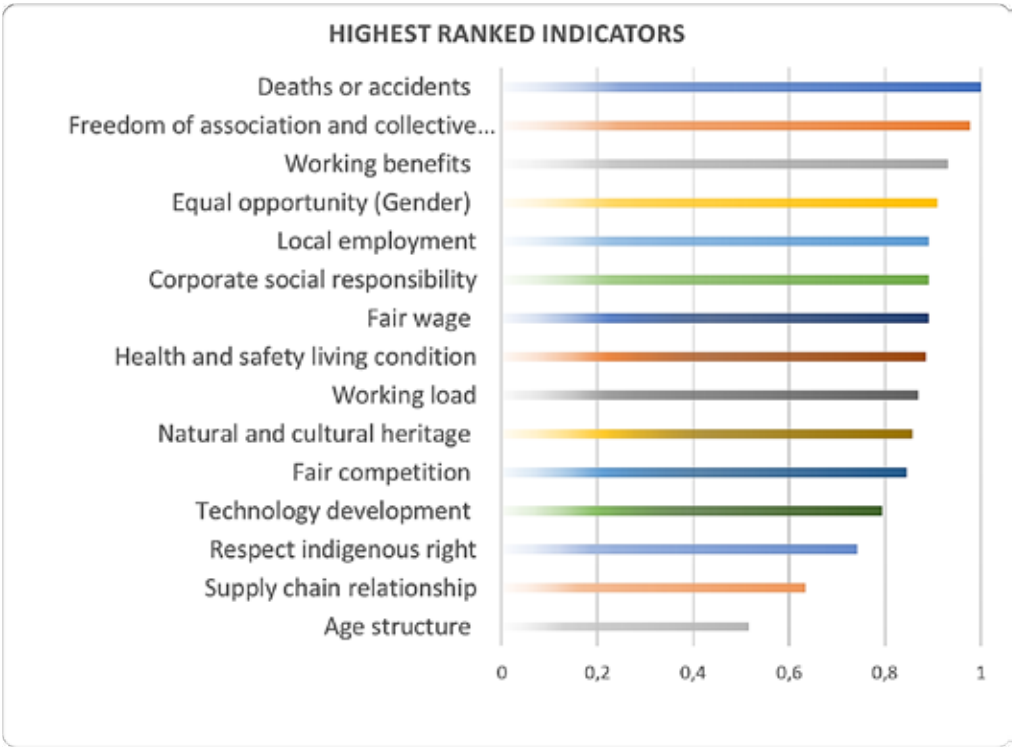
The main processes of selected food supply chains can be grouped into 5 stages: agriculture inputs supply, primary production on farm, processing at factory, distribution and retail, and consumption. The data quality for each stage was defined as follows:

The main processes of selected food supply chains can be grouped into 5 stages: agriculture inputs supply, primary production on farm, processing at factory, distribution and retail, and consumption. The data quality for each stage was defined as follows:

- Agriculture inputs supply: activity data for input materials was refined from national level data, and standard LCA database (e.g., ecoinvent, Agri-footprint) was used as background data.
- Primary production on farm: data for national average farm was refined from central statistical office and used for modelling production on farm in specific food supply chain.
- Processing at factory: first-hand data was collected from survey of representative processing facility in each food supply chain.
- Distribution and retail: representative markets for specific food chain were identified. Route based distribution data to representative markets were collected or estimated. Regional level data for energy consumption and waste generation in retail stage was estimated based on literature or communication.
- Consumption: consumption and waste generation data were estimated according to identified markets. Regional level data of energy consumption and waste generation in consumption stage has been estimated based on literature.

Compared to environmental life cycle assessment, social life cycle assessment (Social LCA) is a relatively new method, and there is no standard methodology for conducting the impact assessment. In this study, the social LCAs focused on the quantitative social impacts of the supply chain. The quantitative social data were derived from the life cycle working environment (LCWE) database. In addition, supplementary data was collected from literature to fill

Figure 2. Social LCA indicators in the order of ranking against a normalised scale.



some data gaps. Field surveys were also conducted at production sites (e.g., processing facilities) to obtain the social information like working hours and male to female employee ratio. After analysing the availability of social data from a whole supply chain perspective, the selected social indicators were working hours, fatal accidents and non-fatal accidents.

For the salmon case study, a survey was conducted to identify and rank the most important social indicators in salmon industry. About 50 respondents including producers, market analysts, researchers and members of branch organizations from Norway completed the survey to rank the indicators in terms of how relevant they are to assess the social impacts of salmon aquaculture. A list of 15 indicators were chosen from the UNEP SETAC guidelines and included in the online survey. The indicators were focused on the stakeholder groups such as workers, employers, consumers and local consumers. According to the survey results, the indicators related to the stakeholder group 'workers' were ranked highest and 'work related fatal and non-fatal accidents' was identified as the most important indicator for social LCA.

(see figure 2 on page 29)

In order to reflect the impacts of transportation systems in different food supply chains, three types of distribution networks were designed for each case studies. The main difference in the distribution networks is the transportation approach from food processing facility to retailers in identified consumer markets.

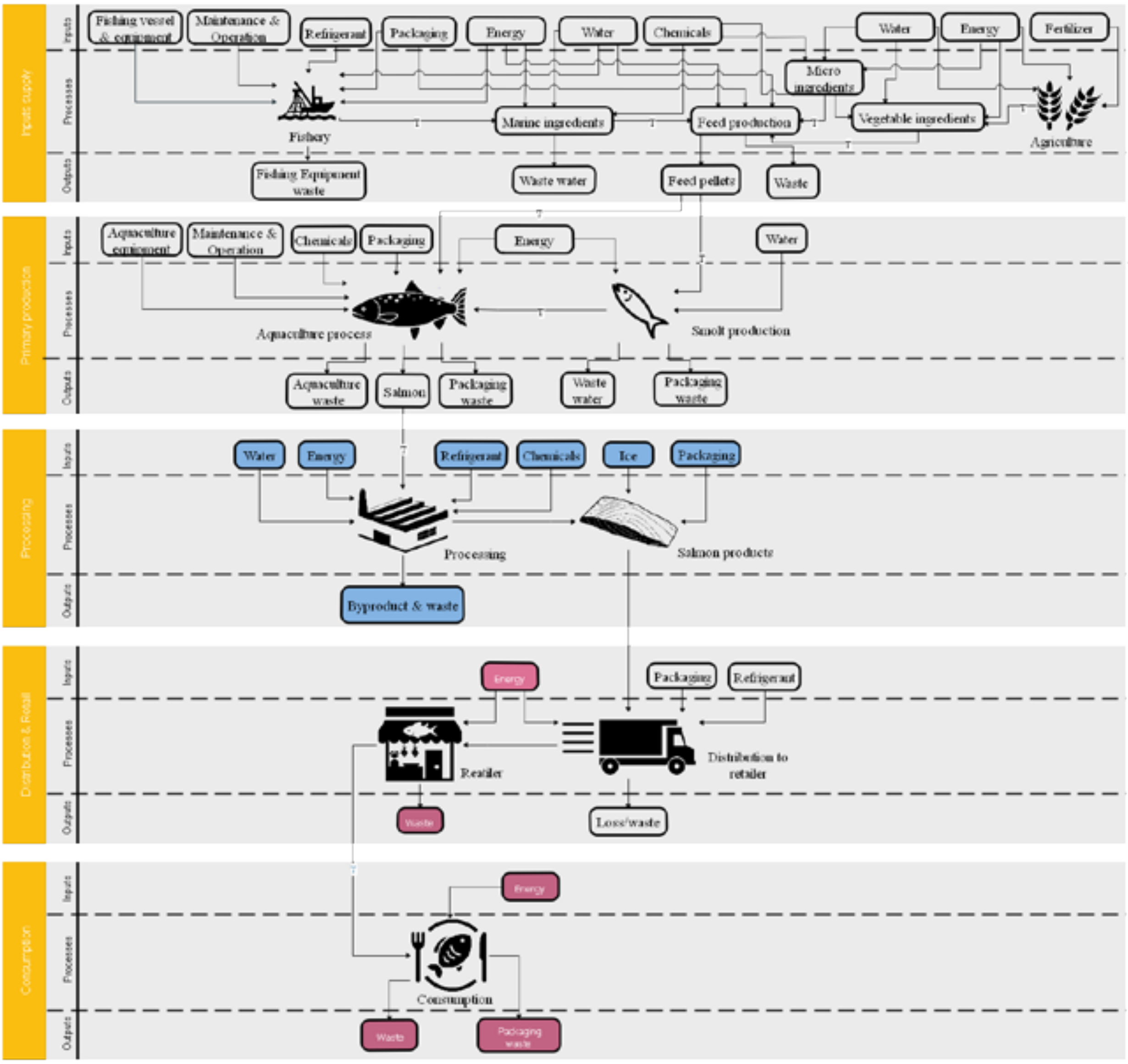
It was assumed that food products are transported mainly by truck, ship and plane to the domestic market, the European market and global markets outside of Europe. Based on data availability (e.g., particular type of food waste at consumption stage) and the market share, one European market and one global market were chosen for each food supply chain.

Therefore, in the VALUMICS study, nine food supply chains were identified, although only the three for the salmon value chain are presented in any detail here.

Farmed Norwegian Salmon

According to the Food and Agricultural Organization of the United Nations (FAO) and World Bank, the global demand for food, especially marine based protein is increasing. Salmon is an important commodity in global seafood market

Figure 3. System boundary of salmon supply chain



and about 70% of the world's salmon production is farmed. Due to the data availability and market share, the salmon supply chain with primary production in Norway was selected as representative of Atlantic salmon products.

The functional unit for LCA models of salmon supply chain is 1 kg of salmon and the system boundary is shown in Figure 3. The boxes without colour represent the processes that use national level data or background data from standard LCA database (e.g., Eco-invent, Gabi database, Agri-footprint database) for LCA modelling. The blue boxes are the processes that required survey data from a processing facility. The red boxes refer to waste in the distribution and consumption stages. The processes involving the different sea lice treatment methods currently used in salmon farming are not considered in this LCA system due to lack of data availability. The processes involving cleaner fish farming and catch are also not included due to lack of data availability and considering that the volume of cleaner fish used for biological lice treatment is significantly lower than the volume of salmon deployed in the net pens. Due to the primary data availability issue, the data for distribution and consumption stage is derived from literature review. The resolution of data requirement from the consumption stage is limited to fish category at national level. The main stages of salmon supply chain in LCA models are feed production, juvenile production and grow-out, (primary and secondary) processing and distribution & consumption.

Feed production

Feed is the main component of primary production on a salmon farm. The composition of salmon feed can be categorized into 5 ingredient types: marine oil, marine protein, vegetable oil, vegetable protein and supplements. Salmon feed has been identified as the hotspot of many environmental impacts in salmon supply chain (Ziegler et al., 2013, Ytrestøyl et al., 2015, Taelman et al., 2013). In order to improve the environmental performance of salmon supply chain, the composition of salmon feed has changed significantly in past decades.

From 1990 to 2012, the share of vegetable ingredients (protein and oil) increased from less than 10% to 67% (Norwegian Seafood Federation, 2013). Although this change reduced some environmental impacts, e.g., greenhouse gas emission, it shifted more environmental burdens to terrestrial ecosystems. In addition, vegetable feed has a positive effect on the FIFO (fish in – fish out) ratio, but it may have an effect on the nutrient content of the salmon. Nutrient balance accounting and resource budget (protein, fat, energy, phosphorous, n-3 fatty acids (EPA, DHA)) are methods that have been used to monitor the retention of nutrients in the farmed fish (Ytrestøyl et al., 2011). Optimizing the feed conversion ratio (FCR: kg feed used/ kg fish produced) has been an important research topic in salmon industry.

To model the feed production, the national average data was refined from previous surveys and references. The marine and vegetable ingredients account around 31% and 66%, respectively. The remaining 3% is from supplements. The main components of LCA model for salmon feed are marine oil and protein, vegetable oil, protein and starch, and some micro ingredients. For marine component part, in addition to the main ingredients (e.g., anchoveta, herring, soybean), the other ingredients (e.g., sprat, capelin, wheat gluten) with minor share of feed composite were also modelled in sub-model of feed. The origin for these ingredients is global, including South America, Asia and Europe.

Juvenile and grow-out

The primary salmon farming has two main stages: the juvenile stage (smolt production) in freshwater in a land-based hatchery and grow out stage in sea cages. The total freshwater production cycle takes approximately 10-16 months and the total seawater production approximately 14-24 months, hence a total cycle of 24-40 months (Marine Harvest, 2017). A suitable feeding strategy not only influences the operation cost and productivity, but also has a significant impact on environmental performance (e.g., climate change, eutrophication) of salmon farming. Hence feeding operations are carefully monitored. Furthermore, governmental monitoring and legal requirements ensure that aquaculture farms report occurrences of sea lice, escapees, the use of medication and water quality and sediment in the areas close to the farms. There is an increasing awareness that monitoring data should be accessible in the public domain to enhance the transparency and help building an image of responsibility for the sector.

Compared to the feed component, the juvenile and grow-out production phase is more straightforward. Apart from the feed, the main inputs for this stage are energy (electricity and diesel) and chemical consumption at the production plant. The material for aquaculture equipment, maintenance and packaging was also included. The waste management scenario (e.g., recycling) for the inputs material was applied and the ratio was based on LCA report by Nofir (https://nofir.no/lca/). Mass allocation was adopted to allocate the impact for the final salmon products, taking into account mortalities.

Processing

The processing data for LCA modelling was taken from a salmon processing plant in the western part of Norway. The product of the processing plant is whole gutted salmon. The by-products and residue from this facility include blood and guts. The ratio of main product (82%), by-product (10%) and residue (3%), and weight loss (5%) as a result of starvation before slaughter was taken from a deliverable report of EU FP7 project SENSE (Ingolfsdottir et al., 2013).

The main inputs of salmon processing unit are electricity for processing machine, detergent and disinfectant for washing and cleaning, and packaging material. All the input data was derived from a factory survey. The chemicals used for washing and cleaning were grouped into three categories for LCA modelling. Alkylbenzene sulfonate was used as detergent. Sodium hypochlorite (NaOCl) was assumed to represent disinfectant. The remaining cleaning chemicals were assumed to be soap. Synthetic rubber was used as the main material for disposable caps and gloves.

Packaging materials include EPS boxes, corrugated board boxes and aluminium and plastic film. Mass allocation was adopted to allocate the impacts between main product (salmon for human consumption) and by-product (guts for marine feed). According to Ziegler et al. (2013), different weighting factor was adopted for food and feed part. The food weighting factor of food is 1 and weighting factor of feed is 0.5. The allocation factor was calculated based on the weighting factor for food and feed as follows: Allocation factor for feed =0.5*(Massfeed / (Massfeed + Massfood)). Allocation factor for food= 1- Allocation feed.

Distribution and consumption

To reflect the effect of different transportation networks on entire food supply chains, domestic, European and International markets were identified. The main criterion of choosing an end market was availability of consumption data. Since the LCA model includes consumption stage, the waste generation from end consumer could influence the total impact in a significant way. Based on the available data, the resolution of food waste at consumption is fish category at specific countries. Depending on the secondary data availability for different countries, the main market for Norwegian salmon was selected. To avoid duplication, end markets for all three case studies were selected.

For salmon, the identified domestic, European and International markets are Norway, Denmark and China respectively. Salmon waste from consumption stage for all markets are shown in Table 1 below. For the food waste at retail stage and in supermarkets, this study adopted the average value for fish waste in supermarket (5%) (Xue et al., 2017).

Distribution networks for Norwegian salmon to each end market are shown in Figure 4. The distance of road transport was estimated from Google Maps, the distance on sea and air transport was estimated from Port website (http://ports.com/) and Distance website (https://www.distance.to/), respectively.

Results and hotspot analysis

The environmental and social impacts of the main stages in Norwegian salmon supply chain are shown in Figure 5 below. As can be seen, the salmon supply chain to China has biggest total values for most environmental and social indicators, influenced in a significant way by air transport.

Comparing the salmon supply chain with other distribution networks, the impact contribution of air transport can greatly increase the value of fossil fuel based abiotic depletion, global warming, ozone layer depletion, human toxicity, photochemical oxidation and acidification. Aviation fuel accounts more than 69% of total GHG emissions from cradle to retailer gate.

Comparing the environmental performance of salmon supply chains in Norway and Denmark, the results indicate that most of the environmental impacts in Norway are more significant than the impacts in Denmark. The on-road transport (truck) is responsible for the greater environmental impacts in domestic salmon supply chain. Although the transport distance to Denmark is longer, lower environmental impacts per functional unit in sea transport reduced the total adverse effect of distribution network.

For the social impacts, the values of all three indicators did not have significant variation in each distribution network. The working hours, fatal accident and non-fatal accident in air transport have the greatest value. Although air traffic is fastest and safest, capacity is limited, especially compared to container ships. In this LCA model, the social information was derived from life cycle working environment (LCWE) database in Gabi software. The capacity of container ship and aircraft in LCWE database is 27,500 ton and 65 ton, respectively. The greater transport capacity of ships significantly reduces the working time and accident rate per ton of product transported per kilometre. All three social indicators in sea transport distribution network have the lowest impact value.

The Figures 6a, b and c suggest that the main impacts of salmon supply chain are from aquaculture production of which feed production is the biggest contributor. In domestic and Danish supply chains, live salmon production on farm accounts for 80%-88% of total environmental and social impacts. This suggests that managing the environmental and social impacts of aquaculture is critical for sustainability of salmon supply chains. For the supply chains in Norway and Denmark, the impact contribution from each main supply chain stage has a similar pattern. In the supply chain to China, the impact contribution of aquaculture stage has a wide variation. It has lowest impact contribution on abiotic depletion (fossil fuels) (16%) and highest impact contribution on terrestrial ecotoxicity and fatal injuries (87%)

Table 1. Salmon waste at consumption stage

End market location	Waste from consumption	Reference
Norway	7%	Gjerris and Gaiani (2013) Xue et al. (2017)
Denmark	7%	Xue et al. (2017)
China	7%	Song et al. (2015)

Figure 4. Distribution systems for Norwegian salmon supply chain

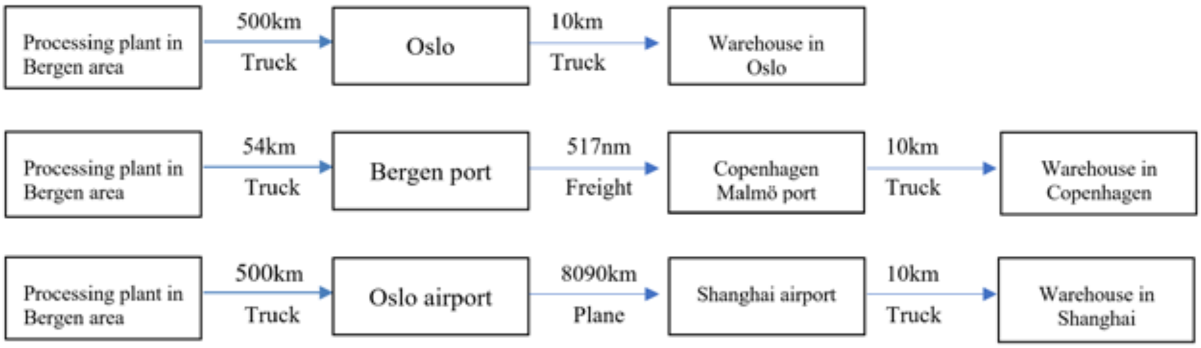


Figure 5. Impact contribution for the salmon supply chain to various countries

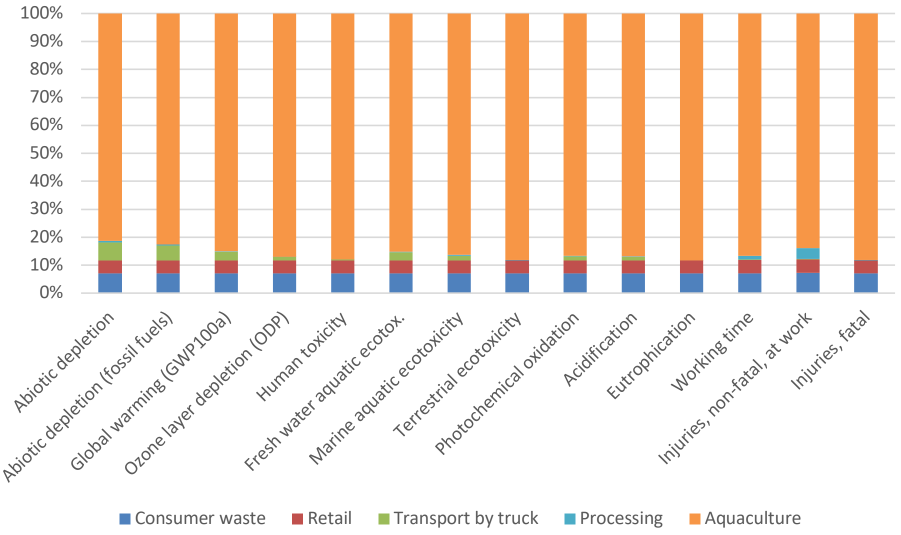


Figure 5a. Impact contribution for salmon supply chain in Norway

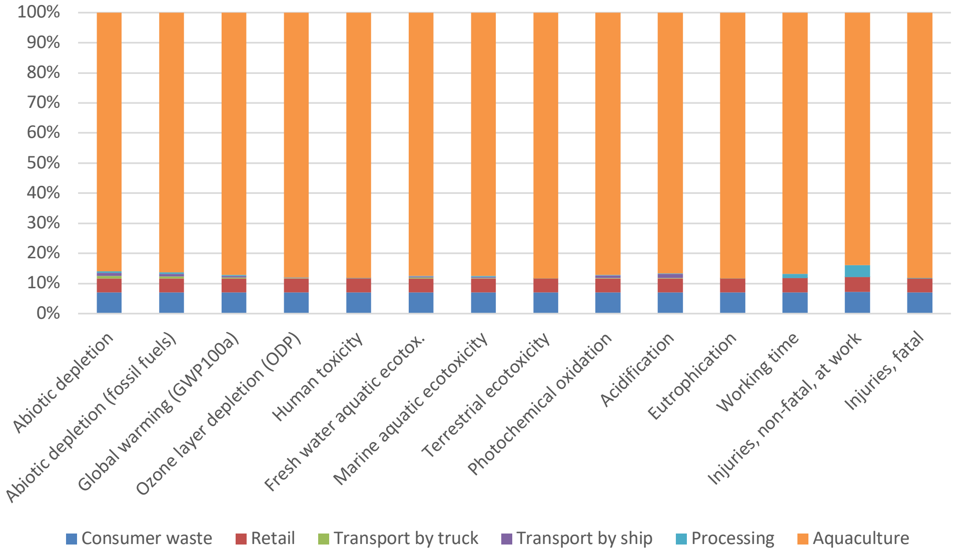


Figure 5b. Impact contribution for salmon supply chain to Denmark

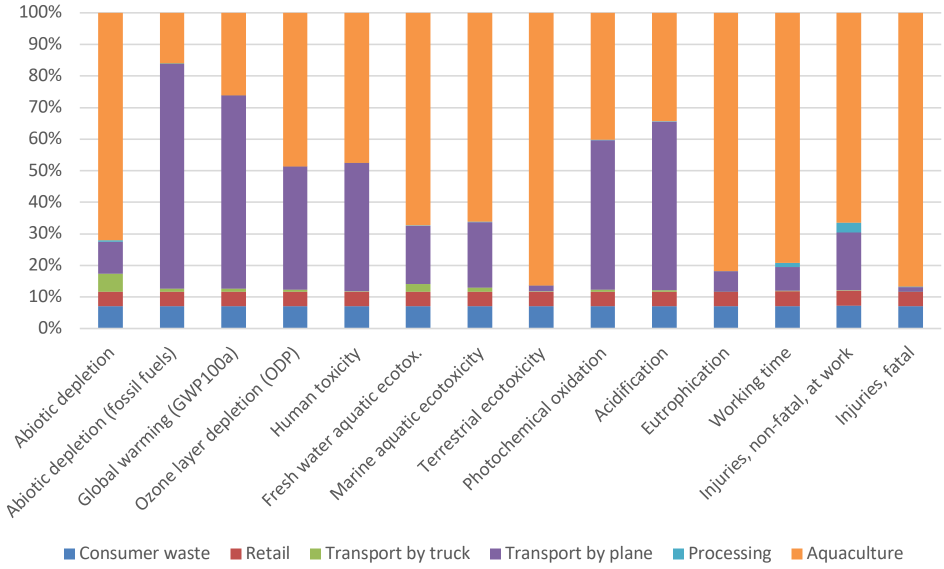


Figure 5c. Impact contribution for salmon supply chain to China

Hotspot analysis

Based on the results of each case study of this VALUMICS deliverable, two general conclusions can be drawn:

1. The destination market and thus the transport system has the potential to significantly influence the environmental and social impacts of food supply chains.
2. Primary production on farm is a common hotspot.

The transport distance and approach are the key factors affecting total impacts. Air transport is a critical part of the global supply chain as it can bridge demand and supply in an efficient way. This rapid distribution network is very important for food commodities since they often have a short shelf-life. However, air transport creates significant impacts, especially environmental ones.

In order to minimize the impacts of long-distance transport, other transport approaches (e.g., sea transport) can be adopted. However, sea transport takes longer and would require a freezing process, which would affect the economic characteristic (e.g., selling price) and relevant consumer preferences. Therefore, air transport is the only viable approach for some food supply chains, which have high demand of freshness. The best possible method to lower the environmental impacts of air transport would be sustainable aviation fuel since the main contribution of environmental impacts comes from the production and consumption of conventional aviation fuel. Conventional aviation fuel is derived from fossil fuels, hence replacing conventional aviation fuel with sustainable fuel offers a great chance to reduce the air transport associated environmental impacts (Pierobon et al., 2018). Most airlines are moving in this direction.

The management of environmental and social impacts of on-farm production is critical to overall sustainability performance of food supply chains. In order to identify the sustainability hotspots of on-farm production, contribution analysis was performed, and Figure 6 shows the contribution of the main stages of on-farm production.

On the salmon farm, feed production accounts for a dominating part in almost all environmental indicators, except marine aquatic ecotoxicity and eutrophication. In beef and dairy farms, feed production is the main contributor to terrestrial ecotoxicity. Feed production also has significant share in the impact of freshwater aquatic ecotoxicity in both farms and the effect of feed in dairy farm is more notable. In contrast, the influence of feed on eutrophication in beef farms is higher than in dairy farms. In the latter, eutrophication is mainly caused by fertilizer. The reason is that dairy farms use more fertilizer to grow the on-farm grass as silage feed. In addition, feed production also leads to a notable share in environmental impacts of abiotic depletion (both fossil fuel and non-fossil fuel), global warming, ozone depletion, human toxicity marine aquatic ecotoxicity and acidification. For non-fatal injury, the contribution of feed production in beef farm is more significant. This is due to higher off-farm feed consumption in beef farms.

In salmon farms, on-farm emissions dominate the impact of marine aquatic ecotoxicity, eutrophication, working hours, non-fatal injury and fatal injury. Smolt production has big contribution on some impacts, especially on abiotic depletion (9.3%), photochemical oxidation (6.3%) and non-fatal injury (17%). The energy consumption and transport process at farming stage had very small contribution for all indicators. The most important contributions are for biotic depletion (fossil fuels) and acidification, which accounts for 4-6% of total impact.

Based on the results from the salmon farm, the salmon feed production is the key hotspot of most of the environmental impacts. Some feed ingredients (e.g. soy protein) have significant environmental impacts and replacing them with lower impact ingredients can significantly improve the sustainability performance of salmon (Rustad, 2016). Currently, the most popular innovative ingredients for salmon feed are insect meal (Popoff et al., 2017, Belghit et al., 2018) and single cell protein from microalgae (Sørensen et al., 2016). Although these alternatives can potentially improve the sustainability of salmon feed, the production of these ingredients needs to be optimised and some challenges still need to be solved before commercial application. Better food and safety regulation for the use of these alternatives in salmon feed also needs to be developed and public acceptance could also be an issue for further development of alternative ingredients for salmon feed (Popoff et al., 2017).

Finally, productivity needs to be further improved to reduce production cost (Govaerts, 2018).

The main social hotspot is on-farm operation. Health and safety issues are mainly caused by musculoskeletal problems and occupational accidents, which can lead to work-related sick leave and health issues. However, the salmon industry is moving towards increased automation of operation and maintenance activities with the use of automated feeding and video monitoring. Automated operations can reduce work-related risks to health and safety of workers. Salmon feed and on-farm operation together account for more than 90% of total impacts for all indicators.

continued on page 36

Figure 6. Impact contribution for salmon, dairy and beef.

Figure 6a. Impact contribution from the salmon food chain

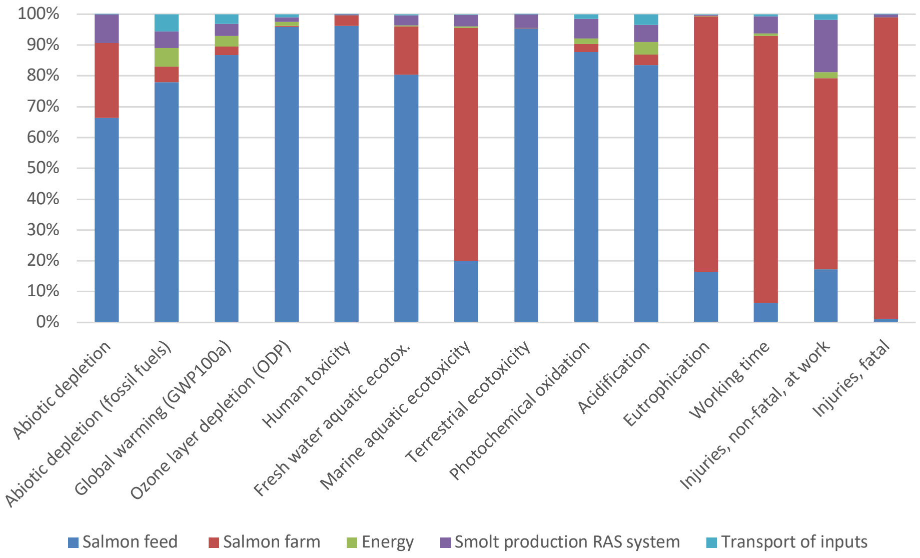


Figure 6b. Impact contribution from the butter (dairy) food chain

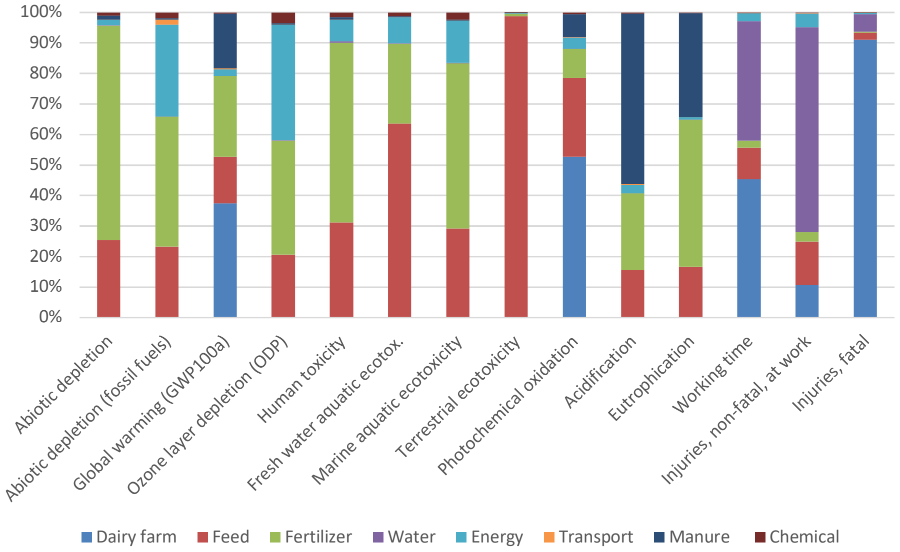
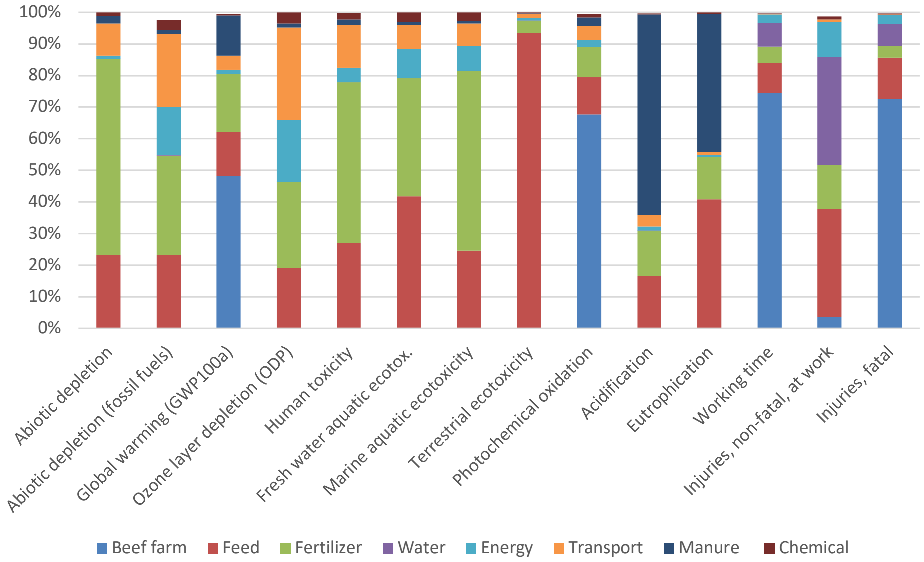


Figure 6c. Impact contribution from the beef fillet food chain



In dairy and beef farms, on-farm emissions had significant share in global warming, photochemical oxidation, working hours and fatal injury. The water supply has more significant influence on working hours and non- fatal injury in the dairy farm compared to the beef farm. Fertilizer production was also responsible for a big share in many environmental impacts, especially abiotic depletion (fossil fuels & non- fossil fuels), human toxicity and marine aquatic ecotoxicity. The impact contribution of fertilizer in dairy is more significant in beef. This suggested that more fertilizer was used for on-farm silage production. The greater fertilizer application also demands more energy input for on-farm practice, for example the diesel consumption for fertilizer spreading. Therefore, the energy consumption in dairy farm had a bigger share in impact contribution. The main impact of energy consumption is for indicator of abiotic depletion (fossil fuels) and ozone layer depletion.

Transport in dairy contributed a very small share in all impact indicators, however, the impact in beef was more significant – and mainly caused by the greater amount of off-farm feed. The manure management in dairy and beef farm had very significant contribution in acidification (56%-63%), eutrophication (34%-44%) and global warming (13%-18%). The main emission for these impacts includes NH3 and nitrate leaching from manure storage and field excretion. Similar findings were identified in previous studies (Chen and Holden, 2018a, Yan et al., 2013b, O'Brien et al., 2012).

For dairy and beef farms, different processes in farm production can influence different impact indicators in a significant way. Improving the safety measures in farming practise can greatly reduce fatal accidents in both farms. Using automatic farming system would reduce the working time, and therefore increase production efficiency (Chen and Holden, 2016). The GHG emission from enteric fermentation also account for a big part of the total GHG emission of milk production. However, this emission depends on biological characteristics of cattle and it is hard to improve through farm management. Dairy farm production consumes great amount of freshwater, more efficient water management can reduce the working time and non-fatal accident rate in upstream of the milk production chain. The best possible options for improving the environmental impacts of dairy and beef farm are feed composition, fertilizer application and manure management.

The hotspots identified in this VALUMICS study confirm results from previous studies. For the salmon supply chain, feed was the main environmental hotspot in different salmon production systems in world (Ziegler et al., 2016, Pelletier et al., 2009). The composition of salmon feed can greatly influence the emission intensity of salmon feed. Ziegler et al. (2013) also found that air transport in salmon supply chain accounts a significant share of GHG emission. The GHG emission of airfreight to Tokyo is almost 3.8 times the GHG emission from aquaculture, which is greater than the result in this study (2.4 times). The main reason for this difference is the greater GHG emission per kg of salmon feed used and the shorter transport distance in this study. In butter and beef supply chains, previous studies found primary production on farm is the main contributor to most of impacts (Flysjö, 2011, Flysjö et al., 2014, Wiedemann et al., 2015, de Vries et al., 2015). The impacts of farm production and total supply chain impacts in this study are within the range of impact values in previous studies. Enteric fermentation is the main contributor to GHG emission in both dairy and beef farms. In this study, the share of enteric fermentation in beef farm (57%) is more significant than the previous studies (around 50%) (Foley et al., 2011). The lower beef productivity and higher feed consumption is the main reason for this difference. For GHG emission on dairy farm, the share of enteric fermentation in this study (42%) is close to previous findings (45%). The shares of GHG emission from other processes in farm follow the similar trends in previous findings (O'Brien et al., 2012).

Going forward...

Significant research and innovation are currently targeted at alternative feed ingredients. Among those alternatives, most initial options were developed to save energy and cost, and ingredients were normally derived from conventional feed crops or vegetation (Yan et al., 2013a, Yorks et al., 1980).

Insect and microalgae protein are increasingly positioned as innovative alternatives for feed ingredients (e.g. Belghit et al., 2018) and they potentially provide greater environmental benefits, especially on climate change. Rustad (2016) found the GHG emission per kg salmon meal produced from the black soldier fly was 0.5 kg (including indirect impacts), which is only around 20% of GHG intensity of salmon feed used in this study. For cattle farming system, insect and microalgae derived protein is still used as feed supplement, not to replace feed in a significant way (Taelman et al., 2015, Donkin et al., 2003). Although the new feed ingredients may have much better environmental performance, their impacts on entire supply chains have not been comprehensively investigated. There are some uncertainties in production performance. For example, how these new feeds affect the growth, mortality and filet yield of salmon. In the dairy system, it is also not clear that whether the new feed has any effect on milk quality, especially the fat and protein content in raw milk. These production parameters can influence the environmental and social impacts of food supply chain, hence more production data is required to evaluate the real impacts of innovative feed in food supply chains.

According to Springmann et al. (2018a), dietary changes (and food choices) could have significant effects on environmental impacts of global food supply chains, especially the regional demand for fish and meat. In high-income countries, Springmann et al. (2018b) found a trend of replacing animal-source food with plant-based ones to improve nutrient level and have a healthier diet. Among European countries, the individual meat consumption decreased from 2010 to 2020, while the demand of salmon keeps increasing (Statista). However, the resolution of projected demands in these studies still needs to be improved. There is no detailed estimation of particular types of food in specific countries. Concerning meat demand, although there is a trend of replacing meat with fish in developed countries, the rapidly increasing meat demand from developing countries may not only affect the local food industries, but also the meat producers in developed countries, for instance, the Irish beef producer in this study. Therefore, a detailed projection for global and regional food demand is required for future scenarios of dietary changes. In addition, to investigate the effect of dietary changes on sustainability performance of food supply chain, it is necessary to understand whether the material and energy inputs, infrastructure facility and emission will linearly change with projected outputs. The changes of input use efficiency and food productivity are the key elements for sustainability of food supply chains.

The evolution of food waste at consumption, processing and distribution losses is also an important future scenario for sustainability improvement. Based on the results in this study, the food waste and loss accounts at least 1%-13% of environmental and social impacts of entire food supply chains. It is found that there is not enough detailed information for particular types of food waste, especially in household consumption. More comprehensive food waste database needs to be developed to evaluate the effect of food waste on specific food supply chain.

The energy system within food supply chains could also be an improvement option in the future. Currently, most of the fuel and electricity in food supply chains is derived from fossil fuels. Replacing diesel with biofuel and using electricity from renewable source can effectively reduce the environmental and social impacts of food supply chains, especially for the supply chains that use air freight. Sustainable aviation fuel can save up to 80% of GHG emission of conventional aviation fuel (Pierobon et al., 2018, de Jong et al., 2017). In addition, sustainable biofuel also has potential to improve the social impact of aviation fuel supply chain (Wang et al., 2018). Apart from the energy system in air transport, substituting the air transport with sea or on-road transport also contributes to improve sustainability of food supply chain. If the transport time is not considered, the main issue for sea or on-road transport system is how to keep food as much fresh as possible. For some food products, frozen food may have less favourable position in market. Therefore, a better cold chain system for sea or on-road transport needs to be designed. According to a pilot study by DNV-GL in 2018, by replacing 30% of the current volume of transport by road to sea will reduce carbon emissions from transport of fresh salmon from Norway to the continent by 70%. The sea route suggested by the study takes up to 2 days more than the land route and therefore a new refrigeration technology called super chilling is suggested to extend the shelf life of the fish during sea transport. The scenarios analysed in the study also show that the cost of transporting fish by sea will be reduced by 20-30% due to the reduced costs of conventional chilling of fish.

For cattle farming system, better manure management (especially in housing stage) and fertilizer application can also effectively contribute to reduce the GHG emission and eutrophication of food supply chain. These two processes are responsible for considerable emission of NH_3, N2O, CH4 and nitrate leaching on farm. In order to assess the sustainability improvement of better manure management and fertilizer application, more data about change of operation and extra inputs and equipment is required.

This LCA and Social-LCA report adopted a holistic approach to evaluate the environmental and social impacts of the selected case studies. Across all three, novel feed ingredients, sustainable aviation fuel and reduction of wasted food can effectively reduce the GHG emission (and other impacts), and the combined approach with three options could decrease GHG emission by 15% to 82% depending on raw material, product type, market and transport. These externalities are not currently priced in the market for these materials and products and have little impact on consumer choice compared to type of product (e.g., meat vs. vegetable).

The future potential to improve the environmental and social sustainability performance of selected food supply chains has been identified in this task. However, data limitations limited a more comprehensive study. As more data is collected for on-farm production processes, food processing, distribution and consumption in the "precision farming" approach, the path towards sustainability can be more accurately measured.

VALUMICS has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727243.

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