Life Cycle Assessment of Recirculating Aquaculture Systems: A case of Atlantic salmon farming in China

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Abstract

Recirculating aquaculture systems (RAS) is an alternative technology to tackle the major environmental challenges associated with conventional cage culture systems. In order to systematically assess the environmental performance of RAS farming, it is important to take the whole life cycle into account so as to avoid ad-hoc and suboptimal environmental measures. So far, the application of life cycle assessment (LCA) in aquaculture, especially to indoor RAS, is still in progress. This study reported on an LCA of Atlantic salmon harvested at an indoor RAS farm in northern China. Results showed that 1 tonne live-weight salmon production required 7509 kWh farm-level electricity, and generated 16.7 tonnes of CO_2 equivalent (eq), 106 kg of SO_2 eq, 2.4 kg of P eq, and 108 kg of N eq (cradle-to-farm gate). In particular, farm-level electricity use and feed product were identified as primary contributors to eight of nine impact categories assessed (ranging 54-95% in total), except the potential marine eutrophication impact (dominated by the grow-out effluents). Among feed ingredients (on a dry-weight basis), chicken meal (5%) and krill meal (8%) dominated six and three, respectively, of the nine impact categories. Suggested environmental improvement measures for this indoor RAS farm included optimization of stocking density, feeding management, grow-out effluent treatment, substitution of feed ingredients, and selection of electricity generation sources. In a generic context, this study can contribute to a better understanding of the life cycle environmental impacts of land-based salmon RAS operations, as well as science-based communication among stakeholders on more eco-friendly farmed salmon.

KEYWORDS

Atlantic salmon, feed production, indoor aquaculture, industrial ecology, life cycle assessment (LCA), recirculating aquaculture systems

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1. INTRODUCTION

Development of a sustainable aquaculture industry plays a key role in meeting global food and nutrition security (HLPE 2014). Aquaculture is the world's fastest growing food production sector, which is projected to supply over 60% of fish for direct human consumption by 2030 (World Bank 2013). Among the main groups of species in world trade, salmon and trout became the largest single commodity by value in 2013, and demand is growing steadily, especially for farmed Atlantic salmon (FAO 2016). At present, farmed Atlantic salmon (*Salmo salar*) accounts for around 60% of the world's salmon production (Pawlowski et al. 2016). The current commercial-scale salmon grow-out takes place mostly in cage aquaculture, though salmon smolts have been produced on land (Bergheim et al. 2009). Despite measures taken to alleviate environmental impacts of the traditional open net-cage salmon farming, significant problems and constraints in relation to parasites (sea lice), diseases and the escape of fish have proved difficult to overcome (Lekang et al. 2016).

Recent efforts to tackle the challenges faced by open-net-cage aquaculture have been shifted to the development of mitigation measures and alternative farming methods, such as closed-containment systems. In particular, the intensive land-based recirculating aquaculture systems (RAS) technology is regarded as having considerable growth potential (Dalsgaard et al. 2013). According to Ebeling and Timmons (2012), indoor aquaculture is probably the only potential method to ensure a relatively high level of seafood safety. In the case of post-smolt Atlantic salmon farming to marketable size, there are currently only a few land-based RAS in operation, mainly located in Denmark, China, and Canada (Iversen et al. 2013).

The environmental impacts of the entire seafood value chain have been a high-priority issue for the pursuit of sustainable aquaculture development. In order to assess the environmental impacts of RAS farming in a systems perspective, it is important to take into account the whole fish supply chain, beyond the traditional focus of environmental engineering and risk assessment at farm site. Understanding the life cycle impacts associated with expanding and intensifying aquaculture is also crucial for designing responsible aquaculture systems (Diana et al. 2013). This has therefore resulted in a growing interest in employing life cycle thinking-based methodology to assess the overall environmental impacts of seafood production systems.

Life cycle assessment (LCA) is an internationally standardized method for addressing the environmental aspects and potential environmental impacts throughout a product's life cycle (ISO 2006). Although LCA has been widely used in the food industry (Sonesson et al. 2010), the application of LCA in aquaculture began in the mid-2000s. The first published aquaculture LCA study (Papatryphon et al. 2004) focuses on environmental impact assessment of the entire life cycle of salmonid feeds with different ingredient compositions. In recent years, LCA has proven to be a valuable tool for assessing the potential environmental impacts of aquaculture production systems and informing certification and eco-labelling criteria for the seafood sector (Cao et al. 2013). The application of LCA to seafood supply chains has demonstrated some previously unassessed environmental impacts of fisheries and aquaculture, leading to new insights into the environmental impacts of seafood products, such as those related to greenhouse gases, toxic emissions, eutrophication, and land use (Ziegler et al. 2016).

The application of LCA in salmonid RAS is still in progress. In the past decade, only a number of LCA studies on salmonid aquaculture systems were published, with varying goals and scopes (see Table S1 in the Supporting Information available on the Web). For instance, Ayer and Tyedmers (2009) conducted an LCA of four salmonid culture systems in Canada (i.e., Atlantic salmon farmed in marine open net, marine floating bag and land-based flow-through systems, as well as Arctic char in land-based recirculating system), and they emphasized the need for further assessment of the environmental impacts of material and energy requirements of closed-containment aquaculture. McGrath et al. (2015) carried out an LCA of a floating tank, flow-through and solid-walled system for Chinook salmon farming in Canada, and presented the primary contributions from feed provisioning and on-site energy use. Liu et al. (2016) compared an open net pen system in Norway with a hypothetical land-based RAS in the US for producing Atlantic salmon, focusing on economic performance and carbon footprint. Due to few published LCA studies on recirculating salmonid fish farming, it becomes difficult to systematically assess the environmental impacts of salmon farmed in RAS, as well as to benchmark the materials and energy requirements of RAS with other salmon farming methods.

So far, there has been no published LCA of indoor salmon RAS farming, based on actual operations at commercial scale. While some salmonid aquaculture LCA publications include the farm-level energy use, few of them give a breakdown of the total electricity use at the most important sub-process level. As emphasized in a recent review of LCA on aquaculture systems by Bohnes and Laurent (2018), one future need of aquaculture LCAs is to construct aquaculture life cycle inventory databases with a special need for developing countries.

This paper presented the results of life cycle inventory and life cycle impacts of Atlantic salmon (*Salmo salar*) harvested in a commercial scale indoor RAS farm in northern China. In a generic context, results of this study can contribute to an improved understanding of the life cycle environmental impacts of salmon produced in land-based RAS and science-based communication among stakeholders on more eco-friendly farmed salmon.

2. METHODOLOGY AND DATA SOURCES

2.1 Life cycle assessment

2.1.1 Goal and scope definition

The goal of the present LCA study was twofold: first, to assess the potential environmental impacts associated with the Atlantic salmon RAS farming system under study (for details of the RAS farm and feed formulations, see Table S2 in the Supporting Information available on the Web), and then to identify environmental hotspots of the whole fish production chain. The functional unit of this study was one tonne harvest-ready live-weight Atlantic salmon at the grow-out farm. The system boundaries were from cradle to farm gate, beginning with resource extraction and ending with harvest-ready salmon at the grow-out farm gate (Figure 1).

Both foreground (feed manufacturing, hatchery & smolt rearing, and salmon grow-out) and background (e.g. energy generation, manufacturing, and feed ingredients production) processes were included. Due to data limitation, three inventory parameters of the smolt hatchery & rearing and feed manufacturing plants were not considered in this study, including infrastructure, on-site wastes and emissions, and transport of raw feed ingredients to the feed manufacturing plant. Among farm-level emissions, only nutrient emissions from the grow-out farm to the receiving water were considered.

This study assessed nine impact categories, including climate change (kg CO_2 eq), terrestrial acidification (kg SO_2 eq), freshwater eutrophication (kg P eq), marine eutrophication (kg N eq), human toxicity (kg 1.4 DB (dichlorobenzene) eq), terrestrial ecotoxicity (kg 1.4 DB eq), freshwater ecotoxicity (kg 1.4 DB eq), marine ecotoxicity (kg 1.4 DB eq), and cumulative energy demand (MJ). As summarized in a review of published aquaculture LCA studies (Henriksson et al. 2012), global warming potential, acidification, and eutrophication are identified as three most frequently addressed impact categories in aquaculture and seafood LCA studies, followed by twelve less adopted impact categories (e.g. energy use, biotic resource use, human toxicity, and ecotoxicity). From an LCA perspective, the “human toxicity” and “terrestrial/marine/freshwater ecotoxicity” indicators reflect the potential impacts of a system on human health and ecosystem, rather than indicating the actual safety levels of products (Notarnicola et al. 2017).

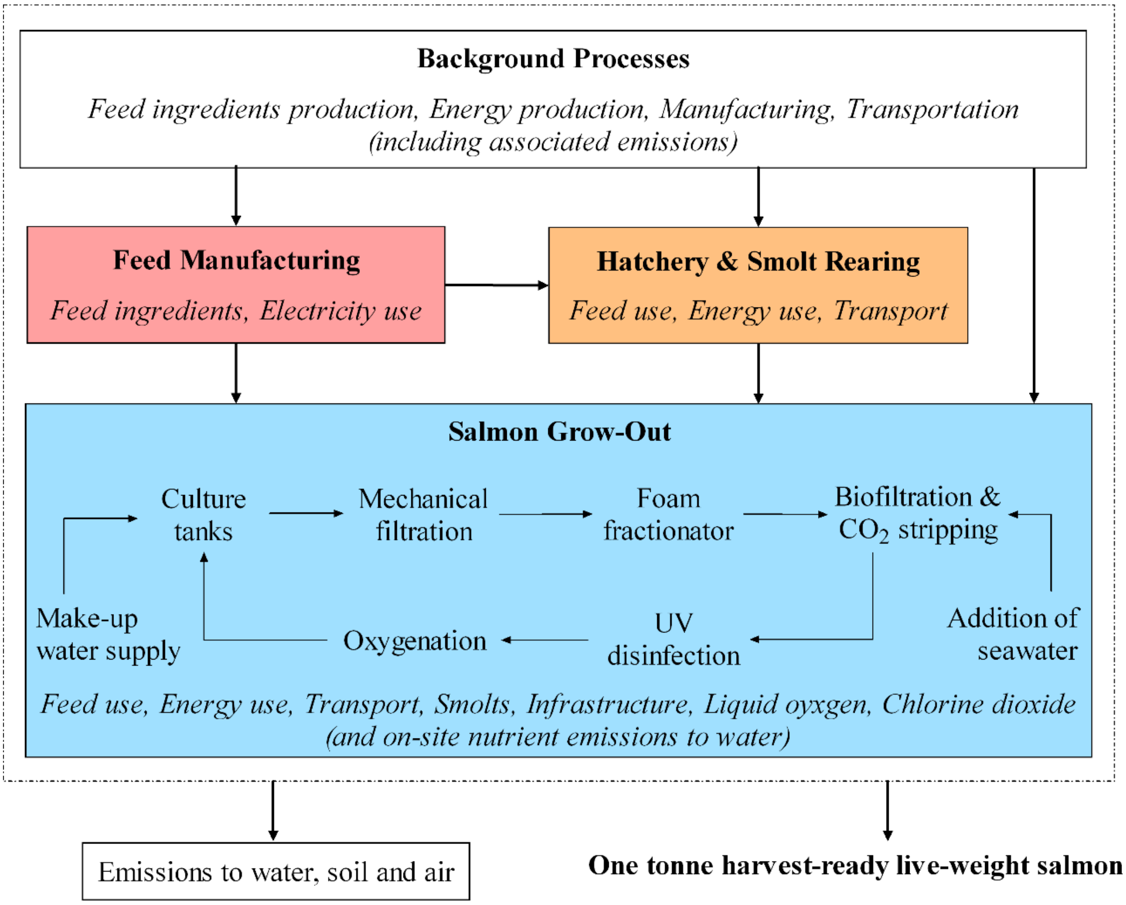

Figure 1 System boundaries for the cradle-to-farm gate LCA of the Atlantic salmon RAS farming

2.1.2 Life cycle inventory

The LCI phase involves the collection and compilation of all relevant input- and output-data of a defined system. The foreground (on-farm) material and energy use data came from the production data of the feed manufacturing plant, the hatchery & smolt rearing facility, and the salmon grow-out farm. In specific, the LCI data of the hatchery & smolt rearing and feed manufacturing plants referred to their respective annual average production in 2015. The total and breakdown of electricity use at the hatchery & smolt rearing and salmon grow-out farms were calculated based on the power rating and operational time of all equipment during the period under study. The LCI data of the salmon grow-out farm was based on a full grow-out period (15 months during December 2014 - February 2016), with a total production of 145 tonnes of live-weight salmon. During this grow-out period, twelve closed-containment systems (each having four rearing tanks and a total rearing volume of 500 m^3) were operated in parallel.

Background data were taken from extensive LCI databases within SimaPro 8.3 software (see Table S3 in the Supporting Information available on the Web). Since the LCI databases in SimaPro contain only a few ready-to-use processes of feed ingredients, assumptions were made for missing feed ingredient production processes, as listed in Table S4 in the Supporting Information available on the Web.

On-site nutrient emissions from the salmon grow-out farm to water were estimated by means of a nutrient budget modeling approach (Aubin et al. 2006). In specific, the phosphorous (P) and nitrogen (N) emissions were calculated based on nutrient balance analysis data from the grow-out farm studied. The solid form of P & N in grow-out effluents referred to the respective nutrient in solid fish wastes collected from the mechanical filtration process. The dissolved P & N referred to the respective nutrient in sludge discharged from the biofiltration process. At the time of this study, both the collected solid fish wastes and sludge were discharged into the adjunct sea. Further information on farm-level P & N emissions to receiving water was provided in Table S5 in the Supporting Information available on the Web.

2.1.3 life cycle impact assessment

Life cycle impact assessment was performed using two LCIA methods available in the SimaPro v8.3 software, i.e. Cumulative Energy Demand v1.09 and ReCiPe v1.13. The Cumulative Energy Demand (CED) method aims to quantify the total ("cumulative") energy demand throughout the cradle-to-farm-gate Atlantic salmon production system. The ReCiPe method is the outcome of alignment between the midpoint-oriented CML 2002 method and the endpoint-oriented Eco-indicator 99 method (Goedkoop et al. 2013). Since the endpoint method (damage-oriented) has a relatively higher uncertainty (Goedkoop et al. 2013), the problem-oriented ReCiPe midpoint (H) v1.13 / World ReCiPe method was chosen for the other eight impact indicators assessed in this study. The abbreviation H stands for the ReCiPe hierarchist perspective, referring to the most common policy principles.

2.1.4 Sensitivity, scenario, and uncertainty analyses

The results of an LCA study can be sensitive to a variety of uncertainty sources, such as LCI data and assumptions made for lacking processes. In order to investigate how the life cycle impacts of the farmed salmon change with alternative LCI parameters, sensitivity analyses were conducted with focus on (i) stocking density (grow-out), (ii) economic feed conversion ratio (eFCR), and (iii) life expectancy of the grow-out infrastructure. Besides, scenario analyses were made to evaluate the potential implications of (i) substitutes of marine- and poultry-derived with crop-derived ingredients for feed production, and (ii) changes of electricity generation sources. In order to check the effects of various uncertainty sources on the modelled LCIA results, Monte Carlo simulation was executed in SimaPro, using 10000 runs to generate 95% confidence intervals (Goedkoop et al. 2016).

3. RESULTS

3.1 Life cycle inventory

During the grow-out period, approximately 35000 Atlantic salmon smolts were transferred to the grow-out farm, with an average mass of 100 gram. Correspondingly, 29000 salmon were harvested with an average mass of 5 kilogram. This grow-out period had an approximate mortality rate of 13% and a culling rate of 4% (mostly male). The stocking density during the grow-out period was 24.2 kg/m^3 (cf. the farm's design stocking density is 45 kg/m^3). The eFCR of this grow-out period was 1.45 (eFCR = kg of feed distributed / kg of fish produced, including losses due to uneaten feed and fish mortalities). The calculated eFCR was slightly higher than the farm's empirical eFCR of 1.4, owing to slight overfeeding applied during this grow-out period. The calculated eFCR of the smolt rearing plant was 1.01, close to the plant's average eFCR of 1.0. The water use rate was 1862 m^3 of seawater per tonne live-weight salmon during the grow-out phase, and 2000 m^3 of freshwater per tonne smolt produced at the hatchery & rearing facility. A summary of key LCI data is provided in Table S6 in the Supporting Information available on the Web.

The total on-site electricity use of the three foreground systems was 8420 kWh per tonne live-weight salmon harvested, among which the salmon grow-out farm accounted for 89.2% (7509 kWh), the hatchery & smolt rearing facility 5.6% (469 kWh), and the feed manufacturing plant 5.2% (442 kWh for feed milling). For the hatchery & smolt rearing facility, the top three electricity users were water circulation pump (2.9%), water-cooling (1.7%), and freshwater supply pump (0.5%). Remarkably, all top four electricity-intensive equipment were in the salmon grow-out farm, including water circulation pump (36.6%), make-up water supply pump (22.1%), UV lamp (16.5%), and biofilter blowers (9.1%). Since no monitoring data were available at the unit operational level, the breakdown of electricity use was calculated by means of the respective technical design data and operational time of the salmon grow-out/hatchery farms and feed milling equipment. Detailed on-site electricity use data appear in Table S7 in the Supporting Information available on the Web.

3.2 Life cycle impact assessment

The LCIA results of the Atlantic salmon RAS farming system are illustrated in Figure 2 (for details, see Tables S8 and S9 in the Supporting Information available on the Web). The on-site electricity use at the grow-out farm dominated six of the nine impact categories: marine ecotoxicity (MET, 52%), freshwater ecotoxicity (FET, 51%), climate change (CC, 46%), freshwater eutrophication (FEU, 42%), cumulative energy demand (CED, 40%), and human toxicity (HT, 39%). Feed production was the primary contributor to the impacts of terrestrial ecotoxicity (TET, 95%) and terrestrial acidification (TA, 48%). In this study, the feed production process includes both the foreground feed manufacturing (milling) process and all upstream (background) processes for production of feed ingredients. The marine eutrophication (MEU) impact was mostly related to the on-site nutrient emissions of the grow-out farm (87%), followed by feed production (12%). For CED, the top two contributors were grow-out electricity use (40%) and feed production (37%). Liquid oxygen contributed between 5% and 22% to all impact categories, with higher values observed in FEU (22%), HT (16%), MET (14%), and FET (13%). The grow-out infrastructure contributed 6-24% of seven impact categories, but very little to TET (1.4%) and MEU (0.5%). The contribution of transport (salmon feed) seems to be negligible to all impact categories (up to 3%).

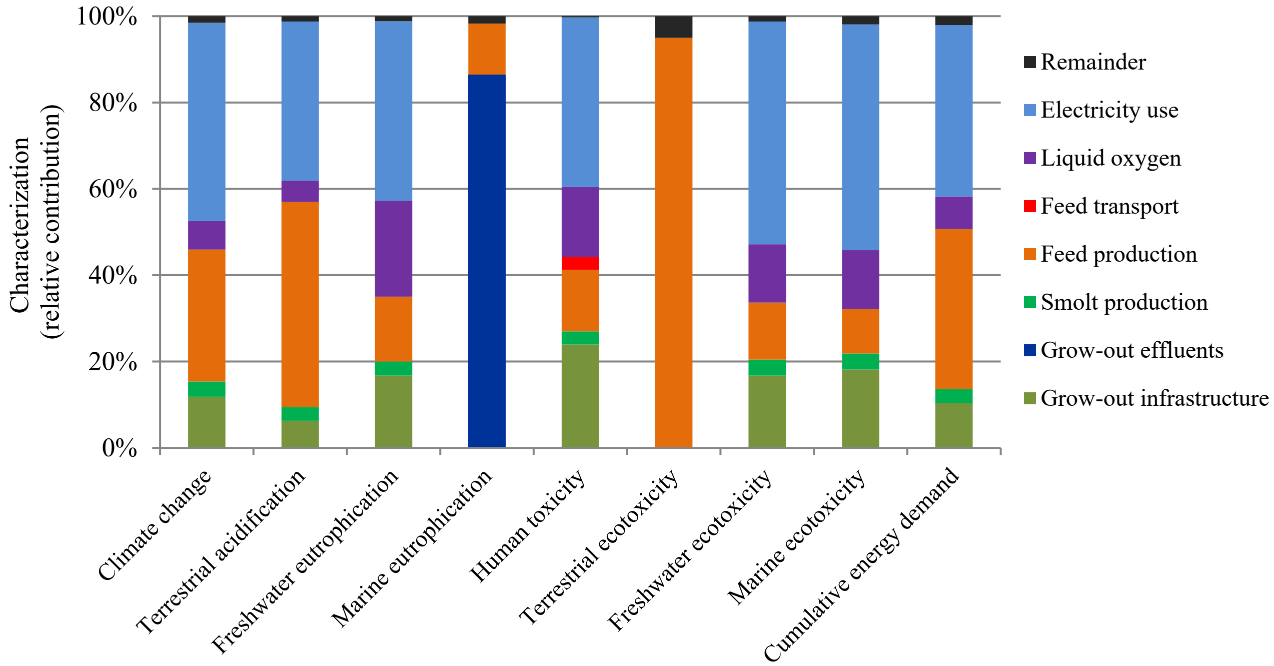

Figure 2 Life cycle contribution analysis of one tonne salmon harvested at the grow-out farm (cradle-to-farm gate) using the ReCiPe method. The term Remainder refers to the sum of processes each less than 2% of the total potential

Given the importance of salmon feed, contribution analysis of the cradle-to-gate life cycle impacts of feed production was performed (Figure 3; for details, see Table S10 and S11 in the Supporting Information available on the Web). Firstly, the marine ingredients (fish meal, fish oil, and krill meal) in total were the primary contributor to climate change (CC, 63%), terrestrial acidification (TA, 61%), and cumulative energy demand (CED, 57%), largely owing to diesel combusted in fishing vessel. In particular, krill meal contributed most to three impact categories, i.e.

TA (40%), CC (37%), and CED (33%). Secondly, the plant-based ingredients in total contributed mainly to TET (50%, among which soybean meal 48% and maize gluten meal 2%), MEU (32%, among which wheat flour 24% and soybean meal 8%), and FET (17%, among which soybean meal 14% and maize gluten meal 3%). Thirdly, electricity use for feed milling contributed mainly to four impact categories: MET (29%), FET (23%), HT (16%), and freshwater eutrophication (FEU, 16%).

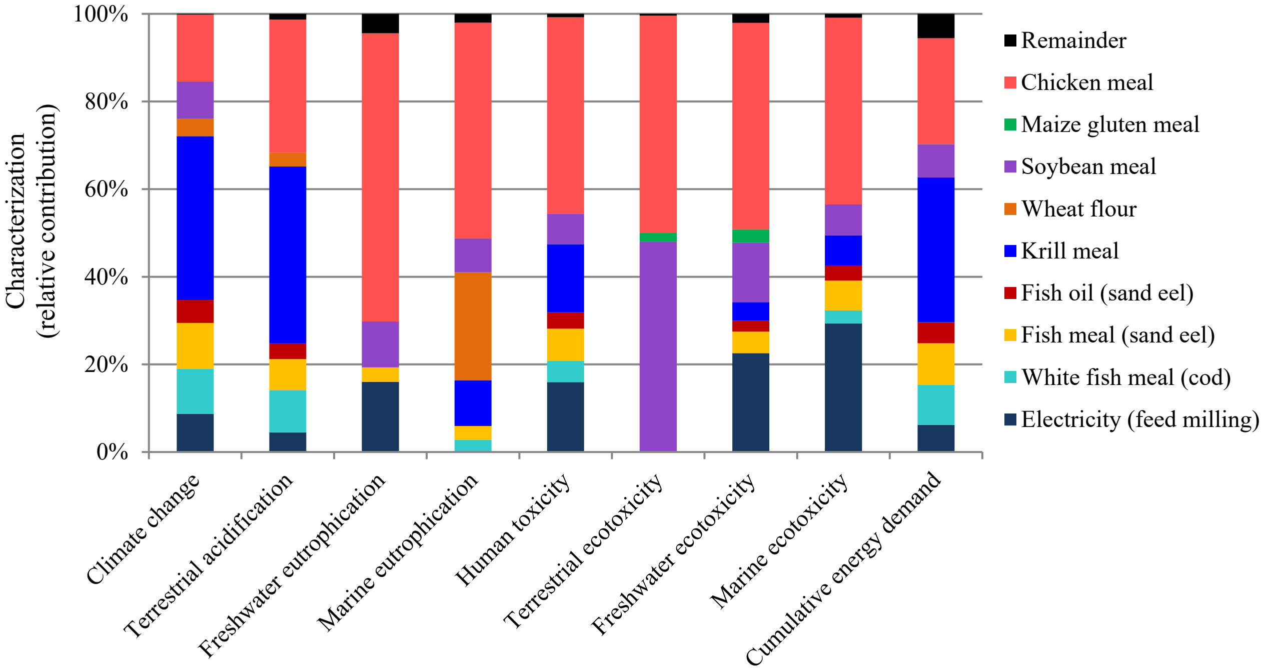

Figure 3 Life cycle contribution analysis of one tonne salmon feed product using the ReCiPe method (cradle-to-gate, excluding infrastructure and transportation requirements of the feed milling plant). The term Remainder refers to the sum of processes each less than 2% of the total potential

Among the feed ingredients used for feed production (Figure 3), chicken meal (only 5% of the salmon feed on a dry-weight basis) dominated six of the nine impact categories assessed, including FEU (66%), TET (50%), MEU (49%), FET (47%), HT (45%), and MET (43%). This was mainly owing to electricity generation and poultry feed production for broiler chicken farms. For the FEU impact (66%), results of specification per process showed that spoil from lignite mining and hard coal mining and for electricity generation accounted for 21% and 16%, respectively, followed by the production of maize grain (10%) and emissions from chicken farms (6%). For the TET impact, results of specification per substance indicated that soil-borne emissions of cypermethrin (as an insecticide) and atrazine (as an herbicide) accounted for 32% and 10%, respectively, out of the total contribution of 50%.

3.3 Sensitivity, scenario, and uncertainty analyses

Table 1 presents the relative changes of the life cycle impacts per tonne live-weight salmon with alternative LCI parameters and scenarios on feed ingredients and electricity generation sources, compared to the baseline. For a detailed explanation of the selection of sensitivity and scenario analysis parameters and the modelling results, see Section 8 of the Supporting Information available on the Web. The results showed that the life cycle impacts per tonne live-weight salmon were most sensitive to the stocking density of the grow-out farm, following by changes of electricity generation sources, feed ingredients, eFCR and life expectancy of infrastructure. When increasing the stocking density from 24.2 kg/m^3 to 45 kg/m^3, the life cycle impacts per tonne salmon reduced by 20-35% in seven of the nine impact categories (except MEU and TET), while the life cycle impacts were similar between the stocking density of 45 kg/m^3 and 60 kg/m^3. Regarding the electricity generation scenarios on replacing 20% of coal-based (baseline) with wind- (S1) and nuclear-based (S2) electricity, respectively, the results showed that S1 and S2 had a similar trend in six impact categories, namely a reduction by 8-15% in CC, TA, FE and HT while up to 0.5% in MEU and TET.

The effect of uncertainty sources on the respective life cycle impacts per tonne salmon and feed was estimated using Monte Carlo uncertainty analysis in SimaPro v8.3 (Table S12 in the Supporting Information available on the Web). Regarding the life cycle impacts per tonne live-weight salmon, marine eutrophication (CV=0.9%) had a lowest level of uncertainty and human toxicity (CV=93%) had a highest level of uncertainty. For the life cycle impacts per tonne salmon feed, a lower level of uncertainty was in climate change and terrestrial acidification (CV=3%), while a higher level of uncertainty existed in human toxicity (CV=42%) and freshwater eutrophication (CV=35%). It is noted that the results of absolute uncertainties of Monte Carlo analysis in SimaPro currently take into account only the uncertainty in life cycle inventory, without considering the uncertainties in the characterization scores themselves (Goedkoop et al. 2016). The results of this Monte Carlo analysis using SimaPro, therefore, can be interpreted as an indicator of the relative uncertainty in each impact category.

Table 1 Sensitivity and scenario analyses for life cycle impacts per tonne live-weight salmon, including the relative change (%) compared to the baseline

LCI parameters	CC (%)	TA (%)	FEU (%)	MEU (%)	HT (%)	TET (%)	FET (%)	MET (%)	CED (%)
Sensitivity analysis									
Stocking density (grow-out)									
S1: 45 kg/m^3	–27.7	–20.7	–30.1	–1.1	–31.5	–1.1	–33.5	–34.5	–24.2
S2: 60 kg/m^3	–27.9	–20.4	–30.7	–1.1	–33.4	–1.3	–34.1	–35.2	–24.4
Economic feed conversion ratio									
S1: eFCR=1.3	–3.1	–4.9	–1.5	–9.9	–1.5	–9.7	–1.4	–1.1	–3.8
S2: eFCR=1.1	–7.3	–11.4	–3.6	–23.3	–3.4	–22.8	–3.4	–2.5	–8.9
Life expectancy of infrastructure									
S1: 10-year	+5.9	+3.1	+8.4	+0.2	+11.9	+0.7	+8.4	+9.1	+5.2
S2: 20-year	–3.0	–1.6	–4.2	–0.1	–6.1	–0.4	–4.2	–4.6	–2.6
Scenario analysis									
Feed ingredients									
S1: substitute krill meal (8%) with soybean meal	–9.8	–19.1	+1.0	–1.2	–1.6	+30.8	+0.6	–0.2	–10.4
S2: substitute chicken meal (5%) with soybean meal	–3.6	–14.4	–9.4	–10.3	–6.1	–28.4	–5.6	–4.2	–7.7
Electricity generation sources									
S1: replace 20% coal with wind	–14.6	–11.8	–12.0	–0.5	–8.2	–0.1	+9.0	+7.8	–7.1
S2: replace 20% coal with nuclear	–14.7	–12.0	–13.5	–0.4	–10.1	–0.2	–13.8	–13.9	+0.9

Note. CC, climate change; TA, terrestrial acidification; FEU, freshwater eutrophication; MEU, marine eutrophication; HT, human toxicity; TET, terrestrial ecotoxicity; FET, freshwater ecotoxicity; MET, marine ecotoxicity; CED, cumulative energy demand.

4. DISCUSSION

4.1 Environmental performance of farmed salmonid fish

In order to better understand the life cycle inventory of Atlantic salmon farmed in the indoor RAS farm (hereafter referred to as the Chinese case), a comparison was made with three respective salmonid fish farming literature on (i) Atlantic salmon in a conceptual land-based RAS in the USA and open net-pen system in Norway (Liu et al. 2016), (ii) Chinook salmon in a pilot marine floating confined tank in Canada (McGrath et al. 2015), and (iii) Atlantic salmon in a land-based, flow-through system and Arctic char in a recirculating system in Canada (Ayer and Tyedmers 2009) (Table S13 in the Supporting Information available on the Web).

For simplification purposes, this comparison addressed only six grow-out operational parameters, including stocking density, production losses, farm-level electricity use, liquid oxygen consumption, eFCR, and on-site nutrient emissions. The comparison showed a substantial variance among the LCI data of different salmonid fish farming systems. Take the on-site electricity use as an example. Compared to the concept-level salmon RAS farming in the USA with a maximum stocking density of 80 kg/m^3 and eFCR of 1.09 (Liu et al. 2016), electricity use in the Chinese case (eFCR 1.45) increased by 38% at the baseline stocking density of 24.2 kg/m^3 and decreased by 20% at the design stocking density of 45 kg/m^3. According to the electricity use data reported by Ayer and Tyedmers (2009), the Chinese case (baseline) accounted for 56% of the land-based, flow-through Atlantic salmon farm (stocking density 38 kg/m^3, eFCR 1.17) and 33% of the recirculating Arctic char farm (stocking density 73 kg/m^3, eFCR 1.45) in Canada. Regarding the on-site nutrient emissions to water, the total N and P emissions per tonne salmon of the Chinese case was close to the value reported in the offshore closed-containment case in Canada (McGrath et al. 2015), since the grow-out farm in China currently discharged all collected nutrients to the sea.

The contribution analysis of this cradle-to-farm gate LCA study (Figure 2) confirmed previous results in the literature on the importance of feed production (and on-site energy use in the case of closed-containment systems) to the life cycle impacts of farmed salmon. Based on the average life cycle impacts of open net-pen farmed salmon in Norway, UK, Canada and Chile, for example, Pelletier et al. (2009) reported that feed accounted for 94% of global warming and acidifying emissions, and 93% of cumulative energy use, while farm-level energy use contributed to 4% of cumulative energy use, 3% of global warming, and acidifying emissions (3%). In an LCA of the actual production cycle of Chinook salmon farmed in an offshore closed-containment system, McGrath et al. (2015) concluded that feed production was the primary contributor of global warming (60%) and acidification potential (57%), while the on-site energy use contributed mostly to cumulative energy use (42%). Similarly, this Chinese case study demonstrated that on-site electricity use and feed production dominated eight (ranging 54-95% in total) of the nine impact categories assessed, except the marine eutrophication impact.

This study indicated that the contribution of infrastructure needs further investigation in future LCA studies on land-based RAS farming. Previous aquaculture LCA studies either excluded infrastructure or reported it with little contribution to the life cycle impacts of recirculating fish production systems. For instance, Aubin et al. (2009) presented that infrastructure contributed between 0% and 5% to the overall cradle-to-farm gate life cycle impacts per tonne live-weight turbot in a French recirculating farm. In an LCA of Chinook salmon farmed in an offshore closed-containment system in Canada, by contrast, McGrath et al. (2015) reported relatively higher contributions of infrastructure (mainly a cylindrical tank made of steel and thermoplastics, 20-year life expectancy) to climate change (7-12%), acidification potential (5-8%), and cumulative energy demand (6-10%). For comparison, this indoor salmon RAS study (Figure 2) illustrated that the grow-out infrastructure (with a 15-year life expectancy) contributed to human toxicity (24%), marine ecotoxicity (18%), freshwater ecotoxicity (17%), freshwater eutrophication (17%), climate change (12%), cumulative energy demand (10%), and terrestrial acidification (6%). Limitations of the present study are briefly discussed in Section 10 in the Supporting Information available on the Web.

4.2 Strategies for improving environmental performance of indoor salmon RAS farming

Environmental hotspots of a life cycle can serve as a basis for developing mitigation measures and strategies toward more eco-friendly salmon production. For the indoor salmon RAS case in this study, feed production, grow-out effluents, and on-site electricity use were identified as main environmental hotspots of the cradle-to-farm gate salmon production system.

Three feed-related issues (grow-out nutrient emissions, eFCR, and feed ingredient production) play a key role in minimizing the life cycle impacts per tonne salmon harvested at the grow-out farm. Toward more sustainable salmon production in RAS, on one hand, it is crucial to regulating nutrient loading of grow-out effluents discharged to the sea, so as to minimize the potential marine eutrophication impact. The collected solid wastes and sludge from the mechanical & biological filtration processes could be used as, for instance, a source of biogas (after anaerobic composting), agriculture fertilizers, and an input in microalgae production (Campo et al. 2010). On the other hand, a lower eFCR could reduce the life cycle impacts of feed as well as the eutrophication potential of grow-out effluents. The sensitivity analysis results (Table 1) demonstrated that, compared to the baseline eFCR of 1.45, the marine eutrophication potential decreased by 10% at the eFCR of 1.3 and by 23% at the eFCR of 1.1. However, appropriate feeding regimes and eFCR in practice depend on a number of interrelated factors, particularly on feed composition, feed digestibility and stability, feeding technology and strategies, fish growth and size, and mortality (Pelletier et al. 2009).

Owing to concerns on overfishing and increasing costs, there have been many efforts to substitute marine protein and fat with plant-based ingredients in production of salmonid feeds (Davidson et al. 2016; Trullàs et al. 2015). From an ecological sustainability perspective, it is preferable to produce salmon feed using ingredients with lower environmental impacts, given that eFCR remains similar during the grow-out period. However, environmental trade-offs across impact categories may emerge from substitution of marine ingredients with plant-derived ingredients, as seen from Table S11 in the Supporting Information available on the Web. Compared to the life cycle impacts per tonne soybean meal, this study showed that (i) 1 tonne krill meal was 2-50 times higher in five impact categories (TA, CC, CED, HT, and MEU) and lower by a factor of 0.1-5 in three categories (FET, FEU, and TET), and (ii) 1 tonne sand eel-based fishmeal was 2.4 times higher in TA but lower by a factor of 0.01-5 in the other eight categories. It is noted that this streamlined LCA analysis (Table S11) did not consider the differences in the protein and lipid content of alternative feed ingredients, which are important for feed production. In an LCA of aquafeed ingredients, for instance, Silva et al. (2018) reported that the production of lipid ingredients required more mass of the ingredient source-component.

On-site electricity use was identified as one main environmental hotspot of the studied salmon RAS farming system, owing to the following two reasons. Firstly, the RAS technology is currently energy-intensive. Ensuring a continuous water flow is crucial to avoiding system failure for any fish farm depending on a piped water supply (Chadwick et al. 2010). In this case study, more than half of the total on-site electricity was used by pumps for water circulation (37%) and water supply (22%) during the grow-out period. Compared to the operational stocking density of 24.2 kg/m^3, however, the farm-level electricity use per tonne salmon could decrease by 46% at the design stocking density of 45 kg/m^3 (see Table S13 in section 9 of supporting information on the Web). Besides optimization of operational stocking density, a further reduction of the farm-level electricity use per tonne harvested salmon largely depends on the development of energy-efficient pumps and the reduction of unit-level energy consumption. Secondly, an alternative solution for fish farms would be to generate on-site renewable electricity, such as solar and wind power (if applicable), since a substantial change in country electricity mix may take a long time.

It is interesting to notice that the life cycle impacts per tonne farmed salmon in RAS, to some extent, were sensitive to stocking density of grow-out rearing tanks (Table 1). Since the indoor recirculating systems require relatively high initial capital investments, RAS farming with high stocking densities and yields are expected to offset investment costs (Martins et al. 2010). In a 10-week stress-oriented experiment conducted at the same salmon RAS farm, Liu et al. (2015) reported that the growth rate of 14-month-old post-smolts decreased by 1.6% at medium-density (15.1-31.1 kg/m^3, initial to final density) and by 3.8% at high-density (30.2-61.3 kg/m^3), compared to low-density (7.6-15.7 kg/m^3), while different stocking densities had no influence on the mortality rate. In this regard, an integrated assessment of the salmon RAS production system is needed in future studies to find win-win solutions between operational performance (such as stocking density, water quality, energy use) and fish welfare (condition/quality) in particular.

4.3 Promoting LCA as a decision support tool for environmental assessment of aquaculture

On the path toward more sustainable aquaculture, life cycle thinking and life cycle approaches should be employed in aquaculture environmental management and decision-making. In particular, life cycle thinking aims to extend the traditional focus of environmental engineering on production site to assess the potential environmental impacts of a product throughout the whole value chain.

Although LCA has been regarded as the most mature life-cycle based environmental systems analysis method to aid in addressing environmental sustainability challenges (Curran 2015), two aspects deserve further attention for the application of LCA in aquaculture. Firstly, aquaculture LCA studies need to obtain representative, precise and preferably site-specific data for both foreground and background processes. The currently available LCI databases (such as ecoinvent v3, LCA food DK, and Agri-footprint) have only a few aquaculture-related background processes from different geographic regions. There have been efforts to improve the LCI databases of aquafeed production, such as the reported LCI data of three Peruvian fishmeal plants (Fréon et al. 2017). However, there are still very few publications on LCI of feed ingredient production and feed manufacturing processes in China. To reduce uncertainties associated with results of aquaculture LCA studies, it is crucial to having a further update on aquaculture-related LCI database, particularly on fisheries, livestock and agriculture production, and processing of feed ingredients in highly relevant regions.

Secondly, aquaculture LCIA results need to be interpreted with caution, especially in the case of comparing the environmental impacts of different fish farming systems. Although LCA has a wide application in land-based products and production processes, a number of aquaculture-specific impacts have not yet been fully considered in LCIA (Samuel-Fitwi et al. 2012), e.g. related to spread of diseases and salmon lice, impacts of trawling on seafloor, effects of escaped salmon on ecosystems, use of medicines and antibiotics, antifouling, and overfishing (Ellingsen and Aanondsen 2006; Ellingsen et al. 2009). It therefore becomes very hard to make a fair comparison of the life cycle impacts of fish products e.g. between land-based RAS and marine cage aquaculture, even if the same LCIA method employed in an LCA study. In order to better address those aquaculture specific environmental impacts in LCIA, multidisciplinary cooperation is needed between LCA practitioners, LCA developers, environmental and ecological modelers, and aquaculture experts.

5. CONCLUSIONS

This paper presented the results of LCI and LCIA per tonne harvest-ready live-weight Atlantic salmon (*Salmo salar*) in an indoor RAS farm, located in northern China. To our knowledge, this study is the first comprehensive, multi-impact category LCA of Atlantic salmon farmed in indoor RAS at commercial scale in the world. It provided a broad overview of the ecological challenges of moving offshore salmon fish farming toward land-based production. The LCIA results, based on the ReCiPe midpoint (H) and Cumulative Energy Demand methods, showed that (i) feed production was the primary contributor to the impacts of terrestrial ecotoxicity (95%) and terrestrial acidification (48%), (ii) the on-site nutrient emissions from the grow-out farm contributed most to the marine eutrophication impact (87%), and (iii) the farm-level electricity use dominated the other six impact categories, ranging between 39% (human toxicity) to 52% (marine ecotoxicity). For the life cycle impacts per tonne salmon feed, krill meal (8%) contributed most to terrestrial acidification (40%), climate change (37%), and cumulative energy demand (34%), while chicken meal (5%)

dominated the other six impact categories (43-65%). In particular, the life cycle impacts per tonne live-weight salmon seemed sensitive to stocking density of the grow-out farm. Results of the sensitivity analysis indicated that the life cycle impacts per tonne salmon reduced by 20-35% in seven of the nine impact categories (except marine eutrophication and terrestrial ecotoxicity) when the stocking density increased from 24.2 kg/m^3 (operational data of the period studied) to 45 kg/m^3 (design data of this grow-out farm).

Results of the present study would be useful for enhancing understanding of the environmental performance of farmed salmon in indoor RAS at commercial scale, and serve as a basis for developing LCA-based innovations toward more eco-friendly farmed salmon. In the development of strategies and mitigation measures toward more sustainable aquaculture production from an LCA perspective, this study also indicates that it is important (i) to analyze the relative contribution of respective mitigation measures to the overall life cycle impacts of a system for identifying priority strategies, and (ii) to check trade-offs between impact categories and among alternative measures for avoiding a shift of environmental problems. Without LCA, environmental improvement measures of a farm may be suboptimal and cause unintended environmental problem shifting. To promote the application of LCA as an environmental decision support tool in the aquaculture industry, future research should focus on improving the currently underdeveloped aquaculture-related LCI database and addressing aquaculture specific environmental impacts in life cycle impact assessment.

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