SUPPORTING INFORMATION FOR:

Song, X., Y. Liu, J. B. Pettersen, M. Brandão, X. Ma, S. Røberg, and B. Frostell. 2019. Life Cycle Assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China. *Journal of Industrial Ecology.*

Summary

This supporting information provides the following supplementary information. Section 1 presents a brief summary of published LCA studies on salmonid aquaculture systems (Table S1). Section 2 describes the recirculating Atlantic salmon grow-out farm, the hatchery & smolt rearing facility, the salmon feed manufacturing plant, and detailed formulations of feed product (Table S2). Section 3 details background data sources (Table S3) and assumptions made for LCI analysis of feed ingredient production processes (Table S4). Section 4 explains the results of nutrient mass-balance modelling for 1 tonne harvest-ready live-weight salmon at the grow-out farm (Table S5). Section 5 provides LCI analysis results of the three foreground systems studied (Table S6). Section 6 lists a breakdown of on-site electricity use to produce 1 tonne live-weight salmon (Table S7). Section 7 gives the results of life cycle impact assessment with regard to per tonne live-weight Atlantic salmon at the grow-out farm (Tables S8-S9), per tonne salmon feed product (Table S10), and per tonne specific feed ingredient (Table S11). Section 8 shows the results of sensitivity, scenario and uncertainty analyses (Table S12). Section 9 demonstrates a comparison of the grow-out LCI data between this study and the selected literature (Table S13). Section 10 reports limitations of the present study.

Section 1: Summary of published LCA studies on salmonid aquaculture systems

Table S1 Summary of published LCA studies on salmonid aquaculture systems

General			Aim of study (environment-related)	Functional unit	System boundary	Impact categories assessed [a]	Reference
Species	Farming system	Country					
Atlantic salmon	Open net-pen RAS (conceptual)	Norway USA	Compare the carbon footprint of the two salmon farming systems, based on concept-level design	1 kg gutted salmon with head on, at the retailer gate	Cradle-to-market	GWP	Liu et al. (2016)
Chinook salmon	A marine confined, floating tank	Canada	Evaluate the life cycle impacts of the pilot offshore farming system	1 tonne live-weight salmon	Cradle-to-farm gate	GWP, AP, MEP, CEU, BRU	McGrath et al. (2015)
Atlantic salmon	Open net-pen	Norway	Quantify and compare the carbon footprint of salmon and other Norwegian seafood products on the global seafood market	1 kg edible salmon delivered to wholesalers in selected countries	Cradle-to-market	GWP	Ziegler et al. (2012)
Atlantic salmon	Open net-pen	Norway	Compare the carbon footprint, energy- and area use of farmed salmon fed with five different diets	1 kg edible salmon	Cradle-to-farm gate	GWP, CEU, land and sea area use	Hognes et al. (2011)
Atlantic salmon	Open net-pen	Norway, Canada, UK, Chile	Analyze the environmental impact of salmon farmed in the four selected countries	1 tonne live-weight salmon	Cradle-to-farm gate	CEU, BRU, GHG Em., Acd. Em., Eut. Em.	Pelletier et al. (2009)
Atlantic salmon & Arctic Char	Marine net-open, floating bag; flow-through; recirculating	Canada	Assess and compare the life cycle impacts of the four salmonid culture systems	1 tonne live-weight fish	Cradle-to-farm gate	GWP, EP, AP, ABD, HTP, MTP, CEU	Ayer and Tyedmers (2009)
Atlantic salmon	Open net-pen	Norway	Analyze the CO_2 emissions both from salmon farming and transportation to the wholesaler and consumer	1 kg salmon fillet	Cradle-to-consumer	GWP	Ellingsen et al. (2009)
Atlantic salmon	Open net-pen	Norway	Evaluate the environmental impact of farmed salmon, compared with farmed chicken and wild caught cod	0.2 kg salmon fillet sold in mid-Norway	Cradle-to-market	GWP, AP/EP, ozone layer, ecotoxicity, fossil fuels, carcinogens, RI	Ellingsen and Aanondsen (2006)

[a] LCIA, life cycle impact assessment; GWP, global warming potential; AP, acidification potential; MEP, marine eutrophication potential; CEU, cumulative energy use; BRU, biotic resource use; GHG Em., greenhouse gas emissions; Acd. Em., acidifying emissions; Eut. Em., eutrophying emissions; EP, eutrophication potential; ABD, abiotic depletion; HTP, human toxicity potential; MTP, marine toxicity potential; RI, respiratory inorganics.

Section 2: Description of the recirculating Atlantic salmon farming system

This case study is on Atlantic salmon farmed in an indoor RAS farm in northern China, including three foreground systems: (i) a salmon grow-out RAS farm located in Yantai, Shandong province, northern China, (ii) a hatchery & smolt rearing facility in Yantai, and (iii) a feed manufacturing plant in Beijing. A brief introduction to the three foreground systems is as follows.

The salmon grow-out RAS plant occupies a total land area of 37500 m^2, around 100 meters from the Bohai Sea and 10 meters above sea level. It has been in operation since 2012, with an annual production capacity of 1000 tonnes live-weight salmon. Groundwater was used in this grow-out plant, inlet at a depth of 80-100 meters, with a constant temperature of 14-16 ºC and a salinity of 25-28‰. The average grow-out period is around 15 months until harvest at market size of typically 5 kilograms.

The salmon grow-out farm has 78 separated closed-containment systems, each with four rearing tanks and a total rearing volume of 500 m^3. The main unit operations of the closed-containment system include: (i) culture tanks with rotary sewage collectors (to remove settleable solids), (ii) automatic fish feeder, (iii) mechanical filtration (to trap solids larger than 30 µm in size), (iv) foam fractionator (to remove dissolved organic compounds and fine suspended solids using air bubbles introduced by a venturi jet pump), (v) biological aerated filtration (nitrification and denitrification) & CO_2 stripping (diffusion of CO_2 out of water), (vi) UV disinfection (ultraviolet light), (vii) oxygenation (using an oxygen cone to mix liquid oxygen with water to keep the oxygen saturation in the target range of 80-90%), and (viii) monitoring & control equipment. Addition of fresh seawater to the system happens at the biofiltration stage. Approximately 90% recirculated process water goes back to the culture tanks after mechanical & biological filtration, oxygenation and UV disinfection. At the time of this study, the collected solid fish wastes and sludge from various unit operations of this farm were discharged into the adjunct sea.

The hatchery & smolt rearing facility is located in Muping District, Yantai, with a distance of 120 km to the grow-out farmt. Imported salmon eggs come from Aquagen AS in Norway. The salmon eggs are transported by air from Norway to Beijing (around 7850 km distance), followed by truck from Beijing to Muping (810 km). Production of smolts takes place in a freshwater RAS and typically has a size of close to 100 gram when transferred to the grow-out farm.

The salmon feed manufacturing plant is located in Miyun District, Beijing Municipality. Raw feed ingredients, mainly derived from fishery, agricultural and livestock products, are milled and reprocessed to fish feed in this plant. The produced salmon feed goes by truck to the smolt hatchery plant (810 km) and the salmon grow-out plant (785 km). This study assumed use of the same salmon feed in the hatchery & smolt rearing facility and the salmon grow-out farm. Detailed feed formulations are listed in Table S2.

Table S2 Feed ingredients of the salmon feed

Feed ingredients	Feed content (on a dry-weight basis)
Steam dried fish meal [a]	30%
Fish oil [a]	15%
Wheat flour	14%
Soybean meal	12%
Krill meal	8%
White fish meal [a]	7%
Maize gluten meal	6%
Chicken meal	5%
Various minerals, vitamins, colour, etc.	3%

[a] The present LCA study assumed that (i) steam dried fishmeal and fish oil came from sand eel, and (ii) white fishmeal came from cod.

Section 3: Background data sources and assumptions about the LCI data of feed ingredient production processes

Table S3 Background processes and their data sources (within SimaPro 8.3 software)

Process	Database	Last updated	Geographic region
Electricity production			
Hard coal	Ecoinvent v3.3	2016	CN-SD (China-Shandong)
Hydro	Ecoinvent v3.3	2016	CN-HB (China-Hubei)
Natural gas	Ecoinvent v3.3	2016	CN-SD (China-Shandong)
Nuclear	Ecoinvent v3.3	2016	CN-ZJ (China- Zhejiang)
Oil	Ecoinvent v3.3	2016	CN-SD (China-Shandong)
Wind	Ecoinvent v3.3	2016	CN-SD (China-Shandong)
Photovoltaic	Ecoinvent v3.3	2016	CN-SD (China-Shandong)
Feed ingredients production			
Fish meal (sand eel)	LCA Food DK	2006	DK (Denmark)
Fish oil (sand eel)	LCA Food DK	2006	DK (Denmark)
Cod, ex harbour	LCA Food DK	2006	DK (Denmark)
Wheat flour	LCA Food DK	2006	DK (Denmark)
Shrimp, ex harbour	LCA Food DK	2006	DK (Denmark)
Soybean meal	Ecoinvent v3.3	2016	GLO (Global)
Chicken meat	Ecoinvent v3.3	2016	GLO (Global)
Maize gluten meal	Agri-footprint	2014	US (United States)
Infrastructure			
Brick (clay)	Ecoinvent v3.3	2016	GLO (Global)
Concrete	Ecoinvent v3.3	2016	RoW (Rest of World)
Reinforcing steel	Ecoinvent v3.3	2016	GLO (Global)
Transport			
Freight-lorry	Ecoinvent v3.3	2016	GLO (Global)
Freight-aircraft	Ecoinvent v3.3	2016	GLO (Global)
Others			
Liquid oxygen	Ecoinvent v3.3	2016	RoW (Rest of World)
Chlorine dioxide	Ecoinvent v3.3	2016	Global

Table S4 Notes on Chinese electricity mix and assumptions about feed ingredients production processes

Process	Data source	Notes & Assumptions
Fish meal (sand eel) Fish oil (sand eel)	Ecoinvent v3.3	According to the ecoinvent v3.3 database within SimaPro 8.3, the production of 1 kg fish meal requires 4.66 kg sand eel (ex harbor), with a byproduct of 0.21 kg fish oil. We applied a mass allocation between fishmeal (83%) and fish oil (17%) in this study.
White fish meal (cod)	Based on ecoinvent v3.3	Based on the above sand eel-based fish meal production process in the ecoinvent v3.3 database, we assumed that the production of 1 kg white fish meal required 4.66 kg cod (ex harbor), with a byproduct of 0.21 kg fish oil. We applied a mass allocation between cod-based fishmeal (83%) and fish oil (17%) in this study.
Krill meal	Parker and Tyedmers (2012)	According to the authors, the production of 1 kg krill meal required 6.94 kg wild-caught Antactic krill, with 0.005 kg fish oil as byproduct.
	Katevas (2014)	According to the reference, the price of per kg krill meal and krill oil was 2.5 and 100 USD, respectively. We applied an economic allocation between krill meal (83%) and krill oil (17%) in this study.
Chicken meal	Based on ecoinvent v3.3	According to the process "Chicken for slaughtering, live weight {GLO}| chicken production | Alloc Def, U" in the ecoinvent v3.3 database within SimaPro 8.3, the production of 1 kg fresh chicken meat required 1.47 kg broilers at farm. Based on the estimated protein content of chicken meat (21%) and chicken meal (65%), we assumed that the production of 1 kg chicken meal required 4.56 kg broilers at chicken farm. Owing to data limitation, this study did not consider heat and/or electricity use in the production of chicken meal from chicken meat.
Chinese electricity mix	Based on ecoinvent v3.3	The Chinese electricity generation processes was updated and used in this study, according to the actual country electricity mix in 2016 (i.e. coal-based 65.2%, hydropower 19.7%, wind 4%, nuclear 3.6%, natural gas 3.2%, oil 3.3%, and solar 1%).

Section 4: Nutrient mass-balance modelling for the production of 1 tonne live-weight salmon at the grow-out farm

Table S5 Nutrient budget modelling of phosphorous (P) and nitrogen (N) for the production of 1 tonne live-weight salmon at the grow-out farm

	Feed distributed [a]	Feed unconsumed [b]	Feed ingested [c]	Digested nutrients [d]	Faecal loss [e]	Grow-out effluents [f]		
						Nutrient, solid	Nutrient, dissolved	Nutrient, total
eFCR=1.45								
Total amount (kg)	1448	48	1400					
Solids (kg dry matter)	1303	43	1260		304			
N (kg)	101.8	3.4	98.4	71.5	22.1	25.4	39.7	65.1
P (kg)	15.1	0.5	14.6	9.4	6.9	7.4	2.8	10.2
eFCR=1.30								
Total amount (kg)	1300	43	1257					
Solids (kg dry matter)	1170	39	1131		273			
N (kg)	91.4	3.0	88.4	64.2	19.8	22.9	35.6	58.5
P (kg)	13.5	0.4	13.1	8.4	6.2	6.6	2.6	9.2
eFCR=1.10								
Total amount (kg)	1100	36	1064					
Solids (kg dry matter)	990	33	957		231			
N (kg)	77.3	2.6	74.8	54.3	16.8	19.3	30.2	49.5
P (kg)	11.4	0.4	11.1	7.1	5.2	5.6	2.2	7.8

[a] 10% moisture content of feed; 1 kg of distributed feed contains 0.07 kg of N and 0.01 kg of P (data collected from the grow-out farm studied).

[b] Assumed a 3.3% of non-ingested feed under the condition of a slight overfeeding in this study. For reference purposes, 3% was used in the literature (Chadwick et al. 2010; McGrath et al. 2015).

[c] Feed ingested = Feed distributed – unconsumed feed.

[d] Calculated mean digestibility of N (73%) and P (65%) in salmon feed at this farm, based on the experimental data from Sun (2014).

[e] Estimated based on an empirical data of the studied grow-out plant, i.e. 1 kg of feed distributed corresponding to 0.18-0.24 kg of fecal.

[f] Based on (i) a nutrient budget modelling approach from Aubin et al. (2006), and (ii) nutrient balance analysis data provided by the grow-out farm studied (i.e. 25% of N and 49% of P in distributed feed went into solid fish wastes collected from the mechanical filtration process, 39% of N and 19% of P in distributed feed dissolved in sludge from the biofiltration process, and the remaining nutrients were assimilated as part of salmon weight-gain).

Section 5: LCI analysis results of the three foreground processes

Table S6 Life cycle inventory for producing 1 tonne (t) of live-weight salmon, 1 t of smolt and 1 t of feed product, respectively [a]

	Salmon grow-out	Smolt production	Feed manufacuring
Outputs – product (t)			
Atlantic salmon, live-weight	1	–	–
Salmon smolts	–	1	–
Salmon feed	–	–	1
Inputs – operational (/t) [b]			
Smolt (kg)	24.1	–	–
Feed (kg)	1448	1010	–
Feed ingredients (t)	–	–	1.01[c]
Electricity (kWh)	7509	1944	300
Water (m^3)	1862 (seawater)	2000 (freshwater)	n/a
Liquid oxygen (kg)	953	714	–
Chlorine dioxide (kg) [d]	1.45	–	–
Salmon eggs transport (tkm) / distance (km) [e]	–	75 / 7850 (air) 7.2 / 750 (truck)	–
Smolt transport (tkm) / distance (km)	2.9 / 120 (truck)	–	–
Feeds transport (tkm) / distance (km)	1137 / 785 (truck)	818 / 810 (truck)	–
Feed ingredients transport	–	–	n/a
Inputs – infrastructure (kg/t) [f]			
Concrete	6201	n/a	n/a
Reinforcing steel	144	n/a	n/a
Brick	3448	n/a	n/a
Outputs – emissions to water (kg/t)			
Phosphorous, dissolved	2.9	n/a	n/a
Phosphorous, solid	7.4	n/a	n/a
Nitrogen, dissolved	39.7	n/a	n/a
Nitrogen, solid	25.4	n/a	n/a

[a] "n/a" is shown where data were missing.
[b] No chemicals were used during the grow-out period studied.
[c] Assuming 1% processing losses in the feed manufacturing plant.
[d] Added into the rearing tanks during hot seasons for disinfection, disease resistance and inhibiting algae breeding.
[e] tkm = tonne × kilometers.
[f] The culture tank material is concrete. This study used the density of 2.4 tonne/m^3 for concrete and 2 tonne/m^3 for brick as well as 15- year lifespan of the grow-out infrastructure.

Section 6: On-site electricity use for the production of 1 tonne live-weight salmon

Table S7 Total and breakdown of on-site electricity use for the production of 1 tonne harvest-ready live-weight salmon

Foreground system	On-site electricity use	
	Value (kWh)	Percent
Salmon grow-out farm		
Water circulation pump	3079	36.6%
Make-up water supply pump	1862	22.1%
UV lamp	1386	16.5%
Biofilter blowers	770	9.1%
Protein skimmer (jet pump)	154	1.8%
Mechanical filter	77	0.9%
Oxygen cone (jet pump)	77	0.9%
Illumination lamps	58	0.7%
Automatic fish feeder	47	0.6%
Salmon grow-out in all	**7509**	**89.2%**
Hatchery & smolt rearing facility		
Water circulation pump	243	2.9%
Refrigerating machines	139	1.7%
Water supply pump	42	0.5%
Air pump	36	0.4%
Artificial light	9	0.1%
Smolt production in all	**469**	**5.6%**
Feed manufacturing plant		
Feed milling	442	5.2%
Feed manufacturing in all	**442**	**5.2%**
In all	**8420**	**100%**

Section 7: Results of LCIA per tonne live-weight salmon, per tonne feed product, and per tonne specific feed ingredients, respectively

Table S8 Life cycle impacts per tonne live-weight Atlantic salmon harvested at the grow-out farm, cradle-to-farm gate (ReCiPe midpoint/hierarchist v1.13 and CED v1.09)

	CC (kg CO_2 eq)	TA (kg SO_2 eq)	FEU (kg P eq)	MEU (kg N eq)	HT (kg 1.4-DB eq)	TET (kg 1.4-DB eq)	FET (kg 1.4-DB eq)	MET (kg 1.4-DB eq)	CED (MJ)
Total	16747	106	2.4	108	2245	15	91	82	203257
Feed production	5115	50	0.4	13	320	14	12	8.5	75354
Feed transport	246	1	0.02	0.1	67	0.1	0.9	1	4000
Smolt production	592	3.4	0.1	0.3	68	0.2	3	3	6677
Smolt transport	0.6	0.003	0.0001	0.0002	0.2	0.0002	0.002	0.004	10
Liquid oxygen	1106	5	0.5	0.2	364	0.1	12	11	15378
Chlorine dioxide	12	0.1	0.01	0.01	6	0.001	0.2	0.2	191
Grow-out electricity	7692	39	1	1	882	0.1	47	43	80656
Grow-out effluents	0	0	0	93	0	0	0	0	0
Grow-out infrastructure	1983	7	0.4	0.3	537	0.2	15	15	23041

Table S9 Relative contribution of the life cycle impacts per tonne live-weight Atlantic salmon harvested at the grow-out farm, cradle-to-farm gate (ReCiPe midpoint/hierarchist v1.13 and CED v1.09)

	CC (%)	TA (%)	FEU (%)	MEU (%)	HT (%)	TET (%)	FET (%)	MET (%)	CED (%)
Total	100	100	100	100	100	100	100	100	100
Feed production	30.5	47.5	15.0	11.8	14.3	95.0	13.2	10.3	37.1
Feed transport	1.5	1.2	0.9	0.1	3.0	0.6	1.0	1.7	2.0
Smolt production	3.5	3.2	3.3	0.3	3.0	1.7	3.7	3.7	3.3
Smolt transport	0.004	0.003	0.002	0.0002	0.01	0.002	0.003	0.004	0.01
Liquid oxygen	6.6	4.9	22.2	0.2	16.2	0.4	13.5	13.6	7.6
Chlorine dioxide	0.1	0.1	0.3	0.01	0.3	0.01	0.2	0.2	0.1
Grow-out electricity	45.9	36.9	41.6	0.9	39.3	1.0	51.6	52.3	39.7
Grow-out effluents	0	0	0	86.5	0	0	0	0	0
Grow-out infrastructure	11.8	6.3	16.7	0.3	23.9	1.4	16.7	18.1	10.3

Table S10 Life cycle impacts per tonne salmon feed product, cradle-to-gate (ReCiPe midpoint/hierarchist v1.13 and CED v1.09)

	CC (kg CO_2 eq)	TA (kg SO_2 eq)	FEU (kg P eq)	MEU (kg N eq)	HT (kg 1.4-DB eq)	TET (kg 1.4-DB eq)	FET (kg 1.4-DB eq)	MET (kg 1.4-DB eq)	CED (MJ)
Total	3532	35	0.3	8.8	221	10	8.3	5.8	52030
Fish meal (cod)	364	3.3	0.002	0.2	11	0.01	0.2	0.2	4851
Fishmeal (sand eel)	369	2.5	0.01	0.3	16	0.01	0.4	0.4	502
Fish oil (sand eel)	185	1.2	0.004	0.1	8.2	0.003	0.2	0.2	2517
Krill meal	1320	14	0.002	0.9	34	0.02	0.4	0.4	17485
Wheat flour	139	1.1	0.002	2.2	0.8	0.001	0.01	0.01	690
Soybean meal	302	0.4	0.03	0.7	15	4.6	1.1	0.4	4639
Maize gluten meal	6	0.04	0.001	0.001	1.0	0.2	0.3	0.04	1018
Chicken meal	539	11	0.2	4.3	99	4.8	3.9	2.5	12584
Electricity (feed milling)	307	1.6	0.04	0.04	35	0.01	1.9	1.7	3222

Table S11 Life cycle impacts per tonne specific feed ingredient, cradle-to-gate (ReCiPe midpoint/hierarchist v1.13 and CED v1.09) [a,b]

	CC (kg CO_2 eq)	TA (kg SO_2 eq)	FEU (kg P eq)	MEU (kg N eq)	HT (kg 1.4-DB eq)	TET (kg 1.4-DB eq)	FET (kg 1.4-DB eq)	MET (kg 1.4-DB eq)	CED (MJ)
Fish meal (cod)	5129	47	0.03	3.5	150	0.1	2.3	2.4	68320
Fishmeal (sand eel)	1218	8.1	0.03	0.9	54	0.02	1.3	1.3	16581
Fish oil (sand eel)	1217	8.1	0.03	0.9	54	0.02	1.3	1.3	16559
Krill meal	16302	173	0.02	11	425	0.2	4.4	4.9	215866
Chicken meal	10574	206	3.3	85	1945	93	77	49	246736
Soybean meal	2492	3.4	0.2	5.6	127	38	9	3.4	38340
Wheat flour	986	7.6	0.01	15	5.4	0.004	0.03	0.1	4892
Maize gluten meal	93	0.6	0.02	0.02	16	3.2	4.3	0.7	16689

[a] For more information on the data and assumptions for feed ingredient production processes, see Tables S3 and S4.

[b] The original electricity mix for processing raw product of fish/shrimp at harbor to produce the corresponding feed ingredients (fish meal/oil and krill meal) in the ecoinvent v3.3 database was replaced with the updated Chinese electricity mix (2016).

Section 8: Sensitivity, scenario and uncertainty analyses

Sensitivity and scenario analyses

Sensitivity and scenario analyses were conducted to investigate how the life cycle impacts per tonne live-weight salmon change with the following LCI parameters and scenarios: (i) grow-out stocking density, (ii) eFCR, (iii) life expectancy of the grow-out infrastructure, (iv) feed ingredients (taking substitution of krill meal and chicken meal with soybean meal as an example), and (v) electricity generation sources (shifting from coal-dominated to less fossil fuel energy).

Those LCI parameters and scenarios were selected based on the results of life cycle contribution analysis of the cradle-to-gate salmon RAS farming system (Figure 2) and feed production processes (Figure 3), which were identified as important contributors of the life cycle impacts per tonne live-weight salmon harvested at the grow-out farm studied. Results of the sensitivity and scenario analyses were listed in Table 1 of the main part of this paper. Below was a summary of the analysis results and background information on the alternative parameters used in the analyses.

Firstly, the influence of grow-out stocking density on the life cycle impacts were modelled in relation to (i) baseline: 24.2 kg/m^3, (ii) scenario 1 (S1): 45 kg/m^3 (the design stocking density of this grow-out farm), and (iii) scenario 2 (S2): 60 kg/m^3 (representing high-density operation but requiring higher operational management skills). Based on the technical design data of this grow-out farm, the following assumptions were made in the sensitivity analysis: (i) the total farm-level electricity use per generation in S1 was same to that associated with the baseline stocking density, while in S2 it was estimated to be 1.4 times of the baseline, and (ii) the total farm-level liquid oxygen consumption in S1 and S2 was 1.6 and 2.2 times, respectively, of the baseline. Results of the analysis showed that, compared to the baseline, S1 and S2 led to a similar change in each specific impact category, reducing by up to 1.3% of MEU and TET and 20-35% in the other seven categories.

Secondly, the effect of eFCR was modelled in two alternative eFCR at 1.1 and 1.3. The selection of two alternative eFCR (1.3 and 1.1) was based on the following information in the literature: (i) Pelletier et al. (2009) reported that the eFCR of farmed salmon was 1.1 in Norway, 1.33 in the UK, 1.31 in Canada, and 1.49 in Chile, and (ii) Liu et al. (2016) reported an eFCR of 1.09 in a conceptual Atlantic salmon RAS plant, based on conceptual-level design. Compared to the baseline eFCR at 1.45, the results of sensitivity analysis showed that the eFCR at 1.3 and 1.1 resulted in a reduction by around 10% and 23%, respectively, in the MEU and TET impact categories. For the other seven impact categories, the two alternative eFCR led to a reduction by 1-11% of the potential environmental impacts.

Thirdly, the 10-year (S1) and 20-year (S2) life expectancy of grow-out infrastructure led to increase by up to 11% and decrease by up to 6% of all impact categories, respectively, compared to the baseline (15-year).

Fourthly, the impacts of feed ingredients were analyzed in two scenarios: S1 – substitution of krill meal (8%) with soybean meal (8%), and S2 – substitution of chicken meal (5%) with soybean meal (5%). Compared to the baseline, the scenario results showed that the life cycle impacts in S1 increased by 31% in TET and decreased by 9-19% in CC, TA and CED, while the life cycle impacts in S2 reduced by 4-28% in all categories (highest reduction in TET and lowest in CC).

Finally, two scenarios of electricity generation sources were compared with the baseline: (i) baseline, Chinese electricity mix in 2016 (coal 65.2%, hydropower 19.7%, wind 4%, nuclear 3.6%, others 7.5%); (ii) S1: replacing 20% electricity generated from coal with wind (coal 45.2%, hydropower 19.7%, wind 24%, nuclear 3.6%, others 7.5%); (iii) S2: replacing 20% electricity generated from coal with nuclear power (coal 45.2%, hydropower 19.7%, wind 4%, nuclear 23.6%, others 7.5%). Since the current Chinese electricity mix is coal-dominated (65%), China has planned to increase the share of non-fossil sources to 20% in national primary energy use by 2030. A key focus of the national energy policy initiatives is on expanding wind-generated electricity (Davidson et al. 2016). The results of S1 and S2 showed 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. Compared to the baseline, the respective MET and FET impact decreased by around 14% in S2, but they increased by 7.8% and 9% in S1 (mainly owing to copper leaching into water from treatment of scrap copper after use in electric power transmissions). For CED, the comparison results showed 7% decrease in S1 and 0.9% increase in S2.

It is worth noting that there are non-linear relationships between fish growth rate and stocking density & eFCR during the grow-out period in practice. In this case study, there may be no significant differences in fish growth rate during the whole grow-out period between the stocking density of 24.2 kg/m^3 and 45 kg/m^3, since this grow-out plant was designed for an optimum stocking density of 45 kg/m^3. When increasing the stocking density from 45 kg/m^3 to 60 kg/m^3, there is currently no operational data at this grow-out plant and there may be some kind of marginal decrease in fish growth rate. In a 10-week stress-oriented experiment conducted at the same salmon grow-out 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-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). According to Chadwick et al. (2010), rearing density of up to 80 kg/m^3 does not limit growth rate of Atlantic salmon in closed-containment systems where water quality is maintained at acceptable levels. For the sake of simplification, this study applied the eFCR of 1.1 and 1.3 directly in the sensitivity analysis, and the sensitivity analysis of feed ingredient substitution did not consider the differences in the protein and lipid content of alternative feed ingredients. Therefore, there would be uncertainties in the results of sensitivity and scenario analyses. In future studies, it is needed to develop models for a systematic analysis of possible relationships between fish growth rate, substitution of feed ingredients, and operational performance (e.g. stocking density, eFCR, electricity use, oxygen requirements) during the whole grow-out period.

Uncertainty analysis

In order to estimate the effect of uncertainty sources on the respective life cycle impacts per tonne salmon and feed product, Monte Carlo uncertainty analyses were conducted using ReCiPe Midpoint (H) V1.13 / World Recipe H in SimaPro v8.3. Table S12 presented the uncertainty analysis results of this study.

Table S12 Monte Carlo analysis for the cradle-to-gate life cycle impacts of one tonne of live-weight salmon at the grow-out farm and one tonne of salmon feed at the feed manufacturing plant, respectively

Impact category	1 tonne live-weight salmon				1 tonne salmon feed			
	Mean	Median	SD	CV (%)	Mean	Median	SD	CV (%)
CC (kg CO_2 eq)	16763	16591	1496	8.9	3532	3523	106	3
TA (kg SO_2 eq)	106	104	12	11	35	35	1.1	3
FEU (kg P eq)	2.5	2.2	1.2	50	0.3	0.3	0.1	35
MEU (kg N eq)	108	108	1.0	0.9	9	9	0.6	7
HT (kg 1.4- DB eq)	2258	1847	2109	93	218	194	91	42
TET (kg 1.4- DB eq)	15	14	2.4	16	10	9	2	17
FET (kg 1.4- DB eq)	91	87	23	25	8	8	1.4	17
MET (kg 1.4- DB eq)	82	79	21	25	6	6	1.2	21

Note: SD, standard deviation; CV, coefficient of variation; confidence interval 95%.

Section 9: Comparison of the grow-out LCI data between this study and the literature

Table S13 Comparison of the grow-out LCI data for the production of one tonne live-weight salmonid fish between this study and the literature

Reference	Species	Farming system	Production losses (mortality/others) (%)	Stocking density (kg/m^3)	Liquid oxygen (kg/t)	Electricity use, on-site (kWh/t)	Economic FCR (t/t)	On-site nutrient emissions (kg/t)	
								Total N (solid/dissolved)	Total P (solid/dissolved)
This study	Atlantic salmon	Land-based RAS, China	17 (13/4)	24.2	953	7509	1.45	65.1 (25.4/39.7)	10.2 (7.4/2.8)
							1.30 (S1)	58.5 (22.9/35.6)	9.2 (6.6/2.6)
							1.10 (S2)	49.5 (19.3/30.2)	7.8 (5.6/2.2)
				45 (S1)	819 [a]	4033	1.45	30.3	5.7
				60 (S2)	844 [a]	4234	1.45	30.3	5.7
Liu et al. (2016) [b]	Atlantic salmon	Land-based RAS (conceptual), USA	16	80	656	5460	1.09 [b]	n/a	n/a
		Open net-pen, Norway	16	25	–	–	1.27	n/a	n/a
McGrath et al. (2015)	Chinook salmon	Marine floating confined tank, Canada	22.7 (17.8/4.9) [c]	26.6	–	7272	1.46	60.2 (9.8/50.4)	11.9 (8.2/3.7)
Ayer and Tyedmers (2009)	Atlantic salmon	Land-based, flow-through, Canada	In mass [d]	38	1445	13400	1.17	26.0 [e]	4.1 [e]
	Arctic char	Land-based, recirculating, Canada	In mass [f]	73	–	22600	1.45	0 [g]	0 [g]

[a] The amount of liquid oxygen assumed in the scenarios with a stocking density of 45 and 60 kg/m^3 was 1.6 and 2.2 times, respectively, of the studied period (with a stocking density of 24.2 kg/m^3). It assumed a same nutrient emission level per tonne salmon (at eFCR of 1.45) for the three densities.

[b] The FU was 1 kg gutted salmon with head on (at the retailer gate) and the eFCR was estimated for a concept-level closed containment system (Liu et al. 2016).

[c] The generation period with a number of stocked smolts (56108), salmon harvested (43366), mortalities (9989) and escapes (2753) (McGrath et al. 2015).

[d] The weight of stocked smolts (14.6 kg) and mortalities (84.4 kg) per tonne live-weight harvested fish (Ayer and Tyedmers 2009).

[e] Wastewater leaving the rearing tanks was untreated and piped back into the channel; no specification on the forms of nutrients (Ayer and Tyedmers 2009).

[f] The weight of stocked smolts (238 kg) and mortalities (301 kg) for the production of 1 tonne live-weight fish (Ayer and Tyedmers 2009).

[g] Wastewater from various stages of the farm, first, passed through a holding tank to settle out solids, and then discharged to the municipal sewer system; the collected solid fish wastes contained 6.8 kg of sequestered N and 3.2 kg of sequestered P per tonne of live-weight fish (Ayer and Tyedmers 2009).

Section 10: Limitations of the present study

A limitation of the present study relates to the following two issues: (i) data and data quality of feed ingredient production (background processes), and (ii) those excluded foreground processes and parameters.

On one hand, this study used generic feed ingredient production data (from databases in SimaPro v8.3), together with a number of literature-based assumptions for missing processes (Table S4, supporting information). Regarding the feed ingredients for production of salmon feed in this study, part of them, including fish meal and oil, were produced in China. However, there is not yet published LCI data on Chinese fisheries and fishmeal production processes. Under such circumstances, it is hard to conclude whether the LCIA results of feed production in this study was overestimated or underestimated, though transport of feed ingredients to the Chinese feed manufacturing plant was excluded from the system studied. On the other hand, the LCIA results of infrastructure (part of foreground systems) may be underestimated, since only building materials of the grow-out farm were included in this study.

To better support LCA as an environmental decision support tool for aquaculture, further LCI-oriented research is needed, especially on cradle-to-gate feed ingredient production processes and more detailed analysis of other relevant processes (e.g. building materials, transportation, on-site wastes/emissions, disinfectants, vitamins, and antibiotics), which may further unveil neglected contributing factors of life cycle impacts of RAS farming.

References

Aubin, J., E. Papatryphon, H. M. G. Van der Werf, J. Petit, and Y. M. Morvan. 2006. Characterisation of the environmental impact of a turbot (Scophthalmus maximus) re-circulating production system using Life Cycle Assessment. *Aquaculture* 261(4): 1259-1268.

Ayer, N. W. and P. H. Tyedmers. 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production* 17(3): 362-373.

Chadwick, E. M. P., G. J. Parsons, and B. Sayavong, eds. 2010. *Evaluation of Closed-containment Technologies for Saltwater Salmon Aquaculture*. Ottawa, Canada: NRC Research Press.

Davidson, M. R., D. Zhang, W. Xiong, X. Zhang, and V. J. Karplus. 2016. Modelling the potential for wind energy integration on China's coal-heavy electricity grid. *Nature Energy* 1: 16086.

Ellingsen, H. and S. A. Aanondsen. 2006. Environmental Impacts of Wild Caught Cod and Farmed Salmon - A Comparison with Chicken. *The International Journal of Life Cycle Assessment* 11(1): 60-65.

Ellingsen, H., J. O. Olaussen, and I. B. Utne. 2009. Environmental analysis of the Norwegian fishery and aquaculture industry—A preliminary study focusing on farmed salmon. *Marine Policy* 33(3): 479-488.

Hognes, E. S., F. Ziegler, and V. Sund. 2011. *Carbon footprint and area use of farmed Norwegian salmon*. SINTEF project report no. F21039. Trondheim: SINTEF Fisheries and aquaculture.

Katevas, D. S. 2014. Krill meal and krill oil: How price and tonnage competitive are they with other fishmeals and oils? *Aquafeed: Advances in Processing & Formulation* 6(4): 12-20.

Liu, B., Y. Liu, and X. Wang. 2015. The effect of stocking density on growth and seven physiological parameters with assessment of their potential as stress response indicators for the Atlantic salmon (Salmo salar). *Marine and Freshwater Behaviour and Physiology* 48(3): 177-192.

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

McGrath, K. P., N. L. Pelletier, and P. H. Tyedmers. 2015. Life Cycle Assessment of a Novel Closed-Containment Salmon Aquaculture Technology. *Environmental Science & Technology* 49(9): 5628-5636.

Parker, R. W. R. and P. H. Tyedmers. 2012. Life Cycle Environmental Impacts of Three Products Derived from Wild-Caught Antarctic Krill (Euphausia superba). *Environmental Science & Technology* 46(9): 4958-4965.

Pelletier, N., P. Tyedmers, U. Sonesson, A. Scholz, F. Ziegler, A. Flysjo, S. Kruse, B. Cancino, and H. Silverman. 2009. Not All Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. *Environmental Science & Technology* 43(23): 8730-8736.

Sun, G. X. 2014. *Feeding strategy study for Atlantic salmon (Salmo Salar L.) in recirculating aquaculture system* (in Chinese). PhD thesis. Qingdao: Institute of Oceanology, Chinese Academy of Sciences.

Ziegler, F., U. Winther, E. S. Hognes, A. Emanuelsson, V. Sund, and H. Ellingsen. 2012. The Carbon Footprint of Norwegian Seafood Products on the Global Seafood Market. *Journal of Industrial Ecology* 17(1): 103-116.