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Recirculating Aquaculture Is Possible without Major Energy Tradeoff: Life Cycle Assessment of Warmwater Fish Farming in Sweden

Kristina Bergman,* Patrik J. G. Henriksson, Sara Hornborg, Max Troell, Louisa Borthwick, Malin Jonell, Gaspard Philis, and Friederike Ziegler

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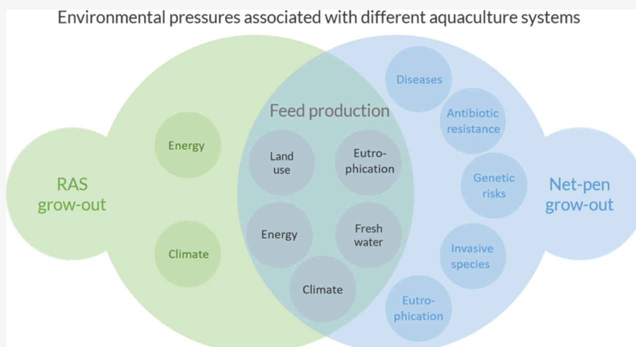
ABSTRACT: Seafood is seen as promising for more sustainable diets. The increasing production in land-based closed Recirculating Aquaculture Systems (RASs) has overcome many local environmental challenges with traditional open net-pen systems such as eutrophication. The energy needed to maintain suitable water quality, with associated emissions, has however been seen as challenging from a global perspective. This study uses Life Cycle Assessment (LCA) to investigate the environmental performance and improvement potentials of a commercial RAS farm of tilapia and Clarias in Sweden. The environmental impact categories and indicators considered were freshwater eutrophication, climate change, energy demand, land use, and dependency on animal-source feed inputs per kg of fillet. We found that feed production contributed most to all environmental impacts (between 67 and 98%) except for energy demand for tilapia, contradicting previous findings that farm-level energy use is a driver of environmental pressures. The main improvement potentials include improved by-product utilization and use of a larger proportion of plant-based feed ingredients. Together with further smaller improvement potential identified, this suggests that RASs may play a more important role in a future, environmentally sustainable food system.



■ INTRODUCTION

To achieve future food and nutrition security without jeopardizing the multiple functions of ecosystems and use resources efficiently, global food production needs to transform.[1] There are major differences in nutritional value, resource requirements, and environmental footprint between food groups and food products.[2,3] Increased understanding of the environmental performance of different production systems' and product nutritional qualities is key to ensuring human health while reducing environmental pressures. In this sense, increasing global seafood production particularly at the expense of red meat has repeatedly been identified as a promising strategy for improved sustainability.[4,5]

In European countries, dietary advice often recommends an increased consumption of seafood[6,7] based on nutritional properties. The bulk of European seafood consumption today consists of only a handful of species, with tuna dominating followed by cod, farmed salmon, Alaska pollock, and shrimp. Seafood is, however, a particularly diverse food group in terms of nutritional value and environmental footprints.[2,8,9] Around 2500 species are globally harvested from the wild and 600 species are farmed, with both systems using a wide range of production methods.[10] Some species can be produced both from fisheries and aquaculture using methods with widely different environmental impacts. Besides seafood from capture fisheries being a limited resource, there are also concerns over unsustainable fishing practices, such as for cold-water shrimp,[11] and the risk of spreading of nutrients, diseases, and parasites to the surrounding ecosystems for the current production systems (open net-pen) for farmed salmon.[12] To reduce the overall environmental impacts of the food system, these differences are important to identify and consider in national strategies and policies.

Consequently, the Swedish environmental legislation is highly restrictive in giving permits for traditional open net-pen systems due to eutrophication in coastal waters and because aquaculture production is marginal. Closed, land-based recirculating aquaculture systems (hereafter referred to as RASs) have therefore attracted interest to meet national strategies in aquaculture development as seen also in Norway,

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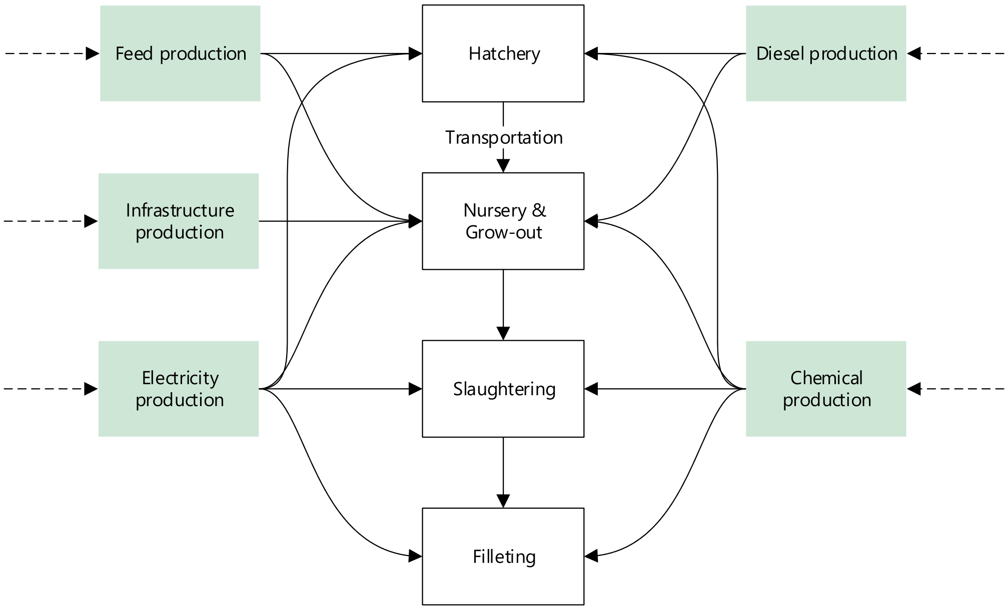

Figure 1. Simplified flowchart of the studied system with primary data in white boxes and secondary data in shaded boxes. Dashed lines indicate upstream processes.

the United States, across Europe, and China.[13,14] A RAS is generally constructed with fish tanks connected to mechanical and biological filters and with water treatment, e.g., for aeration and disinfection.[14] The treated water is recirculated back into the farming tanks while ammonia is converted into nitrate, which can be denitrified or gathered together with sludge. Being completely separated from natural ecosystems, RASs offers solutions to the main environmental issues with open net-pens as there is no risk of spreading nutrients, antimicrobials, parasites, or invasive species. Many of the recently established Swedish RAS production sites produce tropical finfish and crustacean species, such as Nile tilapia (*Oreochromis niloticus*), African Clarias catfish (*Clarias gariepinus*), and Whiteleg shrimp (*Penaeus vannamei*). These warmwater species are highly productive and require low protein inputs[15] but need to be farmed in warm water (around 30 °C).

Closed farming systems offer more controlled rearing conditions that may contribute to a lower occurrence of disease and a more efficient Feed Conversion Ratio (FCR) in the RAS than traditional open net-pen systems.[16] The improved FCR is achieved through healthier fish and better control of feeding. However, RASs require more technical input and energy to facilitate water aeration and purification in order to create suitable conditions for the fish to live and grow than in open farming systems. Previous LCAs of RASs have accordingly highlighted the environmental tradeoffs when turning to the RAS.[17,18] Ayer and Tyedmers,[17] for example, concluded that abiotic depletion (the depletion of non-renewable resources), global warming, and acidification impacts of the RAS powered by a generic Canadian electricity mix are over an order of magnitude higher than those of an open net-pen system. Song et al.,[19] similarly, concluded that electricity generation, together with feed production, dominated eight out of the nine impact categories (ranging 54−95% in total).

The goal of this study is to quantify and evaluate the current environmental performance of tilapia and Clarias produced in a commercial RAS in Sweden, as well as their improvement potential, using Life Cycle Assessment (LCA). This is one of the first LCAs evaluating a commercial RAS and the first to our knowledge to evaluate tilapia and Clarias farmed in a RAS. Increased understanding about the efficiency of these systems will help guide industry, policy, and research to further improve environmental performance and can also form a basis for strategic decisions forming a developing sector.

■ METHODS

Goal and Scope Definition. The functional unit (FU) in this study was 1 kg of fillets without skin of tilapia and Clarias (excluding packaging) following cradle-to-farmgate system boundaries. The study includes fry production, transportation of fry, grow-out in a RAS, and associated inputs (Figure 1, Table 1). The analysis covers impacts up to farmgate, which also include on-site slaughtering and hand filleting of the fish (Figure 1). Impacts associated with grow-out infrastructure and equipment were included, while the existing buildings used for farming and their maintenance were not. The business idea of the company is to use empty former farm buildings whose age (>30 years) motivates excluding their construction from the analysis. Environmental burdens were allocated among co-products (e.g., between fish meal and fish oil) based on mass as well as monetary value, with results presented for both strategies to enhance transparency and usability. Farm inputs whose use depends on space and water volume (e.g., electricity, freshwater, and tanks) were divided between tilapia and Clarias by stocking density (see the Supporting Information, Table S1) as space and freshwater are physically needed to maintain the grow-out, is related to stocking density (kg fish m^{-3}). Inputs for chemicals and equipment for water treatment were divided by fish biomass (kg) as that correlates to the volume of fish (Table S1).

Life Cycle Inventory Analysis. Data related to fish farming (nursery & grow-out, slaughtering, and filleting), representing production in 2017, were gathered directly from the largest farmer of tilapia and Clarias in Sweden. The studied system is a closed freshwater system with recirculating water in

Table 1. Farm Inputs and Outputs per Tonne Live Weight of Tilapia and Clarias Produced (Including Energy and Water for Slaughtering and Hand Filleting)

	tilapia	Clarias
economic inputs per tonne of fish		
fry (pcs)	66,768	23,276
electricity (kWh)	3086	771
diesel (l)	0.09	0.02
sodium hydroxide (kg)	0.015	0.016
sodium hypochlorite (kg)	0.30	0.31
potassium hydroxide (kg)	0.002	0.002
feed (kg)	1100	1100
hydrochloric acid, conc. 20% (kg)	0.3	0.3
transportation with truck (tkm)	6	2
plastic (kg)	2.6	2.5
iron (kg)	1.4	0.7
glass fiber plastic (kg)	4.4	1.1
environmental inputs		
freshwater (m^3)	76	19
land, grow-out site (m^2a)	33	15
economic outputs		
tilapia, live (kg)	1000	
Clarias, live (kg)		1000
environmental outputs		
N (kg)	30	30
ammonia (kg)	0.4	0.4
dinitrogen monoxide (kg)	0.7	0.7
ammonium (kg)	26	26
nitrate (kg)	11	11
P (kg)	2	2

which fish are grown in tanks connected to mechanical drum filters and moving bed biological filters to remove solids and ammonia. Electric pumps and fans were used to circulate and aerate water, and heat exchangers were used to keep water temperature around 30 °C. Fish were slaughtered in ice baths or by hand through piercing of the head. Filleting was also done manually. Energy (for heating and lighting in the combined farming and processing building and for ice production), water (for ice baths and cleaning), and cleaning agents needed for the slaughtering and filleting were not possible to separate from that for the grow-out. Inputs and outputs from the hatchery operation were based on previously published data on Chinese tilapia hatcheries,[20] adjusted to represent a Dutch hatchery by adapting the energy source and transportation by car (see the Supporting Information, Table S10 for details). Excretion of nitrogen (N) and phosphorus (P) for both farm and hatchery was calculated using a mass balance as detailed by Henriksson et al.[20] A tilapia fish feed recipe averaged over 2017 from the producer of the aquafeed for the relevant country was obtained and only adjusted to the specific levels of fishmeal and fish oil used on the studied farm. Microingredients, such as vitamins and amino acids, were excluded since detailed composition and inventory data were lacking. The electricity used on the farm was certified renewable electricity from wind, but the baseline scenario was modeled using the average Swedish electricity consumption mix as to better represent the potentials of upscaling this type of farming system rather than benchmarking this individual farm. Also, Sweden's most prevalent renewable energy source is hydropower. This is already fully utilized, suggesting that an overall increase in electricity demand needs to come from alternative energy sources. Emission estimates from such changes in demand are often assumed to come from peaking power plants, such as gas and oil, or imports, but since Sweden is expanding other renewable electricity sources, our view is that the grid average should be used.

Life Cycle Impact Assessment. Four environmental impacts were selected as relevant to assess for the aim of this study: freshwater eutrophication (ILCD 2011 Midpoint method version 1.10); climate change (IPCC 2013[21] with a timeframe of 100 years); energy demand (CED version 1.10[22]); and land use (simply estimated as the number of square meters needed annually from cradle-to-farmgate). Toxicological impact would also be of interest to assess for a food production system, but it was left out given the lack of readily available characterization factors for relevant chemicals. Acidification was excluded due to its large overlap with climate change.

Dependency on marine and poultry by-product ingredients was calculated using a slightly modified Forage Fish Dependency Ratio (FFDR) from the Aquaculture Stewardship Council (ASC) salmon standard v 1.1[23] (see the Supporting Information for further information).

All LCI modeling and characterization were performed using the SimaPro 8.5 software, with secondary data on feed ingredients from Agri-footprint (version 4.0) and the remaining secondary data from the Ecoinvent 3.4 database. Greenhouse gas (GHG) emissions from land use change (LUC) are included in the Agri-footprint data. The Agri-footprint database provides country and crop-specific emissions driven by LUC based on the PAS2050-1 framework.

Sensitivity Analysis and Alternative Scenarios. Sensitivity analyses were performed to evaluate the influence of modeling decisions and alternative farming practices to identify potential improvements. We investigated the outcome of (1) excluding LUC-associated GHG emissions, (2) utilizing entirely crop-based feed, (3) 100% utilization of filleting by-products, (4) Swedish renewable or global consumption mix as the electricity source, and (5) emitting waste nutrients to nature. When evaluating the effects of the fate of waste nutrients, no additional potential changes in the farming system (e.g., in equipment or energy demand) were considered. Crop-based feed options were based on the commercial alternative recipe for tilapia obtained from the same aquafeed producer as described above, which can maintain the same FCR according to the manufacturer.

Comparison with Other Farmed Fish. To put the environmental performance of this RAS into perspective and to bring attention to environmental tradeoffs, a comparison was made with other RAS LCAs and with fish farmed in open systems. In addition to climate change and freshwater eutrophication impacts, products were compared regarding energy consumption, fuel use, FCR, FFDR, mortality, and use of antimicrobials. Indicators were selected to capture additional relevant sustainability aspects of aquaculture. The comparison included LCAs on an early, experimental RAS production of Arctic char (*Salvelinus alpinus*),[17] a more recent large-scale RAS production of Atlantic salmon (*Salmo salar*),[19] tilapia and pangasius (*Pangasianodon hypophthalmus*) farmed in Asia in traditional ponds or cages,[20] and salmon farmed in open net-pens.[25] The two products from Asia are of the same or similar species as studied here and of relevant origin for the Swedish market,[26] whereas net-pen farmed salmon is both a different species and production system. It was included as it is

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Table 2. Life Cycle Impacts from the Production of 1 kg of Tilapia and 1 kg of Clarias Fillets Using Mass and Economic Allocation

		tilapia fillets		Clarias fillets	
impact category	unit	mass allocation	economic allocation	mass allocation	economic allocation
f. eutrophication	g P eq.	1.9	1.1	1.0	0.5
climate change	kg CO_2 eq.	14.7	7.0	9.3	4.3
land occupation	m^2a	10.2	4.5	5.9	2.2
energy demand	MJ	235	207	81	63

currently one of the most consumed species in Sweden and Europe[27] and represents aquaculture practices that RAS farming of omnivores aims to avoid (e.g., farming of carnivorous fish and farming in open systems). To enable a fair and harmonized comparison across studies using different methodologies as far as possible, climate change and eutrophication impacts were recalculated based on inventory data on the two main drivers for these systems (feed and energy). Here, the comparison stops at farmgate, disregarding edible yield, the fate of by-products, and assuming identical carbon footprints for energy and feed ingredients. While this is simplified, it avoids the strong influence of different LUC emission models and specific electricity mix, allowing a comparison of the systems conceptually, rather than the specific farms. The reported feed composition for each fish was used to calculate impacts with Agri-footprint data, and all the same assumptions and specific method choices as detailed above were used.

RESULTS AND DISCUSSION

Life Cycle Inventory Results. The studied farm produced 20 tonnes of Clarias and 20 tonnes of tilapia in 2017. The economic FCR was 1.1 for both species (Table 1). Filleting was done by hand with fillet yields of 35% for tilapia and 50% for Clarias. Filleting by-products (frames, heads, etc.) were not utilized for food or feed, only for energy production (biogas). All environmental burdens were consequently allocated to the fillets. The farm had four employees who in total worked 9600 h in the year of production. Stocking density values before slaughter were 60 and 250 kg m^{-3} for tilapia and Clarias, respectively. Pumps were almost exclusively powered by electricity, with a backup diesel generator only used on rare occasions of power failure. Chemicals were used to adjust pH and for cleaning.

Feeds are mainly constituted of plant-based ingredients, predominantly maize gluten feed, wheat, and soybean meal. In addition, 9−10% poultry by-products and 10−16% marine ingredients were included for tilapia and Clarias (see the Supporting Information, Tables S2 and S3).

Life Cycle Impact Assessment. Tilapia production was consistently associated with higher impacts across all impact categories (Table 2 and Table S4 for results per live weight), mainly as a result of the lower fillet yields and lower stocking density. The allocation strategy had a large influence on absolute values, requiring caution if comparing with other products. A major driver behind this was the large impact from feed (Figure 2) in combination with using poultry by-products that are associated with disproportionately large environmental impacts.

Despite the low FCR, feed production was the main driver behind all impact categories except energy demand for tilapia and all four impacts and indicators for Clarias (Figure 2; for economic allocation see Figures S1 and S2). Assessment of

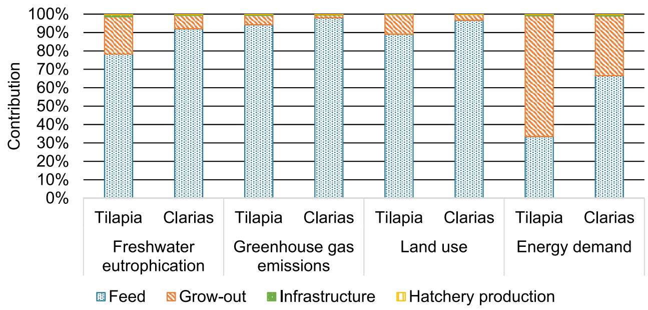

Figure 2. Life cycle contribution of 1 kg of tilapia and Clarias fillets using mass allocation.

microingredients was excluded due to the lack of data but could potentially contribute with up to 10% to climate change according to Hognes et al.[24] The dominating contribution to environmental impacts from feed has been widely observed before in LCAs of conventional production of various species.[28−31] However, it is notable that we see that same pattern for a product farmed in an RAS as previous LCA studies of such systems have shown that the extent of energy- and/or infrastructure requirements needed often overshadow the impact of feed.[19,32,33] Feed had a less dominating impact on energy demand, where the grow-out operations that include electricity use for farming accounted for 66% of the energy needed to grow tilapia and 32% for Clarias. Previous LCA studies of RASs have raised concerns about high GHG emissions related to energy provision.[17−19,33] However, the current system had a considerably lower energy use despite being located in a temperate country. Electricity consumption only varied by ±15% throughout the year while maintaining a water temperature around 30 °C in a climate that falls well below freezing in winter. Well-insulated buildings and the use of heat exchangers facilitated for efficient heat conservation. In addition, there was no need to oxygenate the systems, which can drive energy demand for the RAS.[17] In contrast to findings in LCAs of open net-pen production,[34,35] the grow-out stage of tilapia and Clarias had limited contributions to freshwater eutrophication in comparison to feed production,[30] which was expected as nutrients were retrieved and utilized. Hatcheries had only marginal contributions to overall impacts, as has been concluded for many other systems.[19,20]

Production of both tilapia and Clarias relies on animal inputs in feeds. For Clarias, the animal inputs are split equally between poultry by-products and fish inputs, while the production of tilapia relies more on poultry by-products. Clarias uses 0.48 kg of whole fish and 0.19 kg of fish by-products per kg of fillet, and tilapia uses 0.34 kg of whole fish and 0.14 kg of by-products. Adding poultry by-products, the relationship between total animal-in and fish-out in both cases is just over a one-to-one ratio (1.21 kg per kg of tilapia fillets and 1.33 for Clarias fillets).

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Table 3. Sensitivity and Scenario Analysis of Results Using Mass Allocation (Relative Change Compared to Baseline Scenario)

	freshwater eutrophication		climate change		land use		energy demand	
	tilapia	Clarias	tilapia	Clarias	tilapia	Clarias	tilapia	Clarias
by-products used	−65%	−50%	−65%	−50%	−65%	−50%	−65%	−50%
renewable electricity	−13%	−4%	−2%	−1%	−11%	−3%	−35%	−17%
global electricity mix	+350%	+109%	+91%	+25%	−7%	−2%	+21%	+10%
excluding land use change			−46%	−47%				
nutrients emitted	+312%	+401%						
vegetarian tilapia feed	−7%		−28%		−18%		−13%	

Sensitivity Analysis and Alternative Scenarios. Assumptions related to emissions from land use change strongly influenced results (Table 3; for economic allocation see the Supporting Information, Table S5) as has been shown in other LCAs of foods.[3] Excluding the GHG emissions from the land transformation, primarily driven by soy production on deforested land in Brazil, would reduce the GHG emissions from tilapia and Clarias roughly by half. This demonstrates the major improvement potential of excluding this type of soy as well as poultry fed soy from the feed.

Emitting nutrients to nature instead of using a biological filter to use nutrients as the fertilizer would result in 4 times larger eutrophication impacts for tilapia and 5 times larger for Clarias. No additional changes in the farming system were considered in the alternative scenario, but it is possible that a farming system with less water filtering would save energy. Holding sludge, however, also results in methane and nitrous oxide emissions, both powerful GHG emissions, which was not included, but could potentially give rise to considerable GHG emissions. It is therefore critical that the sludge digestion is done correctly and that the methane should ideally be collected for use as biogas.[36]

Improving by-product utilization from filleting, using more crop-based feed ingredients, and switching to renewable energy would decrease the impacts of the farmed species for all impact categories (ranked from most to least benefits). Of these, the studied farm already sources renewable energy and alternative feed sources are being investigated. Additional improvements not tested include higher fillet yields and lower FCRs. The fate of by-products strongly affects results since the fish fillets make up only 35% of tilapia's live weight and 50% of Clarias'. The by-products are currently used for biogas production, which is considered a waste treatment, thus not allocated any environmental burdens related to fish production. If by-products instead were used to produce feed ingredients and a proportion of burdens were allocated to this part, climate change impacts (mass allocated) would decrease considerably (Table 3). Pure crop-based tilapia feed would further lower impacts between 7 (freshwater eutrophication) and 28% (climate change). This feed was, however, assumed to be mainly based on soybean meal, wheat middlings, and rice bran (Figure 3). Since soy and rice productions contribute to considerable environmental impacts (e.g., from land transformation as mentioned above), it is evident that when replacing fish and poultry ingredients, attention is needed to the type of crop-based ingredient used for overall reduction of pressures. Examples of crop-based feed ingredients with a high protein content and lower climate impact are fava beans and peas (based on Ecoinvent and Agri-footprint databases). There are different ways of viewing the use of processing by-products from, e.g., poultry or fish processing. They could be viewed as free from upstream burdens, as they would potentially

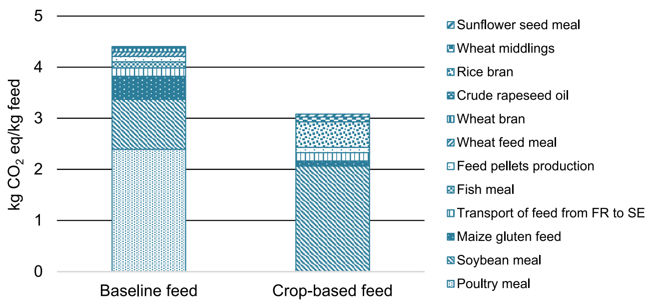

Figure 3. Greenhouse gas emissions of the two tilapia feeds.

otherwise be wasted, and as they could even replace production of another feed input. Here, we see the by-products as an integrated part of the value chain that contributes to the profitability of the main product supply chain and thereby should also share its environmental burdens.

A switch to renewable energy had limited effects on the results. This was expected since the Swedish electricity mix used in the main results is dominated by nuclear and hydropower sources. The difference in primary energy demand between energy sources is explained by energy losses accounted for in nonrenewable electricity production. The environmental footprint would increase (with the exception of land use) if the farm had been located elsewhere where electricity production is based on less renewables than it is in Sweden. Grow-out operation powered by the global electricity production/consumption mix would, for example, outsize the contribution to freshwater eutrophication for both tilapia and Clarias and slightly exceed (by 2%) the contribution of feed to GHG emissions for tilapia. This, together with lower energy consumption, contributes to differences in GHG emissions in earlier RAS LCA studies.

Land-Based Farming of Tilapia and Clarias in Comparison to Other Farmed Fish. All fed aquaculture systems have the environmental burden from feed in common, but depending on the farming system, the overall resource use, emissions, and pressures put on ecosystems are variable (Figure 4). Some of the most critical challenges concerning grow-out from net-pen farming are eutrophication and the risks of spreading invasive species, disease, or antimicrobial resistance.[12,37] Those impacts can almost be eliminated in a closed, land-based RAS but at the costs of energy and potentially climate impacts.

It is essential to acknowledge that several environmental impacts mentioned above have not been analyzed in aquaculture LCAs or cannot be assessed by the LCA methodological framework.[37] For some concerns, national statistics provide perspectives. For instance, the annual production of 1.35 million tonnes of Norwegian salmonids in net-pens (salmon and trout) generated around 160,000

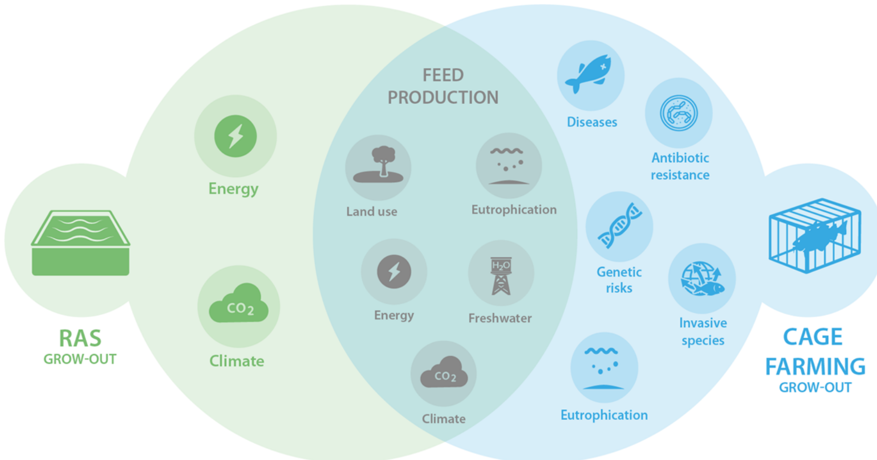

Figure 4. Environmental pressures associated with closed land-based Recirculating Aquaculture Systems (RASs) versus open systems (cage or pond aquaculture).

Table 4. Comparison of Some Performance Indicators for Farmed Fish per Tonne Live-Weight with Recalculated Eutrophication Potential and GHGe Assuming Comparable Electricity and Feed Ingredient Data

system	energy use grow-out, kWh	fuel grow-out, l	FCR	FFDR (incl. by-ps)	mortality grow-out, kg	antibiotics use, g	eutrophication, % of highest	GHGe, GLO electricity, % of highest	GHGe, SE renewable electricity, % of highest
tilapia, RAS[a]	3084	0.10	1.10	0.5	0.20	0	41%	32%	72%
Clarias, RAS[a]	771	0.02	1.10	0.7	0.25	0	32%	23%	67%
Arctic char, RAS[17]	22,600	279.00	1.45	2.2	0.30		100%	100%	100%
salmon, RAS[19]	7509	0.00	1.45	3.7	0.13		41%	42%	60%
Salmon, net-pen,[43,25,42]	0	135.00	1.32	1.9	0.05	0.1	79%	16%	52%
tilapia, ponds[20,44]	528	87.60	1.48	0.4	0.10	1.4	65%	22%	66%
pangasius, ponds[20,44]	57	1.23	1.59	0.5	0.20	93.0	75%	27%	86%

[a]This study; Ayer & Tyedmers;[17] Song et al. 2019;[19] Winther et al. 2020;[43] Ziegler et al. 2013 (mortality);[25] Henriksson et al. 2018 (antibiotics use);[42] Henriksson et al. 2015;[20] Rico et al. 2013 (antibiotics use).[44]

escapees in 2018.[38] Escapees are together with salmon lice the most potent threat to the wild salmon stocks.[39,40] Salmon lice and the treatments used to control its occurrence are putting additional pressure on ecosystems. Use of antimicrobials and other therapeutants remain an issue for aquaculture sectors including salmon farming in Chile or pangasius farming in Vietnam.[41,42] The environmental footprints of such treatments in open sea-based production are relevant to consider ensuring fair comparisons with RASs. An advantage of farming tropical species in temperate regions is that there is no risk of introducing nonindigenous species or mixing with wild fish stocks genetically. An additional benefit with freshwater species is that it allows for easy recirculation of wastes on agriculture land since wastes do not contain salt.

Differences between open and closed systems, as well as within systems and species, are shown in a comparison of seven species and production systems of farmed fish regarding both non-LCA indicators (e.g., mortality during grow-out and antimicrobial use) and two critical LCA impact categories (climate change and eutrophication) (Table 4). RAS-farmed Clarias, tilapia, and salmon had the lowest eutrophication impacts (for absolute values, see the Supporting Information, Table S6), while Arctic char farmed in the RAS was associated with the highest eutrophication potential. This was for Arctic char driven by high electricity use, also contributing to GHG emissions, while grow-out dominated eutrophying emissions from net-pen and pond systems (Table S7). Salmon in net-pen, however, had the lowest GHG emissions by assuming a global electricity mix followed by tilapia in ponds and Clarias in the RAS (Table 4). If grow-out processes instead were powered by renewable electricity, the relative environmental impact from feed increases (Table S8, Table S9) and differences between aquaculture systems and species are to some extent evened out. Antibiotics may be used in open cage and pond systems but were completely absent (or in two cases not measured) for the land-based RAS.

The RAS-farmed Clarias and tilapia had lower FCRs than all other systems. Interestingly, the FCR for RAS salmon was higher than that for salmon farmed in net-pens, which goes against previous findings that RASs generally have lower FCR.[16] This could potentially reflect differences in optimization. Tilapia and Clarias from Sweden had similar levels of forage fish dependency to tilapia and pangasius farmed in Asia (all below 1 kg of fish per kg of fish produced, meaning they are net fish producers). The three salmonid systems all rely on forage fish to a greater extent (from around 2 kg of fish per kilo of fish produced for salmon in net-pen in Norway to around 4 for salmon in the RAS in China). Other animal-based inputs into feed for the fish compared vary from 0 and 1 (Table S6).

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Edible yields differ between species. The fillet yield for tilapia in this study (35%) was considerably lower than those for Clarias (50%) and for salmon (58−88% edible).[45] The relative environmental impacts would therefore change if measured per edible yield instead of per live weight. Furthermore, the nutritional profiles differ in terms of protein and omega-3 contents.[2]

■ RECOMMENDATIONS

This study showed that the tradeoff between energy demand (with associated emissions) and avoiding risk to the marine environment (spreading of nutrients, disease, parasites, antimicrobial resistance, and escapees) can be smaller than previously reported for RASs. Along with the large improvement potentials observed, this suggests that RAS-farmed fish can contribute to a more sustainable food system including more seafood.

It is essential to acknowledge that many highly relevant environmental interactions for aquaculture are not possible to assess using the LCA framework, many of which RAS systems outperform open net-pen technology. This emphasizes the need to look beyond LCA results when examining sustainability of aquaculture.

Current small-scale farms could benefit from scaling-up, especially when it comes to possibilities to filleting by-products more efficiently. Up-scaling of RAS farms in Sweden would however be made easier if the environmental legislation was altered so permits were given based on environmental pressures rather than on the amount of feed used, as is the case today.

RAS systems are an emerging production technology under continuous improvement. The results here should be regarded as a snapshot of a still evolving industry in Sweden. The tilapia and Clarias RAS exhibited major improvement potentials for activities contributing most to climate change such as feed choice and utilization of by-products. Farms should focus on utilizing as much as possible fish and optimize toward using low-impact feed ingredients. Future RAS farms in Sweden are encouraged to buy specifically certified eco-labeled wind power as this most likely would increase renewable generation capacity rather than marginalizing other users. The studied RAS already shows promise, and through development in more sustainable directions identified here, land-based farming of tropical fish can contribute to a sustainable future food sector in Sweden.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c01100.

> A detailed description of allocation for input data, hatchery data, and aquafeed recipes is provided in the Supporting Information. Results calculated with the alternative allocation method, functional unit, and input data are also provided (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Kristina Bergman − *RISE Research Institutes of Sweden, Agrifood and Bioscience, 402 29 Göteborg, Sweden;* orcid.org/0000-0001-5888-4943; Email: kristina.bergman@ri.se

Authors

Patrik J. G. Henriksson − *Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden; Stockholm Resilience Centre, Stockholm University, 106 91 Stockholm, Sweden; Worldfish, 11960 Penang, Malaysia*

Sara Hornborg − *RISE Research Institutes of Sweden, Agrifood and Bioscience, 402 29 Göteborg, Sweden*

Max Troell − *Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden; Stockholm Resilience Centre, Stockholm University, 106 91 Stockholm, Sweden*

Louisa Borthwick − *RISE Research Institutes of Sweden, Agrifood and Bioscience, 402 29 Göteborg, Sweden*

Malin Jonell − *Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, 104 05 Stockholm, Sweden; Stockholm Resilience Centre, Stockholm University, 106 91 Stockholm, Sweden*

Gaspard Philis − *Department of Biological Sciences, Norwegian University of Science and Technology, 6009 Ålesund, Norway*

Friederike Ziegler − *RISE Research Institutes of Sweden, Agrifood and Bioscience, 402 29 Göteborg, Sweden*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.0c01100

Notes

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