Food Product Environmental Footprint Literature Summary:

Land-Based Aquaculture

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Executive Summary:

Land-Based Aquaculture

Aquaculture is the fastest growing food production sector globally. The United Nations Food and Agriculture Organization (FAO) sees little possibility to increase supply from wild capture fisheries to meet the growing demand for fish protein, as 75% of the world's fishing grounds are fully exploited, over exploited or severely depleted. Despite declines in wild fishery production, global demand for seafood continues to grow, and land-based aquaculture is slated to see continued growth to meet increased market demand. In this context, some systems of marine aquaculture production, especially for high value species, are moving towards land-based farming, enabled by technological equipment for water re-circulation. The mainstay of U.S. land-based aquaculture is the production of channel catfish, which occurs largely in earthen ponds in southeastern states, and oysters, which occurs in coastal areas. The U.S. is also the leading global importer of fish and fishery products. Ninety-one percent of the seafood we eat (by value) is imported, half of which is from land-based aquaculture.

Roughly half of the current global aquaculture production in terms of total harvested tonnage occurs in marine environments, such as fish raised in net pens or near-shore cages, or shellfish grown in bottom culture bags and rack bag systems. The focus of this summary, however, is to summarize life cycle assessment (LCA) research on the environmental impact of land-based aquaculture production systems. These studies can help identify the aspects of land-based aquaculture production that most contribute to environmental impacts, as well as potential trade-offs between impact categories. Such lessons can be useful in informing both developers of land-based aquaculture systems and selective buyers of land-based aquaculture products. The vast majority of studies focus only on impacts within the growing system, hence the downstream stages of processing through consumption are not covered in this review. Fish species represented in the reviewed studies include Atlantic salmon, rainbow trout, Arctic char, turbot, African catfish, tilapia, sea bass, common carp, tench, roach, perch, sander, and pike.

Key Findings

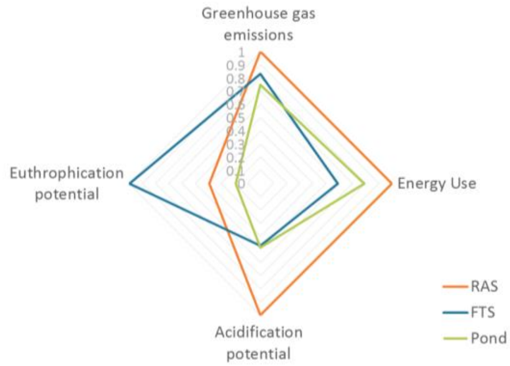
Potential benefits of land-based fish farming systems include minimized threats of cultured fish escaping and competing with wild populations, improved control of diseases and parasites, true management of water quality (temperature, oxygen rate, nutrient and suspended solids content), and better control of nutrient releases to the environment. Challenges include high capital costs, increased energy demand and operational costs, and potential for rapid chemistry alterations, which requires continuous monitoring. The three typical production systems in use include:

- **Recirculating aquaculture system (RAS)** – Closed systems, commonly tank based, in which water is processed to remove suspended solids and nutrients, and re-used. These systems have high energy use for pumping and filtering water, but are typically modular, and hence, are scalable and can be located nearly anywhere, including urban environments.
- **Flow-through systems (FTS)** – These commonly take the form of raceways or tanks with a one-time flow through of water with varying degrees of input and output water treatment methods. Water sources include river flows, well

water, or water pumped from a nearby coast. Compared to RAS, water use is high and nutrient releases are more challenging to control, but pumping energy needs are typically reduced.
- **Pond systems** – Possibly the earliest and most natural form of LBA, these consist simply of earthen or lined ponds or ditches, often using ecological processes to manage water quality.

The chart to the rights show a comparative overview of the environmental impacts per kilogram of fish produced by the dominant LBA systems, shown as an average of studies reviewed. In general, RAS have greater on-site energy demand, primarily electricity, than FTS because of pumping needs. This can reflect in higher energy use per kilogram fish, as well as higher carbon footprint and acidification potential. Due to the flow through aspect of FTS nutrient releases tend to be higher than both RAS and Pond systems, which is reflected in the eutrophication impact category. Feed production is another important contributor to nearly all environmental impact categories. Because of the general importance of feed, the amount of feed per kilogram of fish produced is also a strong determinant of a system's environmental impact.

Relative comparison of impacts for the three main aquaculture systems per kilogram of fish yield



Feed

The supply of feed remains one of the more controversial, and environmentally impactful aspects of land-based aquaculture. Historical perception has been that production of high value carnivorous fish such as salmon and trout requires feed containing fishmeal and fish oil, thus linking land-based aquaculture to wild fishing industries that may not be sustainable. In the past, because modern commercial fishing techniques generated significant by-catch, such fish-based aquafeeds were the most economical option. One study in 2009 demonstrated that the ratio of wild fisheries inputs to farmed fish output was 0.63 for the aquaculture sector as a whole (globally) but remained as high as 5.0 for farmed Atlantic salmon. Aquaculture's share of global fishmeal and fish oil consumption has risen substantially, as greater amounts of fishmeal are fed to omnivorous species, and high levels of fish oil are used to provide long-chain omega-3 oils in farmed fish. A number of LCA studies reviewed have found tradeoffs between impact categories when fish-based feeds are substituted with plant-based feeds.

Several studies have compared different types of feeds against each other, and have come to competing conclusions. In some studies, shifting from fish-derived ingredients to plant ingredients does not reduce energy or other environmental impacts (except for net primary production), but other researchers have documented the potential for energy savings and environmental benefits from using plant oils in lieu of fish oils. The general conclusions among these studies are that feed impact is highly dependent on source, and impacts of feed types, whether fish- or plant-derived can vary widely.

Conclusions

As wild fisheries diminish and demand for seafood continues to grow, land-based aquaculture is a promising production method with wide-ranging applicability. This review of existing LCA literature concludes the following:

- Much of the environmental impact of recirculating aquaculture systems is linked to electricity use. Thus, utilizing renewable electricity generation can significantly reduce the environmental footprint.
- Generally speaking, recirculating aquaculture systems have lower eutrophication impact than flow-through systems because low flow rates and high concentrations make nutrients easier to manage.
- Feed is an important driver of land-based aquaculture's environmental impact. While there is strong need to reduce wild fishery inputs to land-based aquaculture feed, replacement with plant-based alternatives does not necessarily result in reduced environmental impacts in all categories.

Overview

Land-based aquaculture is the fastest growing food production sector globally. The United Nations Food and Agriculture Organization (FAO) sees little possibility to increase supply from wild capture fisheries to meet the growing demand for fish protein. Approximately 75% of the world's fishing grounds are fully exploited, over exploited or severely depleted. Despite declines in wild fishery production, global demand for seafood continues to grow, and aquaculture is slated to see continued growth to meet increased market demand (Ecoplan International Inc., 2008). In this context, some systems of marine aquaculture production, especially for high value species, are moving towards land-based farming, enabled by technological equipment for water re-circulation. In addition, land-based aquaculture systems remain popular for freshwater species such as catfish and trout.

The U.S. has not kept pace with the rest of the world in the growth of its land-based aquaculture sector (Figure 1). The mainstay of U.S. land-based aquaculture is the production of channel catfish, which occurs largely in earthen ponds in southeastern states and oysters, which occurs in coastal areas. Yet, the U.S. remains the leading global importer of fish and fishery products. Ninety-one percent of the seafood we eat (by value) originates abroad, half of which is from land-based aquaculture[1]. There are compelling reasons for a need to expand land-based aquaculture production in the U.S., not the least of which is offsetting the $9 billion trade deficit in imported seafood products. Yet, to date, the slow growth of this industry has been due in part to the potential environmental impacts associated with some forms of land-based aquaculture, and resultant public opposition, combined with uncertain and/or conflicting regulatory authority among multiple state and federal agencies[2]. In addition, the economic market in much of the U.S. has not been conducive to starting land-based aquaculture businesses.

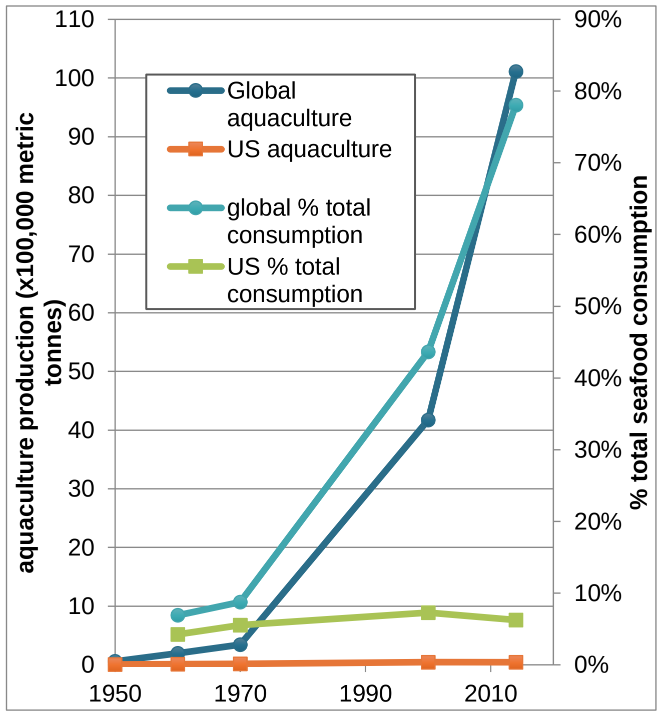


FIGURE 1. Global and U.S. growth in aquaculture. Dark blue and orange lines refer to total annual production on the left axis, light blue and green lines are the percentage of total seafood consumption met by land-based aquaculture (domestic aquaculture, in the case of the U.S.), on the right axis.

[1] http://www.nmfs.noaa.gov/aquaculture/aquaculture_in_us.html

[2] http://www.fao.org/fishery/countrysector/naso_usa/en

This summary offers highlights from life cycle assessment (LCA) research on the environmental impact of land-based aquaculture production systems. These studies can help identify the aspects of land-based aquaculture production that most contribute to environmental impacts, as well as potential trade-offs between impact categories. Such lessons can be useful in informing both developers of land-based aquaculture systems and selective buyers of land-based aquaculture products. It also may offer direction for policy that leads to minimally impactful land-based aquaculture systems.

This literature summary is one of a series commissioned by the Oregon Department of Environmental Quality. For additional information on the background and objectives, as well as on LCA methods and definitions of terms, please refer to the Food Product Environmental Footprint Foreword.

Available LCA Research

With the growth of land-based aquaculture production and concern for its environmental impact, so too have the number of LCA studies of aquaculture farms also grown. Roughly half of the current global aquaculture production (in terms of total harvested tonnage) occurs in marine environments[3] – fish raised in net pens or near-shore cages, shellfish grown in bottom culture bags and rack bag systems, etc. – and the impacts of these systems have been studied via LCA. The focus of this summary, however, is land-based aquaculture systems. Potential benefits of such fish farming systems include minimized threats of cultured fish escaping and competing with wild populations, improved control of diseases and parasites, true management of water quality (temperature, oxygen rate, nutrient and suspended solids content), and better control of nutrient releases to the environment. Challenges include high capital costs, increased energy demand and operational costs, and potential for rapid chemistry alterations, which requires continuous monitoring. Popular production systems can generally be categorized into the following:

- Recirculating aquaculture system (RAS) – Closed systems, commonly tank based, in which water is processed to remove suspended solids and nutrients, and re-used. These involve high energy use for water pumping and water filtration processes, but are typically modular and therefore easily scalable and can be located nearly anywhere, including urban environments.
- Flow-through systems (FTS) – These commonly take the form of raceways or tanks with a one-time flow through of water with varying degrees of input and output water treatment methods. Water sources include river flows, well water, or water pumped from a nearby coast. Compared to RAS, water use is high and nutrient releases are more challenging to control, but pumping energy needs are typically reduced.
- Pond systems – Possibly the earliest and most natural form of land-based aquaculture, these consist simply of earthen or lined ponds or ditches, often using ecological processes to manage water quality. Management techniques and intensity vary.

[3] http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en

We identified 12 publications that apply LCA to land-based aquaculture systems. With one exception (Sun, 2009), all studies focus only on impacts up to the farm gate. Therefore, little information is directly available on the downstream stages of processing, packaging, distribution, retail and consumption of aquaculture products (see Figure 2). In addition, we identified five reviews of aquaculture LCA and seven additional studies that use LCA to analyze feeds relevant to aquaculture.

Fish species represented in the reviewed studies include Atlantic salmon, rainbow trout, Arctic char, turbot, African catfish, tilapia, sea bass, common carp, tench, roach, perch, sander, and pike. Studied production systems were located in Canada (British Columbia and Nova Scotia), France, Germany, Netherlands, Denmark, Egypt, Tunisia, and Iran. In addition, one study on RAS production of shrimp in the US (Sun, 2009) was also reviewed.

Contrary to most LCA studies of food products, the reviewed studies on land-based aquaculture consistently consider an array of environmental impact categories, including greenhouse gas emissions (GHGE), non-renewable energy use, eutrophication potential (EP), and acidification potential (AP). Many studies also include a measure of the systems' use of "net primary production[4]" (a unique indicator to fishery and aquaculture systems), as well as water use or water dependence and land surface use.

FIGURE 2. Generic system diagram for land-based aquaculture. Stages in blue were not included in nearly all of the LCA studies considered in this summary.

Key Findings

As mentioned, nearly all of the LCA studies reviewed consider only cradle-to-farm-gate stages, so findings here focus on the impact of producing live fish at the farm gate. Figures 3 and 4 show the aggregated results of 25 scenarios (11 RAS, 10 FTS, 4 pond) from 11 studies. A few general observations related to Figures 3 and 4 are presented here. More detailed consideration of key aspects will follow in later sections.

In general, RAS have greater on-site energy demand (primarily electricity) than FTS because of pumping needs. This can reflect in higher energy use per kilogram fish, as well as GHGE and AP, but as the range of values in Figures 3 and 4 suggest, it is not the case for all examples. Two of the "pond" scenarios shown also have high on-site energy demands. One of these is a

[4] Net primary production is a measure of the rate of biomass accumulation within an ecosystem and an indication of the relative trophic level (location on the ecological food chain) of a given aquaculture system. Aquaculture systems that rely on fish- or animal-based feeds will typically have higher net primary production use than those that rely predominantly on plant-based feeds.

semi-extensive pond farm in France where management is focused on producing fish of high organoleptic (taste, color, odor, feel) quality; annual complete drainage of the ponds results in a high diesel consumption for pumping (Wilfart et al., 2013). The other is a semi-intensive tilapia farm in Egypt, where low stocking density make energy for water pumping and aeration high per kilogram of fish (Yacout et al., 2016). Of the literature reviewed however, ponds averaged the lowest energy use.

While all studies included the impact of feed and energy use, most studies do not include estimates of the direct emissions that can occur when nutrients in feeds degrade to nitrous oxide (N_2O), a potent greenhouse gas, during fish rearing. The one exception was a study of

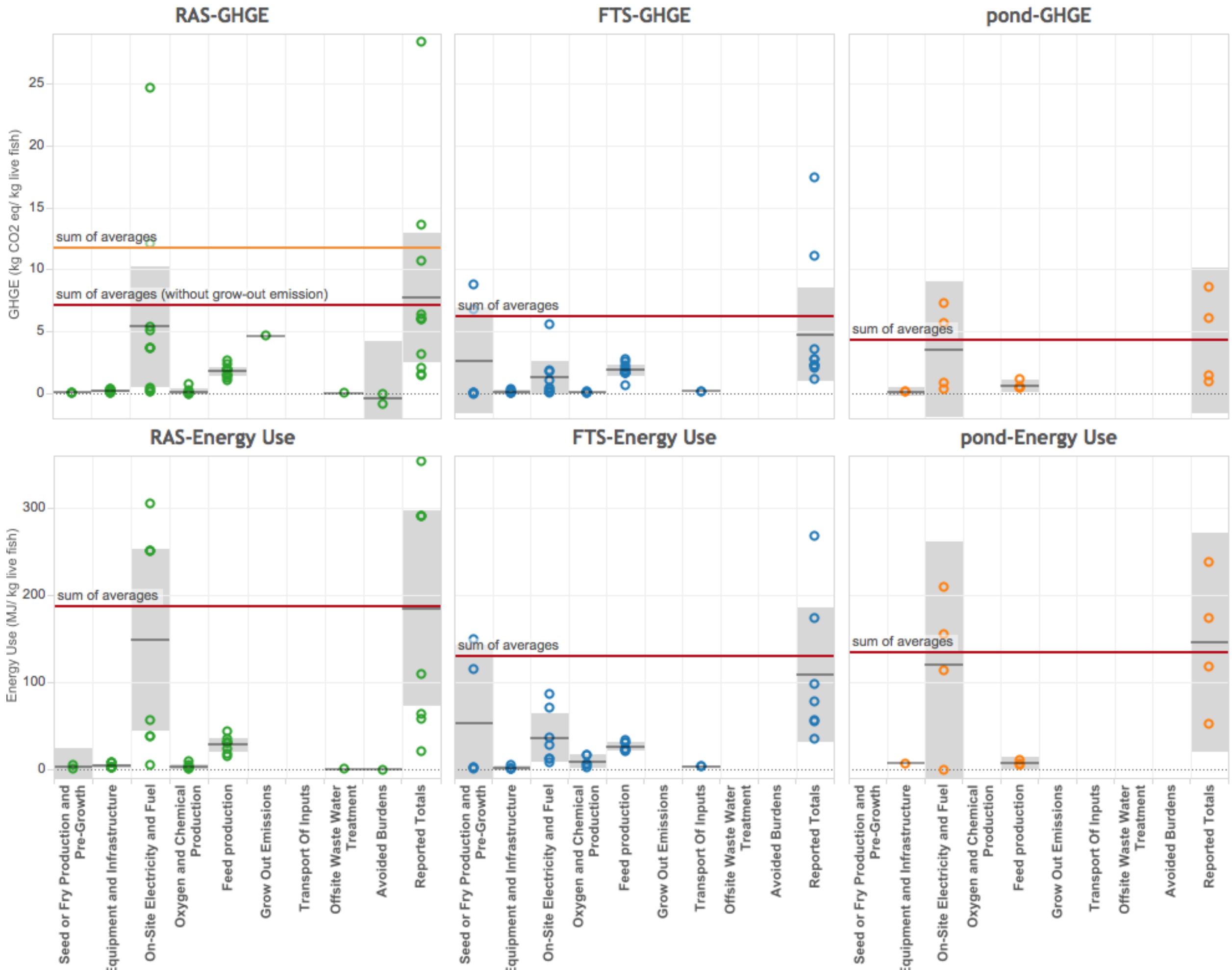


FIGURE 3. Cradle-to-farm gate life cycle greenhouse gas emissions and energy use for land-based aquaculture, divided into common system types, and showing contributions from dominant stages and processes. RAS = recirculating aquaculture systems; FTS = flow-through systems.

Circles represent individual study results, offering a sense of the data spread or cluster. Horizontal black bars represent averages for each stage, and grey blocks are 95% confidence intervals around the averages. The "Reported Totals" column shows totals from a given study, although it is important to recognize that not all studies include the contributing processes represented here. Red bars indicate the sum of the averages from each contributing process.

RAS production of turbot in France where differences between measured nutrients in water effluent and those expected from nutrient balance modeling led to uncertainty regarding nitrogen emissions to the atmosphere (Aubin et al., 2006). To address this uncertainty, the study considered three scenarios, one of which included high N_2O emissions to air, leading to the high value for “grow out emissions” in RAS-GHGE in Figure 3.

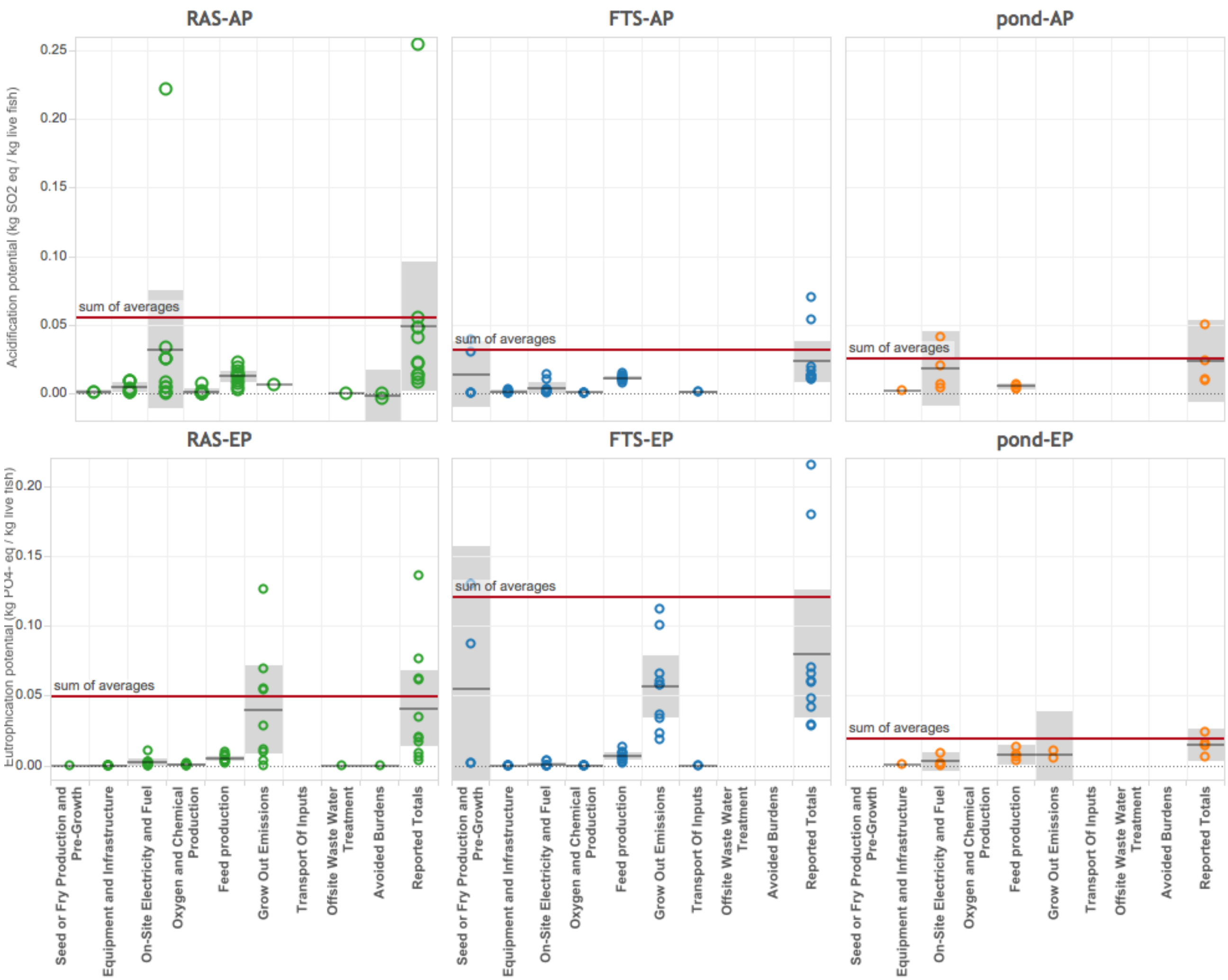


FIGURE 4. Cradle-to-farm gate acidification potential (AP) and eutrophication potential (EP) for land-based aquaculture, divided into common system types, and showing contributions from dominant stages and processes. RAS = recirculating aquaculture systems; FTS = flow-through systems.

Circles represent individual study results, offering a sense of the data spread or cluster. Horizontal black bars represent averages for each stage, and grey blocks are 95% confidence intervals around the averages. The “Reported Totals” column shows totals from a given study, although it is important to recognize that not all studies include the contributing processes represented here. Red bars indicate the sum of the averages from each contributing process.

Feed production is an important contributor to nearly all environmental impact categories. Note that the high values in the “seed or fry production and pre-growth” process for FTS in Figure 3

and 4 are due to a study that included the feed necessary for pre-growth fish rearing in the stage (it is included in “feed production” in other studies). This seed/fry feed production could not be disaggregated in the results. It is also worth noting, however, that this particular study (on sea bass production in Tunisia) has high values throughout and represents a flow-through production system where water is pumped from the sea and feed conversion ratios appear higher than other studies.

Because of the general importance of feed, the feed conversion ratio (FCR) – kilograms of feed per kilograms of fish produced – is a strong determinant of system environmental impact. In general, fish are much more efficient at converting feed to animal biomass than are terrestrial livestock, with FCRs approaching one. (In some cases, FCRs below 1 are reported because the ratio is calculated using weight of as-delivered feed, which is dry, and live fish mass, which contains a high fraction of water.) FCR is dependent on a wide array of parameters including fish species, selective breeding, environmental conditions (temperature, water flow, water quality), stocking density, fish size (i.e., harvest size) and feed quality.

Production Systems

Figures 3 and 4 provide a comparative overview of the environmental impacts per kilogram of fish produced by the dominant land-based aquaculture systems. Such an overall analysis considering multiple impact categories is critical in this comparison as impacts are often shifted from one category to another when changing production systems. For example, high flow rates of low concentrated effluents are the main obstacle to the economic treatment of wastewater from FTS. By comparison, the flow rate of RAS wastewater is 10–100 times lower and 10–100 times more concentrated, which allows for easier and more cost effective treatment (Martins et al., 2010). This is clear when comparing eutrophication impacts between FTS and RAS in Figure 4. This often comes at the cost of increased energy use (and thus, GHGE and AP) to pump recirculating water in RAS. Water dependence is also lower in RAS systems, making them practical in areas where large flows of water are not available. d’Orbcastel et al. (2009) found water dependence to be 93% smaller in RAS than FTS, whereas Wilfart et al. (2013) demonstrated water dependence per kilogram of fish to be 3 to 16 times greater in pond systems (for more and less intensive ponds, respectively) than in RAS. The question of which impact category is more important to minimize becomes a subjective question dependent on local and broader value choices.

On-site Electricity Impacts

Since the energy-related impacts for RAS (and other production methods) are largely driven by electricity demand, they are highly sensitive to the generating source of electricity. This gives a potential advantage to siting RAS in regions with relatively low grid electricity impacts, such as the Pacific Northwest. One study of RAS located in Nova Scotia, Canada, where the grid is 80% coal-generated, demonstrated that if RAS was instead operated on the average Canadian grid (61% hydro, 18% coal, 13% nuclear, 4% oil, 4% natural gas), GHGE decreased 63% and AP decreased 75% (Ayer and Tyedmers, 2009). Note that Oregon's electricity grid mix is 47% from fossil fuels, whereas the US national average grid is 67% from fossil fuels[5]. In another study, switching from grid electricity (in Denmark) to wind power reduces GHGE in RAS by 90% (from 13.6 kilograms CO_2eq per kilogram fish to 1.3 kilograms CO_2eq per kilogram) (Samuel-Fitwi et al., 2013b). A third study showed that if wind power were used to support RAS, GHGE would be 19% of those using natural gas electricity, AP would be 44%, and EP would be 71% (Dekamin et al., 2015). Clearly, the impacts of RAS are highly dependent on the generating source of electricity, and reducing these impacts through renewable generation causes feed production to stand out as the dominant impacting process.

Feed

The supply of feed remains one of the more controversial – and environmentally impactful aspects of aquaculture in general. Historical perception has been that production of high value carnivorous fish such as salmon and trout requires feed containing fishmeal and fish oil, thus linking aquaculture to a potentially unsustainable wild fishing industry. In the past, because modern commercial fishing techniques generate significant by-catch[6], such fish-based aquafeeds were the most economical option. Naylor et al. (2009) demonstrate that the ratio of wild fisheries inputs to farmed fish output has fallen to 0.63 for the aquaculture sector as a whole (globally) but remains as high as 5.0 for farmed Atlantic salmon. However, aquaculture's share of global fishmeal and fish oil consumption has risen substantially, as greater amounts of fishmeal are fed to omnivorous species, and high levels of fish oil are used to provide long-chain omega-3 oils in farmed fish. A number of LCA studies, discussed here, have found tradeoffs between impact categories when fish-based feeds are substituted with plant-based feeds. There is promise for marine algae to replace fish oil in aquafeed, but current production costs makes this infeasible. Another promising aquafeed alternative involves converting food wastes into high-protein feed via insect larvae. A few recent LCA studies shed light on this possibility.

Papatryphon et al., (2004) considered varying degrees of replacement of fish-derived ingredients with plant ingredients in salmonid feeds and found that while total replacement significantly reduced the use of net primary production (food chain level), it was not optimal for the other impact categories of EP, AP, energy use and GHGE. A later study confirmed these results, finding that the production of plant oils required similar quantities of energy as the production of fish oils, and substitution of the fish oils with plant oils in aquafeeds did not reduce environmental impacts (except for net primary production).

[5] https://www.oregon.gov/energy/pages/oregons_electric_power_mix.aspx

[6] The unwanted fish and other marine creatures caught during commercial fishing for a different species.

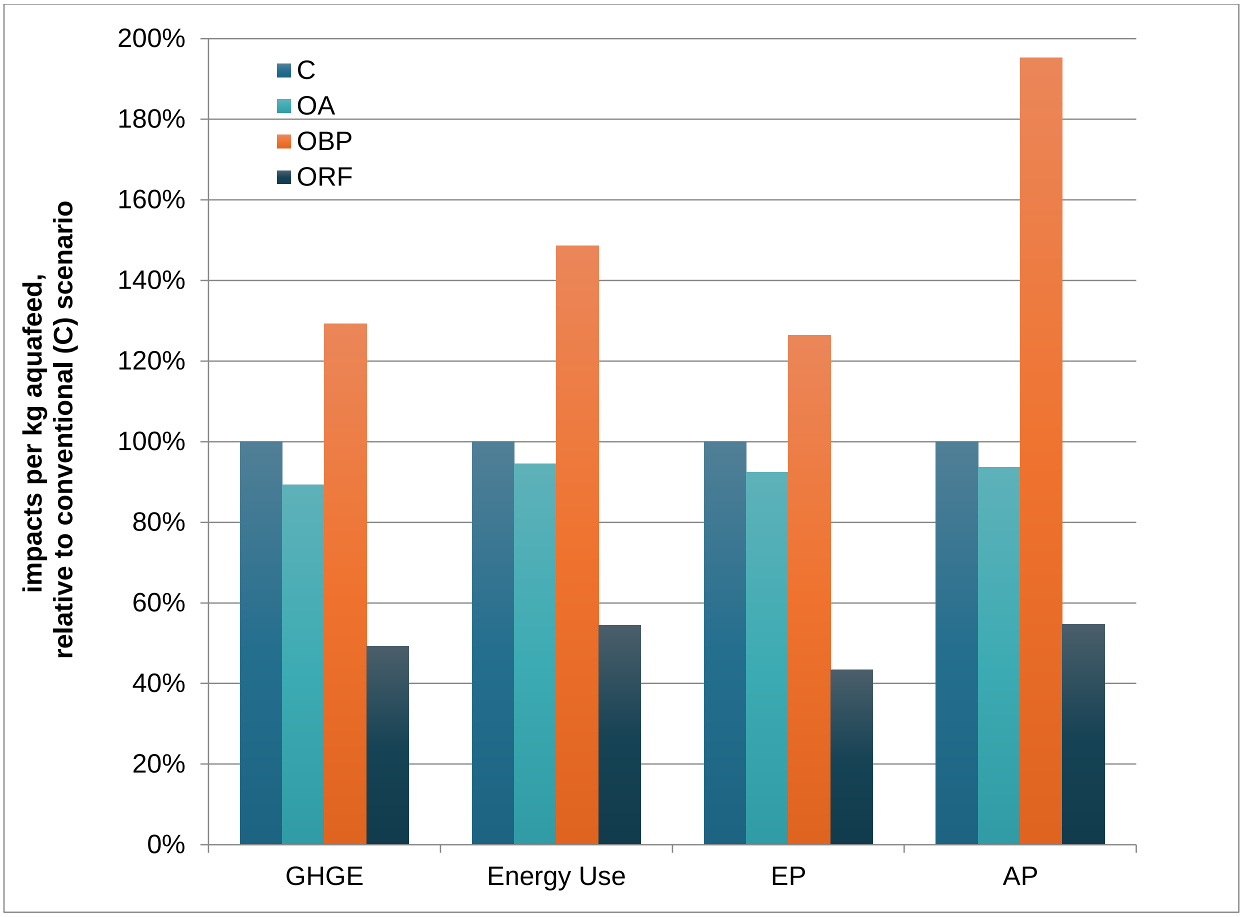


FIGURE 5. Comparison of environmental impacts of different salmon feed formulations in British Columbia (BC) relative to the "conventional" scenario.

The scenarios considered are: C = (conventional) – average inputs to all conventional salmon feeds produced over one year by a feed mill in BC; OA – identical to first except all crop ingredients were certified organic, but conventional animal meals and oils used; OBP – same organic crop ingredients but all animal-based ingredients were derived from by-products of fisheries for human consumption (derived from BC herring fishery); ORF –organic crop ingredients, poultry by-product meal was replaced with fish meal, 25% of fish meal was replaced with organic soy meal, and all fish oil substituted with organic canola oil. Note that these feed formulations are not necessarily nutritionally equivalent or biochemically optimal for salmon production. Results from Pelletier and Tyedmers (2007).

This study also showed that GHGE and AP are more influenced by the origin of fish-derived ingredients (fish species and energy required to catch them) than by their substitution with plant-based sources (Boissy et al., 2011). Somewhat different conclusions, summarized in Figure 5, were drawn in a study of feeds for salmon aquaculture in British Columbia (Pelletier and Tyedmers, 2007). This study found that while organic crops performed better than conventional crops, these benefits were small when compared to the impacts of animal-based ingredients in the aquafeed, resulting in only minor improvements per kilogram of aquafeed. The study also found that due to high fuel inputs when fishing for human consumption and low yield rates of meals and oils from by-products of these fisheries, using fisheries by-product meals and oils over conventional meals and oils – a practice required by most current organic aquaculture standards – only further increased environmental impacts. On the other hand, replacing fishmeal and oil with organic soybean meal and canola oil resulted in roughly half the impacts of the usual aquafeed. While such a substitution may not affect growth rate, fish fed only plant-based oils do not contain desirable concentrations of long-chain omega-3 oils. The general conclusions among these studies are that feed impact is highly dependent on source, and impacts of feed types, whether fish- or plant-derived, can vary widely.

Because many of the feed ingredients considered in the above studies are co-products (e.g., fish meal and fish oil, soybean meal and soybean oil), the authors acknowledge the influence that the choice of allocation – how environmental impacts are distributed to co-products – has on results. An alternative LCA approach, known as consequential LCA, attempts to avoid such allocation by asking a different question: what are the environmental impacts of a change in the system, including the indirect impacts of changes in demand for ingredients? A consequential LCA was applied to the substitution of fish-derived protein with plant-based protein in aquafeeds (Samuel-Fitwi et al., 2013a). This approach found that replacing fishmeal with soybean meal or rapeseed meal in aquafeed decreased GHGE per metric ton of trout feed by 57%, AP by ~25%, EP by 15% and land use by ~25%. This does not mean that the previous LCAs that showed an increase in impact when substituting fish- with plant-based ingredients were wrong, but that the secondary impacts of changes in demand have a strong influence. It is important to note that such consequential LCAs carry a relatively high degree of uncertainty because they are based on predictions of market dynamics.

Fly Larvae

Efforts to identify more sustainable feed sources for the livestock sector, including land-based aquaculture, have led to consideration of rearing insects for livestock feed. The nutritional value of insects is high, especially as a protein source for livestock, and insects can turn organic waste streams, such as manure or food waste, into high quality feed products. Recent LCA studies considering the environmental implications of fly larvae-based animal feeds have found decreases in land use relative to replaced feeds, but increased energy use and GHGE (Salomone et al., 2017; Smetana et al., 2016; van Zanten et al., 2015). As insect-based feeds are still a recent development, there are many uncertainties that could influence this conclusion. Salomone et al., (2017), for example, demonstrated the sensitivity of GHGE results to direct emissions from the insects during growth, for which very limited data is available.

Fish Genetics

Fish growth rates and feed conversion efficiencies can directly influence the environmental performance of land-based aquaculture systems. An LCA study of African catfish grown in RAS showed that while improvement of the feed conversion ratio always reduces environmental impacts, selective breeding to improve the thermal growth coefficient, a common indicator of fish production, only leads to decreased environmental impacts when rearing density is the limiting factor (Besson et al., 2016). This result emphasizes the need for breeding programs aimed at improving feed efficiency and not just growth rate.

Transgenic fish (fish with genetic material into which DNA from a different species has been introduced via genetic engineering) have been lauded as a promising opportunity for land-based aquaculture improvement, and use in closed LBA minimizes many of the concerns regarding escapes into wild populations. Growth rates of transgenic fish can be increased 400% to 600% while also reducing feed conversion ratios by up to 25% (Wakchaure et al., 2016). To our knowledge, however, there have been no LCA studies of transgenic fish, and none are being used in land-based aquaculture at present.

Downstream

The only LCA study to consider the downstream processing and distribution impacts of LBA was a study on RAS production of shrimp (Sun, 2009). The baseline scenario in this study was RAS production along the Gulf Coast in Texas, where all water needs were met with seawater. To consider the environmental impacts of transportation, shrimp farmed using RAS in Michigan which required the production of artificial seawater was compared to frozen shrimp produced in Texas and trucked to Michigan. Processing and transport contributed about 25% to the total GHGE of the Texas case, but total GHGE in the Michigan case were 2.6 times greater, driven by the inputs needed to make artificial seawater. Impacts of the Michigan scenario were many times larger across a wide array of impact categories. RAS production in Texas was also compared with a conventional shrimp farming system in Thailand, with shrimp frozen and transported via container ship to the U.S. Here, the U.S. production was 15-82% lower in AP, EP, and GHGE; distribution and processing contributed roughly half of the AP and one third of the GHGE for the Thai scenario.

Research Gaps

Land-based aquaculture is an emerging and rapidly developing industry. While a number of LCA studies were identified, numerous research gaps remain. Specifically, analyses of U.S.-based production systems are needed in order to better understand the impacts of feed source, production location, and possibly distribution in a U.S. context. Given the potential to influence overall system GHGE, additional research is needed to better understand N_2O emissions resulting from degradation of feeds in land-based aquaculture production. Little attention has been given to the impacts of land-based aquaculture product chains after the farm gate. This is perhaps because these stages are less affected by aquaculture practices, but they should be included in considering the full benefits (or detriments) of land-based aquaculture. Clearly, there are environmental trade-offs between dominant LBA production systems, and these need to be considered in a local context, and balanced with other indicators such as economics, market demand, and local expertise. Different LBA systems are often associated with different species, so it would also be helpful for each type of system to identify best opportunities to optimize environmental impacts. Promising feed alternatives require further investigation as production methods gain scale in order to direct development toward environmentally sustainable methods. Given the variability in impacts of feed type and source, it appears that optimizing the environmental impact of land-based aquaculture feed formulation will require consideration of specific sources of both fish- and plant-derived ingredients.

Conclusions

As wild fisheries diminish and demand for seafood continues to grow, land-based aquaculture is a promising production method with wide-ranging applicability. This review of existing LCA literature concludes the following:

- Much of the environmental impact (GHGE, energy, AP) of recirculating aquaculture systems is linked to electricity use. Thus, utilizing renewable electricity generation can significantly reduce the environmental footprint.
- Generally speaking, recirculating aquaculture systems have lower eutrophication impact than flow-through systems because low flow rates and high concentrations make nutrients easier to manage.
- Feed is an important driver of land-based aquaculture's environmental impact. While there is strong need and desire to reduce the wild fisheries inputs to aquaculture feed, replacement with plant-based alternatives does not necessarily result in reduced environmental impacts in all categories. However, environmental impacts of both fish-derived and plant-derived ingredients show strong dependence on the specific source of the ingredient.

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