Executive Summary

Sustainable Aquaculture: Development of New Quantitative Metrics for Use in Marketing Aquaculture Products

Consumers are increasingly seeking fresh, locally grown, low environmental impact foods. However, data quantifying environmental impact is lacking for aquaculture producers who want to reassure consumers or use in marketing campaigns. This project collected data from 5 aquaculture farms in the North Central Region (NCR) and used life cycle assessment (LCA) to quantify the environmental impacts of existing operations. Species and production systems included largemouth bass and yellow perch in pond culture, rainbow trout in raceways, yellow perch in aquaponic systems, and barramundi in recirculating systems (RAS). Data collected indicated that electricity and feed inputs were the most significant contributors to environmental impact. All aquaculture operations had lower values for global warming potential, acidification and non-carcinogenic impacts when compared to swine production. Fish farms now have quantified data identifying the environmental impact of aquaculture operations and can use those to market their products to consumers.

Termination Report

Project Title: Sustainable Aquaculture: Development of New Quantitative Metrics for Use in Marketing Aquaculture Products [Termination Report]

Total Funds Committed: $127,131

Initial Project Schedule: September 1, 2021-August 31, 2023 [Extended to August 31,2025]

Current Project Year: September 1, 2024-August 31, 2025

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Relevance: Consumers are seeking low environmental impact foods, but quantitative data are lacking.

Response: The project is conducting LCA of multiple aquaculture operations in the North Central Region.

Results: One objective is being pursued in this project:
Develop quantitative metrics from existing aquaculture farms in the NCR and compare these values to other food production systems producing competing protein foods.

Purdue student working on Sustainable Ag Project

The goals of this LCA study was to assess the cradle-to-market environmental sustainability of existing fish farms in the NCR. This model provides verified and quantified values of the environmental impacts associated with the targeted system/species combinations. The results obtained also help identify the components of the analyzed aquaculture operations that contribute most to the environmental impacts (i.e. hotspots) for further improvement.

Seven aquaculture operations in the North Central region (NCR) were contacted and invited to participate in developing the LCA data. Five responded positively to the initial invitation and provided sufficient data to complete the LCA analysis. The five farms are a pond operation producing yellow perch (*Perca flavescens*), a pond operation producing largemouth bass (*Micropterus nigricans*), an indoor RAS operation producing barramundi *(Lates calcarifer*) a yellow perch farm raising fish in aquaponics systems, and a raceway operation producing rainbow trout (*Oncorhynchus mykiss*).

We acquired a complete life cycle inventory (LCI) of the 5 farms. The five farms evaluated in this study included a barramundi farm in Indiana, a rainbow trout farm in Wisconsin, a yellow perch farm in Ohio, a largemouth bass farm in Illinois, and a yellow perch aquaponic operation in Ohio. For all farms, an approximate composition of the feed was used based on the data provided by each of the farm managers, since the complete formulation of the feed from commercial mills is confidential information. Fish fingerlings used in the different farms were purchased from fish hatcheries, except for the rainbow trout and the yellow perch pond farms, where they hatch their own fish.

The operational data of all the fish farms studied were provided by the farm. The barramundi farm in Indiana produces 7,882 kg per cycle, the rainbow trout farm in Wisconsin produces 200 kg per cycle, the yellow perch aquaponic farm in Ohio produces 453.6 kg per cycle, the yellow perch pond farm in Ohio produces 3409 kg per cycle, and the largemouth bass farm in Illinois produces 45,454 kg per cycle.

The barramundi farm is an indoor production facility using a recirculating aquaculture system (RAS) with a total capacity of 378.5 m^3. The rainbow trout farm operates outdoors using 56 flow-through raceways with a total area of 32.4 hectares. The indoor yellow perch farm operates using an aquaponic recirculating system with a total capacity of 49,205 l. The yellow perch aquaculture farm operates four 1-acre and two 0.5-acre ponds for a total capacity of 5 surface acres of water. The largemouth bass farm operates using seven outdoor ponds for a total capacity of 72,846 m^3 (59.1 acre-feet) of water.

The midpoint environmental impact was used to analyze the environmental performance in this study, using the TRACI v2.2 Midpoint E v1.02 methods. The TRACI v2.2 method provided eighteen midpoint indicators, but this study focused on ten indicators, including ozone layer depletion potential (OLDP, kg CFC-11 eq), global warming potential (GWP, kg CO_2 eq), smog (kg O_3 eq), terrestrial acidification potential (TAP, kg SO_2 eq), freshwater eutrophication potential (FEP, kg P eq), human carcinogenic (CTUh), human non-carcinogenic (CTUh), human respiratory effects (kg PM2.5 eq), aquatic ecotoxicity (AE, CTUe), and fossil fuel depletion (MJ surplus).
The LCA of barramundi culture revealed notable environmental impacts across several categories. Electricity usage was a dominant contributor in multiple impact categories, including ozone depletion (71.19%), carcinogenic effects (62.68%), respiratory impacts (59.64%), and fossil fuel depletion (55.89%). Feed production was another key hotspot, contributing heavily to categories such as global warming (49.31%), smog formation (46.19%), acidification (71.02%), eutrophication (74.63%), and ecotoxicity (66.36%).

The LCA of rainbow trout culture highlighted significant contributions to various impact categories, with electricity consumption and fish feed production emerging as the primary contributors. Ozone depletion was primarily influenced by electricity use (97.8%). Similarly, global warming potential (GWP) was heavily impacted by electricity (73.8%) and fish feed production (25.6%). Smog formation was largely influenced by electricity usage (59.6%). Acidification impacts were almost equally divided between electricity (50.2%) and fish feed production (48.8%). Eutrophication was almost entirely attributed to the production of rainbow trout (99.3%). Carcinogenic effects were predominantly caused by electricity usage (88.4%), while fish feed contributed 11.6%. Non-carcinogenic effects were primarily driven by fish feed production (67.6%). Respiratory effects were overwhelmingly linked to electricity consumption (86.6%). Ecotoxicity was largely attributed to electricity (63.9%) and fish feed (35.9%). Fossil fuel depletion was dominated by electricity (89.6%).

The LCA of yellow perch aquaponics farming revealed that electricity consumption is the predominant contributor across multiple impact categories. It accounted for 99.75% of ozone depletion, 96.27% of global warming, 90.57% of smog formation, and 91.24% of acidification. It also contributed 98.49% to carcinogenics, 98.48% to respiratory effects, 94.65% to ecotoxicity, and 98.43% to fossil fuel depletion.

Results of yellow perch farming in the NCR revealed that fish feed and electricity significantly contribute to the environmental impact. Global warming impacts were primarily driven by electricity use (55.94%) and feed production (44.06%). Smog formation and acidification impacts displayed similar trends, with feed accounting for 63.81% and 66.78% of the impacts, respectively. Carcinogenic and respiratory effects were heavily influenced by electricity use, contributing 75.20% and 74.74%, respectively. Non-carcinogenic and fossil fuel depletion impacts were largely attributed to fish feed, with contributions of 81.16% and 21.88%, respectively, and electricity production contributing 18.84% and 78.12%, respectively. Finally, ozone depletion and ecotoxicity impacts were primarily associated with electricity use (94.64%) and a combination of fish feed (54.01%) and electricity (44.92%), respectively.

Feed, electricity, and other production inputs were the main contributors to the environmental burden of producing 1 kg of largemouth bass. Ozone depletion was largely driven by electricity consumption, which accounted for 84.9% of the total impact, while the remaining 15.1% was attributed to feed production. Similarly, GWP was dominated by feeds, contributing 73.2% of the total emissions, with electricity accounting for the remaining 26.8%. The smog formation impact category revealed a similar trend, with feeds responsible for 82.3% of the total impact and electricity contributing 17.7%. Acidification impacts were also dominated by feeds, which accounted for 88.3%, with electricity contributing 11.7%. Eutrophication impacts were primarily associated with largemouth bass farming as the primary contributor (87.1%) due to nutrient runoff and waste from aquaculture activities. Carcinogenic impacts were split between electricity (50.7%) and feeds (49.3%). Non-carcinogenic impacts were heavily influenced by feed production, contributing 93.3%, with electricity accounting for only 6.7%. Respiratory effects, ecotoxicity, and fossil fuel depletion further highlighted the dominance of feeds as a key driver of environmental impacts. For respiratory effects, feeds contributed 55.6%, with electricity at 44.4%. In ecotoxicity, feeds dominated at 80.2%, while fossil fuel depletion shows a closer split, with feeds at 45.5% and electricity at 54.5%.

These aquaculture metrics were compared to conventional protein-producing food systems such as chicken, pork, and beef. All aquaculture farms evaluated displayed lower impacts than swine production in GWP. When comparing acidification and respiratory effects, aquaculture species again had lower values. Swine production had notably high acidification potential (3.01 kg SO_2 eq), while values for yellow perch (0.021 kg SO_2 eq) and largemouth bass (0.059 kg SO_2 eq) were substantially lower. Similarly, aquaculture had lower respiratory effects in terms of particulate matter formation impacts compared to swine (0.0808 kg PM2.5 eq), with yellow perch and largemouth bass generating only 0.0025 and 0.0041 kg PM2.5 eq, respectively. In the toxicity-related impact categories, swine production had notably higher values than most aquaculture systems. For instance, carcinogenic effects from swine exhibited 0.000217 CTUh, compared to 1.19×10^{-7} CTUh for largemouth bass and 8.27×10^{-8} CTUh for yellow perch. Similarly, swine exhibited higher non-carcinogenic impacts (0.00124 CTUh) and ecotoxicity (2.65 CTUe).

Overall, while aquaculture systems exhibited elevated impacts in certain categories (e.g., smog and energy-related metrics), they demonstrated lower burdens in climate-related and toxicity categories compared to pork. Chicken consistently outperformed all other protein sources across most impact categories, which is in line with broader literature citing high production efficiency and streamlined supply chains in poultry systems. These results highlight the potential of aquaculture as a sustainable protein option in temperate climates. However, optimizing energy use (e.g., integrating renewable energy sources), diets, and improving nutrient management remain critical to minimizing environmental trade-offs in future system designs.

Outreach Overview

This effort produced the first LCA of multiple aquaculture farms in the US. The data generated indicated that electricity and feeds were the most significant contributors to environmental impact. Data also provided marketing opportunities for aquaculture farms, specifically the lower global warming potential of all aquaculture operations when compared to swine production. Future studies focused on alternative energy use and sustainable feeds can further reduce the environmental impact of aquaculture and provide additional marketing opportunities for aquaculture. A popular article is in development for publication in either Aquaculture Magazine or World Aquaculture.

Targeted Audience

- Fish farmers who are seeking an objective and quantitative metric for marketing the sustainability of their products.
- New producers who are sorting through options of system/species combinations for their operations.
- Consumers desiring sustainable foods.

Outcomes/Impacts

Multiple aquaculture production systems and species were evaluated using LCA. Regardless of the systems or species, electricity and feeds were the environmental hotspots (i.e., factors contributing to environmental degradation). Those two areas should become focal points in future research focused on reducing the environmental impacts of aquaculture. Global warming potential of all aquaculture operations was lower than published values for swine production and offers a marketing opportunity for aquaculture farms.

Recommended Follow-Up Activities

Future studies should focus on alternative energy sources for aquaculture (wind, solar, anaerobic digestors) as sources of energy, as well as local grid networks. Dietary research should focus on sustainable feeds by incorporating an additional metric into formulation approaches (e.g., global warming potential).