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Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada

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ABSTRACT

This study employed life cycle assessment (LCA) to quantify and compare the potential environmental impacts of culturing salmonids in a conventional marine net-pen system with those of three reportedly environmentally-friendly alternatives; a marine floating bag system; a land-based saltwater flow-through system; and a land-based freshwater recirculating system. Results of the study indicate that while the use of these closed-containment systems may reduce the local ecological impacts typically associated with net-pen salmon farming, the increase in material and energy demands associated with their use may result in significantly increased contributions to several environmental impacts of global concern, including global warming, non-renewable resource depletion, and acidification. It is recommended that these unanticipated impacts be carefully considered in further assessments of the sustainability of closed-containment systems and in ongoing efforts to develop and employ these technologies on a larger scale.

1. Introduction

Aquaculture is the fastest growing animal food-producing sector in the world [1]. Hundreds of different species of finfish, shellfish, and aquatic plants are farmed globally in a variety of culture environments and production systems. The environmental impacts of aquaculture vary according to the species being cultured and the production system employed, however, particular concern has been raised about the environmental impacts of farming carnivorous finfish such as salmon. Salmon farming is conducted almost exclusively in marine net-pens, and a number of environmental impacts have been attributed to this form of aquaculture. They include: alteration of benthic environments beneath net-pens [2–4]; the potential amplification and spread of disease and parasites to wild fish populations [5–8]; potential ecological and genetic impacts of escaped salmon, particularly amongst vulnerable populations of wild conspecifics [6,9–11], the release of chemotherapeutants and other chemicals into coastal waters [3,12,13]; high levels of industrial energy inputs [14–16]; and seeming net loss of marine-derived nutrients through relatively high fish meal and oil inclusion rates in feeds [17–19].

Research efforts are ongoing to develop alternatives to marine net-pen technology that will reduce or eliminate these environmental impacts. In recent years, particular emphasis has been placed on the development of closed-containment systems, a term widely used to describe a range of production systems that employ an impermeable barrier to isolate the culture environment from surrounding ecosystems. Theoretically, by culturing fish in a closed environment, fish farmers can exert greater control over the rearing conditions, allowing them to improve the quality of the fish while at the same time reducing proximate environmental impacts. Some of the potential advantages of closed-containment systems are: (1) minimized fish escapes; (2) minimized predator interactions; (3) reduced disease transmission; (4) lower feed inputs; (5) higher stocking densities; and (6) improved waste management capabilities.

Several industry proponents and environmental groups have suggested that the environmental impacts of salmon farming could be greatly reduced if closed-containment systems were more widely employed [20–24], and a variety of closed-containment technologies have been developed in Canada to-date. These include marine floating bag systems [25,26], land-based saltwater flow-through systems [27], land-based freshwater recirculating systems [28], and most recently, a proposed marine floating concrete tank system [24].

The environmental impacts of closed-containment systems have yet to be formally assessed in Canada. Preliminary assessments of these systems have focused primarily on their economic viability and various biological performance indicators such as fish health, feed input rates, stocking density and mortality rates

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[22,27,29]. However, these systems are often described and promoted to consumers as sustainable, environmentally-friendly alternatives to net-pen farming [23,28,30–32]. For example, the salmon harvested during a recent pilot study of a land-based farm in British Columbia were sold for a premium price at local retail outlets and marketed as "eco-salmon" [27]. Similarly, the Monterey Bay Aquarium's Seafood Watch program lists another salmonid, Arctic char (*Salvelinus alpinus*), as one of their "best-choice" species for consumers to purchase, primarily because this species is typically cultured in land-based recirculating systems [33].

By focusing solely on the local ecological impacts of salmonid farming, researchers have ignored several other important environmental impacts, in particular those associated with the range of industrial processes that are linked with farming salmonids. The wide-spread acceptance of these alternative systems as being sustainable and ecologically-friendly is therefore not supported by rigorous research. In order to fully understand the environmental implications of employing these systems on a larger scale, a more detailed, quantitative assessment is required, in particular one that broadens the scope of consideration beyond the proximate ecological impacts that are the focus of historical concern.

Consequently, this study employed life cycle assessment (LCA) to quantify and compare the potential life cycle environmental impacts associated with producing salmonids using four culture systems in Canada: (1) a conventional marine net-pen system; (2) a marine floating bag system; (3) a land-based saltwater flow-through system; and (4) a land-based freshwater recirculating system. By quantifying the environmental impacts over the entire life cycle of salmonid production, LCA provides more comprehensive information on the environmental implications of these alternative technologies. Although LCA was originally developed to evaluate the life cycle environmental impacts of manufactured products [34], in recent years it has been increasingly applied to study the environmental performance of a range of food production systems, including agriculture [35–38], capture fisheries [39–43], and aquaculture [44–48].

In the present study, the life cycle environmental impacts of each culture system were quantified and compared in an effort to (1) show how a shift from conventional net-pen farming to each of the three alternatives would change the environmental impacts of salmonid farming; and (2) identify the particular aspects of each system's production chain that contribute most to its overall environmental impact. By quantifying a broader range of the environmental impacts of closed-containment systems, this study will contribute valuable information to the ongoing efforts by aquaculturists, government departments, and environmental groups to improve the environmental performance of salmonid farming. The study will also generate useful information for groups that inform consumers about the environmental impacts of providing this seafood product, and will provide regulators and policy makers with a basis upon which to guide further research and development in this sector.

1.1. System descriptions

Global farmed salmon production has more than doubled since 1994, and Canada is the world's fourth largest producer. Atlantic salmon (*Salmo salar*) accounts for over 85% of the farmed salmon produced in Canada, with smaller amounts of chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon being produced only in British Columbia [49]. In 2004, salmon aquaculture accounted for 67% of Canada's total aquaculture production by weight and 75% of total production by value [50].

At present, marine net-pens are the only form of large-scale, commercially operating salmon aquaculture systems in Canada. Closed-containment systems remain a niche technology and the research and development of large-scale commercially viable systems are ongoing. There are some commercially operating land-based recirculating systems in Canada that are producing other finfish such as Arctic char (*S. alpinus*) and Atlantic halibut (*Hippoglossus hippoglossus*). Farming other salmonids such as Arctic char is advantageous because these fish can tolerate higher stocking densities and they command a higher market price than salmon.

1.1.1. Conventional marine net-pen system

The conventional net-pen system modeled in this analysis is based on the culture of Atlantic salmon in a typical British Columbia farm. Salmon are reared in an open mesh net that is suspended within a rigid framework typically constructed of galvanized steel, aluminum, wood, or plastic, and that is buoyed at the surface and held in place by a system of anchors. The modeled system consists of 10 net-pens, each with 30-m sides and a depth of 20 m [14].

1.1.2. Marine floating bag system

The first alternative culture system modeled is similar in structure to the net-pen system except the netting is replaced with an impermeable bag that is suspended in the water. The studied system was operated in British Columbia, where Atlantic salmon were cultured in six circular bags that were made of a heavy-gauge plastic and housed in a steel frame which was buoyed at the surface and held in place by a system of anchors. Fresh seawater was continuously pumped into the bags by electrical upwelling pumps, and portable liquid oxygen tanks were used to provide supplemental oxygen to the cultured fish. Wastewater exited the bags through a specially designed outlet at the bottom and entered the marine environment untreated.

1.1.3. Land-based saltwater flow-through system

The second alternative culture system modeled was based on the culture of Atlantic salmon in a land-based saltwater flow-through system located in British Columbia. Atlantic salmon were cultured in three circular land-based concrete tanks. Fresh seawater was continuously pumped into the tanks from an adjacent ocean channel and wastewater leaving the tanks was piped back into the channel untreated. Similar to the floating bag system, portable liquid oxygen tanks were used to provide supplemental oxygen to the cultured fish.

1.1.4. Land-based freshwater recirculating system

The fourth system modeled was based on the culture of Arctic char in a land-based freshwater recirculating system located in Nova Scotia. The system is entirely contained inside a warehouse and consists of a series of circular concrete tanks of various sizes. New water is continuously pumped into the tanks from an on-site freshwater well. Approximately 99% of the water is recirculated back into the system after passing through an extensive mechanical and biofiltration process. Wastewater that is lost from the system at various stages passes through a holding tank where solids are settled out and the remaining wastewater enters the municipal sewer system. The solid fish wastes are collected in the holding tank for future use as a substitute for conventional synthetic fertilizers for plants fertilizer in an adjacent greenhouse.

2. Methodology

2.1. Life cycle assessment

Life cycle assessment is a methodological framework used to quantify a wide range of environmental impacts that occur over the entire life cycle of a product or process [51]. It is often referred to as a "cradle to grave" analysis [52], and the assessment generally includes a quantification of the resource use and emissions