Journal of Cleaner Production xxx (2008) 1–12

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

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

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Keywords:
LCA
Alternative aquaculture technologies
Salmonid culture systems
Canadian aquaculture

A B S T R A C T

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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doi:10.1016/j.jclepro.2008.08.002

[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 associated with all of the major phases of the production chain, including the extraction and processing of raw materials, manufacturing processes, transportation at all stages, use of the product by the consumer, and recycling or disposal of the product after use [53]. The LCA methodology has been standardized by the International Organization for Standardization in the 14040 and 14044 environmental management standards [54].

2.2. Goal and scope definition

The goal and scope definition of an LCA provides a description of the product system(s), the system boundaries and the functional unit. The functional unit is the reference unit of the study and provides the basis on which alternative products or processes can be compared and analyzed [51]. The functional unit of the present study is 1 t of harvest-ready live-weight fish, whether Atlantic salmon or Arctic char. Conceptually then, the system boundaries of the study are from cradle to farm-gate (Fig. 1). The subsequent processing, wholesaling, retailing, preparation and disposal of the fish have not been quantified in this study. It was also assumed that the same conventional salmon feed was used in all four studied systems, and that the same hatchery rearing process was used to produce smolts.

The life cycle environmental impacts associated with the studied systems were quantified using the problem-oriented (midpoint) approach, CML 2 Baseline 2000 [52]. In a midpoint approach, results of the life cycle inventory are characterized into relevant environmental impact categories and expressed in reference units to indicate their potential contribution to specific global environmental impacts. For example, all emissions that contribute to global warming are expressed in kg of CO_2 equivalents. This value does not describe the actual magnitude or resulting damage of the environmental impact, but rather the potential contributions to global environmental impacts.

The environmental impact categories quantified in this analysis were abiotic depletion (ABD), global warming potential (GWP), human toxicity potential (HTP), marine toxicity potential (MTP), acidification potential (ACD), and eutrophication potential (EUT). The cumulative energy demand (CED) of each system was also quantified using the Cumulative Energy Demand method v 1.03 [55]. This method provides a summation of the industrial energy use throughout the life cycle of a product or process. Global warming potential, acidification, eutrophication, and abiotic depletion have been typically included as impact categories in LCAs of seafood products to-date [56]. Human and marine toxicity potentials were also selected in order to ensure that impacts to ecological health, human health, and resource depletion were adequately addressed [52,53].

2.3. Life cycle inventory

The life cycle inventory involves the collection and compilation of the data required to quantify all of the relevant inputs and outputs associated with the production of the functional unit. In this study, primary data were collected to quantify the operational inputs and outputs associated with each of the closed-containment systems, while secondary data from published sources were used to characterize the net-pen system and various background processes such as electricity production and transportation (Table 1).

2.4. Co-product allocation

Co-product allocation is a common methodological problem in LCA in which the environmental impacts of a multi-function system must be apportioned between the product under study and the co-products of the system [57]. The ISO standards recommend that allocation should be avoided whenever possible by sub-dividing the system or by applying system expansion. If allocation cannot be avoided, the apportioning of environmental burdens should be done in a manner that reflects the underlying physical relationships between the inputs and outputs of the system, or in a manner that reflects other relationships between them [54].

In the present study, the allocation of environmental burdens between co-products in the feed production stage was done according to the gross nutritional energy content of the co-products [16,58]. A second allocation problem arose at the farm-gate stage for the recirculating system where in addition to the harvest of market-size fish, solid fish wastes were captured and reused as fertilizer. In this instance, system expansion was applied to avoid allocation, and it was assumed that the reuse of captured nitrogen and phosphorous as plant fertilizer would offset the production of an equivalent amount of synthetic nitrogen and phosphorous fertilizers.

2.5. Life cycle impact assessment

This phase is focused on understanding and evaluating the magnitude and significance of the potential environmental impacts

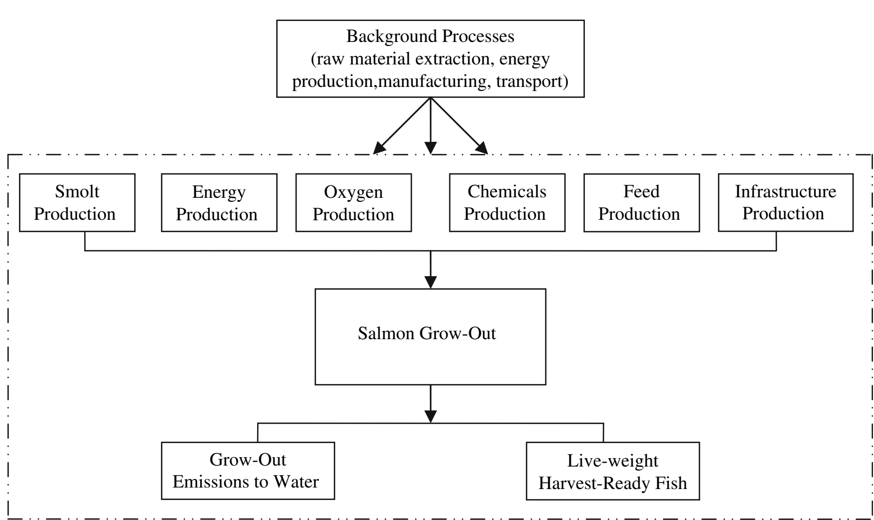

Fig. 1. A simplified life cycle flow chart for salmonid farming.

Table 1
Background processes and associated data sources

Inventory material	Database[a]	Period	Geographic region
Fuels			
Propane	Franklin	Late 1990s	United States
Diesel	Franklin	Late 1990s	United States
Gasoline	Franklin	Late 1990s	United States
Heating oil	Ecoinvent v 1.2	2000	Switzerland
Infrastructure materials			
Steel	Franklin	Late 1990s	United States
Zinc	Ecoinvent v 1.2	2000	Europe, average
Polyethylene	Ecoinvent v 1.2	2000	Europe, average
Polystyrene	Ecoinvent v 1.2	2000	Europe, average
Polyvinyl chloride	Ecoinvent v 1.2	2000	Europe, average
Nylon	Ecoinvent v 1.2	2000	Europe, average
Foam	Ecoinvent v 1.2	2000	Europe, average
Concrete blocks	Ecoinvent v 1.2	2000	Germany
PVC pipe	Franklin	Late 1990s	United States
Concrete	IDEMAT 2001	1990–1994	Europe, Western
Stainless steel	IDEMAT 2001	1990–1994	Europe, Western
Electricity generation			
Hydro	Ecoinvent v 1.2	2000	
Coal	Franklin	Late 1990s	United States
Oil	Franklin	Late 1990s	United States
Natural gas	Franklin	Late 1990s	United States
Water quality inputs			
Liquid oxygen	Ecoinvent v 1.2	2000	Europe, average
Soda ash	Ecoinvent v 1.2	2000	Europe, average
Calcium chloride	Ecoinvent v 1.2	2000	Europe, average
Transportation			
Tractor–trailer	Franklin	Late 1990s	United States
Avoided products			
Nitrogen fertilizer	LCA food	1997	Denmark
Phosphorous fertilizer	LCA food	1997	Denmark

[a] See database references in Simapro 7.0 [59].

of the studied product system [52]. Results of the life cycle inventory stage are grouped into categories (classification) and expressed in reference units to indicate their potential contribution to specific global environmental impacts (characterization). These two steps (classification and characterization) are mandatory steps according to ISO guidelines [52]. Other optional steps such as normalization, ranking, and weighting were not carried out in this analysis. The life cycle impact assessment was assisted by the use of the dedicated LCA software package Simapro 7.0 from PRé consultants [59].

3. Data collection and sources

Operating data for the three closed-containment systems were obtained directly from facility records and interviews with facility managers. Operating data for the conventional net-pen system were obtained primarily from a detailed ecological footprint analysis of the B.C. salmon farming industry [14].

The salmon feed modeled in this analysis was based on a detailed LCA report comparing conventional and organic feeds, in which total inputs to salmon feeds were quantified, effectively reflecting a "generic" diet as opposed to only one specific formulation, produced by a major B.C. based feed mill in 2003 [16]. Conventional salmon feeds typically contain products and co-products from several industrial food production systems, including fish meals and oils from dedicated reduction fisheries, various agricultural products such as wheat and canola meal, and by-products of animal production, such as blood meal and feather meal from poultry processing [14].

Efforts were also made to quantify the major infrastructure inputs to each of the four culture systems wherever the information was available. These data were obtained through on-site measurements and facility records and descriptive documents from the facility managers. The culture systems modeled in this study are quite varied in terms of the amount and type of infrastructure required. The net-pen system is quite simple technologically and is comprised primarily of steel, concrete, and nylon, while the land-based recirculating system contains substantial amounts of mechanical infrastructure and building materials such as concrete and PVC.

Typically, up to 80% of the required data used to describe the background systems in an LCA are not collected directly by the analyst but are obtained from databases and published literature [52]. For all materials and processes in this study for which no direct data were collected, values were obtained from the extensive databases that are made available within SimaPro 7.0. These included data on the resource use and emissions associated with the production of infrastructure inputs, fuels and electricity, and the production of inputs to water quality such as liquid oxygen (Table 1).

4. Results

4.1. Life cycle inventory

Based on the LCI, the four systems required substantially different amounts of infrastructure-related inputs per tonne of live-weight fish produced with a clear pattern of greater inputs associated with higher levels of containment (Table 2). Interestingly, this was despite the fact that closed-containment systems were able to achieve much higher stocking densities than the net-pen system (ranging from 35 to 73 kg/m^3 as opposed to 20 kg/m^3). In the end, however, this was not enough to offset the much smaller rearing capacities of these alternative systems.

The amount of feed required to produce 1 t of live-weight fish varied between the four studied systems (Table 2). Feed input per tonne was lowest for the flow-through and bag systems (1165 and 1170 kg, respectively), and was particularly high for the recirculating farm (1448 kg) because of a high mortality rate during the grow-out cycle.

Results of the life cycle inventory indicate that in parallel with higher material inputs, closed-containment systems required substantially larger inputs of on-site energy when compared to conventional net-pen operations (Table 2). The net-pen system operated on a relatively small amount of fossil fuels (Table 2), used primarily to power generators. In contrast, the closed-containment systems operated primarily on electricity, and the amount required increased dramatically from the marine bag system to the two land-based systems (from 1492 kWh/t for the bag, up to 22,600 kWh/t for the recirculating system). The primary demand for electricity in the alternative systems was the need to continuously pump and circulate water. The bag system was operating at sea level and therefore had the lowest pumping requirements. On the other hand, the flow-through system was situated well above high tide and water had to be pumped at a positive head, up to 40 feet at low-tide [60], resulting in a much greater energy demand. Electricity demand was highest for the recirculating system (Table 2). This was largely because in addition to continuously pumping water, there was significant electricity demand from mechanical equipment such as oxygen and ozone generators, fans and chillers, and electronic monitoring systems. The recirculating system also employed oil-fired heaters to raise temperatures in the warehouse in the winter and required approximately 280 l of heating oil for every tonne of live-weight fish produced (Table 2).

In addition to the increase in on-site energy demand, the closed-containment systems generally required more artificial inputs to maintain proper rearing conditions (Table 2). For the bag and flow-through systems, portable liquid oxygen tanks were used to provide supplemental oxygen, with the flow-through system requiring

Please cite this article in press as: Nathan W. Ayer, Peter H. Tyedmers, Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada, J Clean Prod (2008), doi:10.1016/j.jclepro.2008.08.002

Table 2
Inputs and outputs for the production of 1 t of live-weight fish from the four culture systems analyzed

	Marine net-pen	Marine floating bag	Land-based flow-through	Land-based recirculating
General system parameters				
Geographic setting	British Columbia	British Columbia	British Columbia	Nova Scotia
Culture medium	Saltwater	Saltwater	Saltwater	Freshwater
Total culture volume (m^3)	180,000	12,000	2250	960
Average stocking density (kg/m^3)	20	35	38	73
Inputs – infrastructure (kg/t)				
Concrete	6.5	28.7	390	919
Steel	2.9	1.0	1.0	13.8
Zinc	0.2	–	–	–
Polyethylene	0.4	0.1	–	–
Polystyrene	0.2	0.04	–	–
Nylon	5.7	5.1	0.1	–
Foam	0.2	0.9	–	–
PVC pipe	–	–	–	4.2
Polyester scrim	–	2.3	–	–
Total	16.1	38.1	391	937
Inputs – operational (/t)				
Smolts (kg)	20.6	119	14.6	238
Feed (kg)	1300	1170	1165	1448
Propane (l)	9.5	–	–	–
Diesel (l)	28.8	11.6	–	–
Gasoline (l)	36.3	–	–	–
Heating oil (l)	–	–	–	279
Electricity (kWh)	–	1492	13,400	22,600
Primary source	90% Hydro	90% Hydro	90% Hydro	77% Coal
Liquid oxygen (m^3)	–	375	1011	–
Calcium chloride (kg)	–	–	–	481
Soda ash (kg)	–	–	–	804
Outputs – operational (kg/t)				
Species	Atlantic salmon	Atlantic salmon	Atlantic salmon	Arctic char
Harvest weight (kg)	2.0–5.5	4.0–5.0	4.0–5.0	1.5
Mortalities	90.0	13.6	84.4	301
Cu emissions to water	0.5	–	–	–
N emissions to water	31.3	28.4	26.0	0
P emissions to water	4.9	4.4	4.1	0
Sequestered N	–	–	–	6.8
Sequestered P	–	–	–	3.2
Total live-weight fish produced during grow-out cycle (t)	3600	416	96.2	46.2

Notes: For specific details on data sources and calculations consult [63].

nearly three-times as much liquid oxygen than the bag system per tonne harvested. Supplemental oxygen in the recirculating system was delivered through on-site oxygen generators which, as noted above, added to the facility's electricity demand. The recirculating system also required the addition of soda ash and calcium chloride to the water to maintain fish health and optimal pH levels (Table 2). Interestingly, over a tonne of these materials had to be added to the system for every tonne of live-weight fish produced.

The net-pen system produced the most direct emissions to water, including nitrogen and phosphorous via fish wastes, and copper leachate from anti-fouling paints that are applied to the nets. The bag and flow-through systems did not require anti-fouling paints, and released slightly less nitrogen and phosphorous per tonne than the net-pen system as a result of the lower feed inputs to these systems. Solid fish wastes were removed from the wastewater leaving the recirculating system and the liquid wastes were treated in the municipal sewage system prior to discharge, therefore it was assumed that there were no significant emissions of nutrients to the marine environment [61].

4.2. Culture system comparison

The first objective of this study was to determine how the life cycle environmental impacts of salmonid farming would change if production shifted from conventional marine net-pen systems to each of three alternative culture systems. Although local ecological impacts were not quantified in this analysis, a general qualitative assessment suggests that the three alternative systems have a distinct advantage over the net-pen in terms of reducing the potential for escapes and interactions between farmed and wild fish. Both the bag and flow-through systems reported no escapes [27,29] and the recirculating system was not connected to any lakes or ocean channels so escapes were not of concern. In terms of the release of waste products to the marine environment, the bag and flow-through systems offered no advantage over the net-pen, while the recirculating system was the only system at which wastes were managed.

In terms of life cycle impacts, it is apparent from the results of the system comparison (Fig. 2) that a shift from conventional net-pen farming to either of the land-based systems would result in a substantial increase in life cycle impacts for the categories considered, while a shift to production in the marine bag system would result in a marginal decrease in life cycle impacts.

The land-based recirculating system resulted in dramatically higher life cycle contributions to six of the seven environmental impact categories considered in this analysis, with the exception of eutrophication potential (Table 3). The recirculating system contributed approximately 40% less eutrophying emissions compared to the net-pen system because of the capture and treatment of nutrients in the wastewater. Otherwise, life cycle impacts of the recirculating system were at least an order of magnitude higher than those of the net-pen, with the exception of

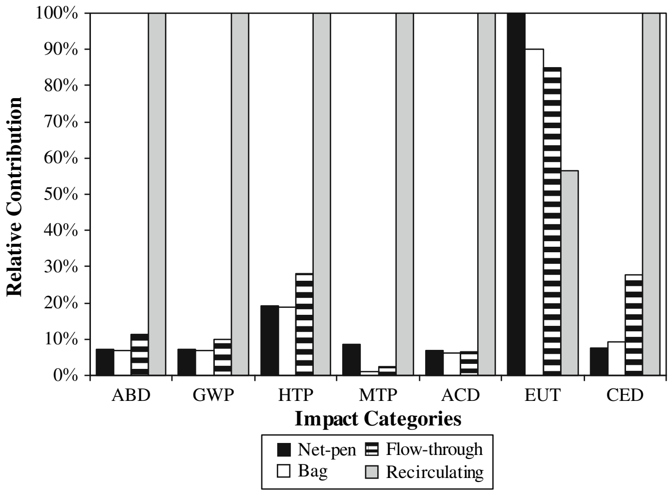

Fig. 2. Relative comparison of the life cycle contributions to environmental impact categories for the four studied culture systems. ABD = abiotic depletion; GWP = global warming potential; HTP = human toxicity potential; MTP = marine toxicity potential; ACD = acidification; EUT = eutrophication; and CED = cumulative energy demand.

human toxicity potential, which was approximately five times greater (Table 3).

Compared to the net-pen system, the flow-through system resulted in greater life cycle contributions to four of the seven impact categories considered, with the largest difference, of approximately 200%, associated with cumulative energy demand. This greater energy demand also resulted in larger contributions to several other environmental impact categories, such as abiotic depletion (60%) and global warming potential (25%) (Table 3). Production in the flow-through system resulted in lower life cycle contributions to acidification and eutrophication potential of 8% and 15%, respectively, when compared with the net-pen system. These reductions were primarily a result of the lower feed inputs per tonne of salmon produced in the flow-through system.

Use of the marine bag system resulted in a marginal improvement over the net-pen system in six of the seven impact categories considered, with the exception of cumulative energy demand, which increased by over 20% (Table 3). The most significant improvement was in marine toxicity potential, which decreased by approximately 88%. This is because rather than applying anti-fouling paints, the floating bags are periodically raised out of the water and sprayed clean. As a result, there is no copper leachate from anti-fouling paints entering the marine environment. Improvements in the other five impact categories ranged from 2% to 14% and were primarily the result of the lower feed inputs per tonne of live-weight fish produced (Table 3).

Table 3
Life cycle impacts associated with the production of 1 t of live-weight fish from the four culture systems analyzed

	ABD (kg Sb eq)	GWP (kg CO_2 eq)	HTP (kg 1,4-DB eq)	MTP (kg 1,4-DB eq)	ACD (kg SO_2 eq)	EUT (kg PO_4 eq)	CED (MJ)
Net-pen							
Smolt production	0.01	2.1	0.6	94.4	0.02	0.01	46.1
Grow-out infrastructure	1.2	185	2.9	1070	1.4	0.3	2560
On-site fuel use	0.4	55.8	3.6	2200	0.3	0.03	798
Grow-out emissions	0	0	3.0	740,000	0	28.1	0
Feed production	10.5	1830	629	78,900	16.3	6.9	23,500
Total	12.1	2073	639	822,000	18	35.3	26,900
Bag							
Smolt production	0.1	12.3	3.5	548	0.1	0.03	267
Grow-out infrastructure	0.4	61.5	3.5	3070	0.4	0.04	940
Electricity production	1.0	114	38.1	16,400	0.2	0.03	7810
On-site fuel use	0.2	35.9	1.0	204	0.4	0.1	486
Oxygen production	0.3	31.7	11.5	4860	0.1	0.01	2160
Grow-out emissions	0	0	0	0	0	25.4	0
Feed production	9.4	1640	566	70,900	14.6	6.2	21,100
Total	11.5	1900	624	96,000	15.8	31.8	32,800
Land-based flow-through							
Smolt production	0.01	1.5	0.42	66.7	0.01	0	32.5
Grow-out infrastructure	0.2	31.6	2.3	4190	0.3	0.02	401
Electricity production	9.0	1020	342	147,000	1.6	0.2	70,100
Oxygen production	0.8	85.6	31.1	13,100	0.1	0.02	5820
Grow-out emissions	0	0	0	0	0	23.5	0
Feed production	9.4	1630	563	70,600	14.6	6.2	21,500
Total	19.4	2770	939	235,000	16.6	29.9	97,900
Land-based recirculating							
Juvenile production	0.4	69.2	10	19,000	0.6	0.1	884
Grow-out infrastructure	1.3	161	18.3	13,000	3.2	0.1	2470
Electricity production	143	23,700	2070	9,020,000	220	10.4	291,000
On-site fuel use	6.2	974	96.8	74,800	2.1	0.2	14,400
Chemicals production	5.0	749	433	468,000	6.9	0.9	9970
Avoided burdens[a]	−0.2	−70.6	−0.4	0	−0.3	−0.04	−469
Grow-out emissions	0	0	0	0	0	0	0
Feed production	15.7	2660	711	91,200	22.6	8.4	34,700
Total	171	28,200	3340	9,690,000	255	20.1	353,000

Notes: ABD = abiotic depletion; GWP = global warming potential; HTP = human toxicity potential; MTP = marine toxicity potential; ACD = acidification; EUT = eutrophication; and CED = cumulative energy demand.

[a] The recirculating system collected solid wastes for use as fertilizer and was therefore assumed to be offsetting the production of an equivalent amount of synthetic nitrogen and phosphorous fertilizer. These values are negative because the system was credited with having avoided the environmental burdens associated with the production of these synthetic fertilizers.

Please cite this article in press as: Nathan W. Ayer, Peter H. Tyedmers, Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada, J Clean Prod (2008), doi:10.1016/j.jclepro.2008.08.002

4.3. Contribution analysis

The second primary objective of this analysis was to determine the environmental hot-spots for each culture system's industrial life cycle. These are essentially those stages in the interconnected production systems that contribute disproportionately to the overall environmental impact. In general, the results of the contribution analysis reveal that several hot-spots are common to each of the four production systems (Fig. 3a–d). These include the provision of feed, the production of electricity, and grow-out emissions to water.

The life cycle of conventional salmon feed production consists of a series of industrial fishing and agricultural activities that are required to produce the various high-energy feed ingredients [14]. In particular, previous LCAs have indicated that the production and combustion of fossil fuels associated with the provision of animal-derived feed inputs, such as poultry by-product meal and fish meals and oils, make substantial contributions to several global environmental impacts [16]. The environmental performance of the net-pen system was strongly influenced by the life cycle contributions associated with the provision of salmon feed, accounting for over 85% of impacts in five of the seven categories considered (Fig. 3a). For the marine bag system, feed production accounted for the largest share of life cycle impacts in six of the seven impact categories considered, ranging from 64% to 92% (Fig. 3b). In the land-based flow-through system, feed production was the largest contributor to four of the seven impact categories considered, ranging from 48% to 88% of total contributions (Fig. 3c). In the recirculating system, however, feed production was the second largest contributor in six of the seven impact categories considered. In all instances, feed-related contributions were substantially exceeded by those associated with the production of electricity required to operate the recirculating system (Fig. 3d). In general, the importance of feed as a hot-spot decreased as the direct energy inputs to the culture systems increased.

The two land-based systems consumed a substantial amount of electricity during the grow-out cycle (Table 2), and results of the contribution analysis reveal that the consumption of electricity is an important hot-spot in the life cycle of these systems. For the recirculating system, electricity provision accounted for over 80% of the life cycle contributions for all categories considered. This result is heavily influenced by the fact that nearly 80% of the electricity currently produced in Nova Scotia is from coal-fired generating plants which contribute to a range of environmental impacts, including harmful air and water emissions and the depletion of non-renewable resources [62].

For the flow-through system, electricity production accounted for over 70% of the cumulative energy demand of the system, and was the second largest contributor in four other environmental impact categories (Fig. 3c). For the marine bag system, electricity production was the second largest contributor in five of the seven impact categories considered, however, the magnitude of

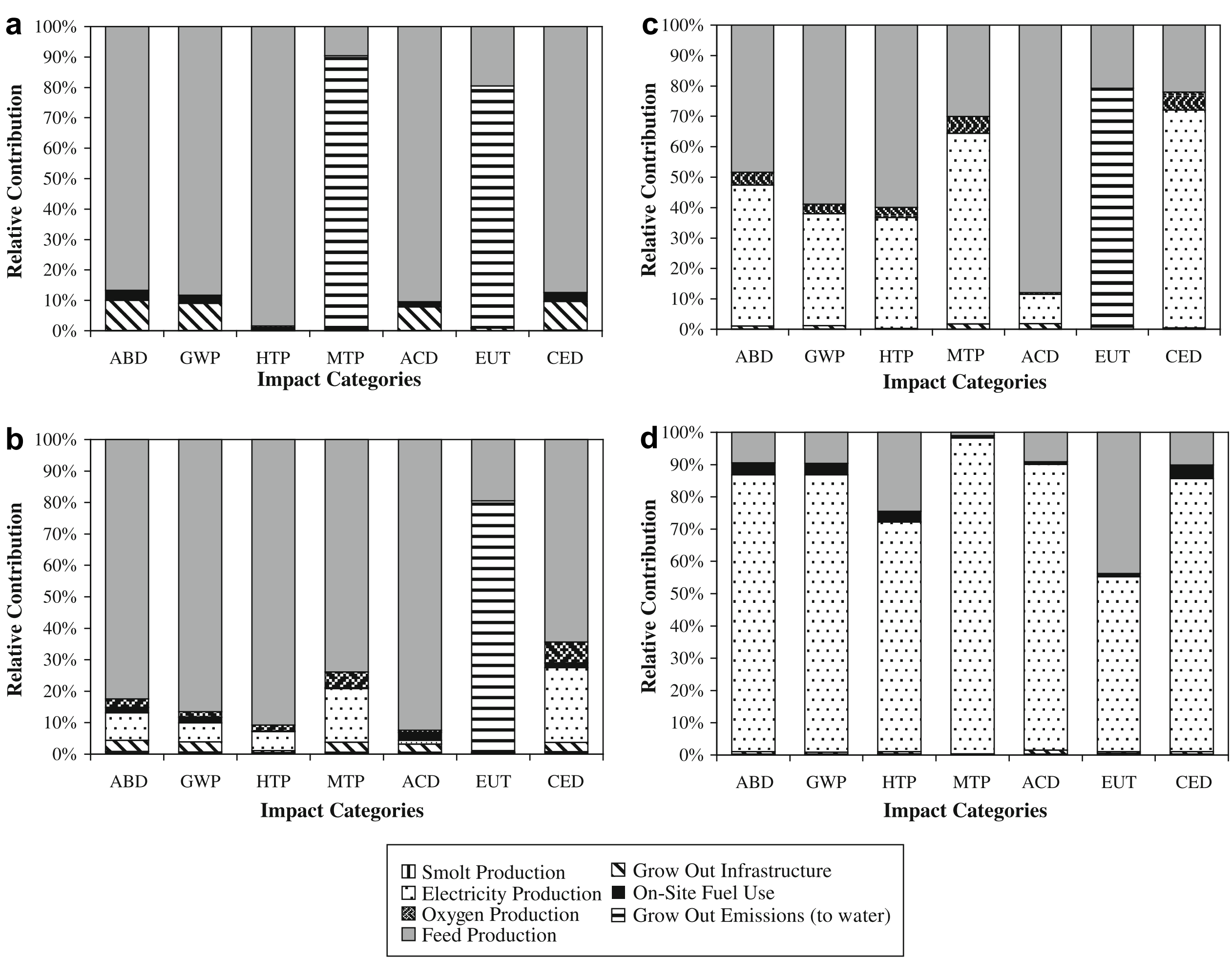

Fig. 3. Contribution analyses for the four studied culture systems: (a) marine net-pen; (b) marine bag; (c) land-based flow-through; and (d) land-based recirculating. ABD = abiotic depletion; GWP = global warming potential; HTP = human toxicity potential; MTP = marine toxicity potential; ACD = acidification; EUT = eutrophication; and CED = cumulative energy demand.

contribution was considerably less than that of feed production (Fig. 3b). Importantly, nearly 90% of the electricity produced in British Columbia is derived from hydropower, with natural gas accounting for most of the balance. The life cycle impacts associated with hydroelectricity production contributed minimally to the overall environmental impacts of the systems (accounting for 7% or less). It was the production of electricity from natural gas that accounted for most of the environmental impacts associated with electricity provision for the bag and flow-through systems.

Direct emissions to water were a hot-spot for the net-pen system in terms of marine toxicity potential (release of copper from anti-fouling paints) and eutrophication potential (release of the nutrients nitrogen and phosphorous to marine waters), accounting for 90% and 80% of the contributions to these impacts, respectively. Interestingly, the direct release of nutrients to the marine environment was also a hot-spot for the marine bag system and land-based flow-through system. Although one of the potential advantages of closed-containment systems is that wastes can be collected and treated, wastewater from these two systems was released untreated back into the marine environment. As a result, direct emissions of nutrients to marine waters accounted for approximately 80% of the life cycle contributions to global eutrophying emissions for both systems (Fig. 3b and c).

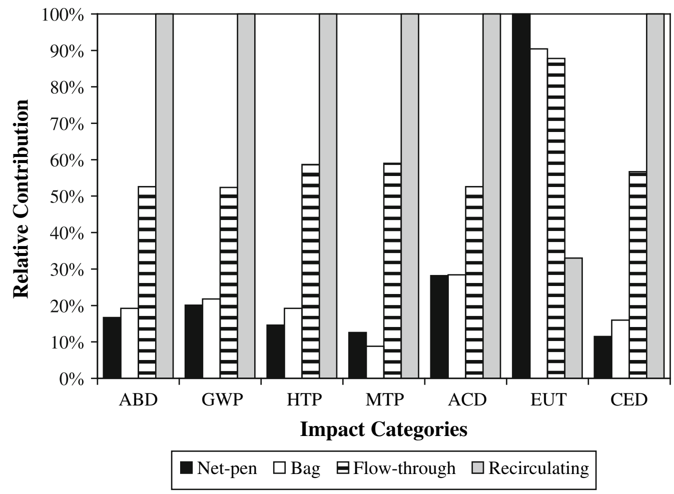

Fig. 4. Relative system comparison with all closed-containment systems assumed to be operating on the average Canadian electricity mix. ABD = abiotic depletion; GWP = global warming potential; HTP = human toxicity potential; MTP = marine toxicity potential; ACD = acidification; EUT = eutrophication; and CED = cumulative energy demand.

4.4. Sensitivity analysis

Although all three closed-containment systems had substantially higher cumulative energy demands than the net-pen system, the life cycle impacts of the recirculating system were disproportionately higher than those of the other systems. This was due, in part, to a difference in electricity source. The bag and flow-through systems were operating on 90% hydroelectricity while the recirculating system was operating on nearly 80% coal-generated electricity. In order to assess the sensitivity of these systems to electricity source, a comparison of the four culture systems was conducted in which all three closed-containment alternatives were assumed to operate on the same generic Canadian electricity mix (61% hydro, 18% coal, 13% nuclear, 4% oil and 4% natural gas).

When the results of this sensitivity analysis (Fig. 4 and Table 4) are compared with the original systems comparison (Fig. 2 and Table 3), it is apparent that the life cycle environmental impacts of these systems are very sensitive to the primary energy mix used to generate electricity. The change in electricity source essentially reversed the results of the original comparison between the bag and net-pen systems, with the bag system now having greater life cycle impacts in six of the seven categories considered, rather than showing a marginal improvement in environmental performance as in the base-case scenario. Abiotic depletion, global warming potential, and acidification levels for the flow-through system increased by 95–100% on the Canadian electricity mix, and the cumulative energy demand increased by 35%. Conversely, life cycle impacts associated with the recirculating system decreased in six of the seven categories considered. The largest decreases were in global warming potential (down 63%) and acidification potential (down 75%), with decreases in other impact categories ranging from 33% to 58%. Importantly, despite the lower overall magnitude of emissions on the Canadian electricity mix, the recirculating system remained the most impactful by a considerable margin in six of the seven impact categories considered.

This sensitivity analysis reveals that the environmental performance of the bag and flow-through systems benefited greatly from running on an electricity mix derived primarily from hydropower as modeled in the base-case analysis. While there certainly are environmental impacts associated with hydroelectric dams, such as changes to ecosystems, land use, and wildlife habitat, these systems produce fewer harmful air emissions relative to systems based on fossil fuel combustion.

4.5. Sensitivity analysis for co-product allocation decisions

Co-product allocation issues arose in the feed production stage for all systems, and at the farm-gate stage for the recirculating system. The rationale for the methods chosen to address the allocation issue was outlined in Section 2.4. In the ISO guidelines on co-product allocation, it is also recommended that whenever several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted to illustrate the consequences of departing from the chosen method [54].

Other allocation procedures that were considered in this analysis were allocation according to the economic value of co-products, or allocation according to the mass of co-products. These methods have been the most commonly applied allocation procedures in past LCAs of food production systems [58]. Sensitivity analysis was conducted to determine the impact on the overall results of the

Table 4
Life cycle impacts associated with the production of 1 t of live-weight fish from the four culture systems analyzed with all closed-containment systems assumed to be operating on the average Canadian electricity mix

	ABD (kg Sb eq)	GWP (kg CO_2 eq)	HTP (kg 1,4-DB eq)	MTP (kg 1,4-DB eq)	ACD (kg SO_2 eq)	EUT (kg PO_4 eq)	CED (MJ)
Net-pen	12.1	2073	639	822,000	17.9	35.3	26,900
Bag	13.9	2250	840	574,000	18	31.9	37,300
Land-based flow-through	38.1	5410	2570	3,840,000	33.3	31	132,000
Land-based recirculating	72.5	10,300	54,380	6,510,000	63.4	11.6	233,000

Notes: ABD = abiotic depletion; GWP = global warming potential; HTP = human toxicity potential; MTP = marine toxicity potential; ACD = acidification; EUT = eutrophication; and CED = cumulative energy demand.

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study if either of these two approaches had been applied. Since all four systems were assumed to be using the same feed, a change in allocation procedure in the feed production stage did not affect the relative comparison of environmental impacts between systems, and had only a marginal effect on the magnitude of impacts within each system (generally less than 4% change). Sensitivity analysis was also conducted for the allocation decision faced at the farm-gate stage for the recirculating system, in which solid wastes are being stockpiled for use in an adjacent greenhouse. The results indicate that as the amount of nutrients captured is so small compared to the amount of fish harvested, the impact of this allocation decision was negligible (generally less than 1% change). A detailed summary of all sensitivity analyses can be found in the background document [63].

5. Discussion

5.1. Comparison of environmental performance

For the suite of environmental impact categories considered in this life cycle assessment, the marine floating bag system demonstrated the best environmental performance of the four culture systems modeled. Although the bag system was not equipped to collect and treat wastewater (which is one of its potential advantages over net-pens), it still released fewer eutrophying emissions than the net-pen system as a result of lower feed inputs per tonne of live-weight fish produced, and reduced the potential for escapes and interactions between farmed and wild salmon. Although the bag system had a substantially higher cumulative energy demand than the net-pen system, the on-site electricity was supplied primarily by hydropower, which produces fewer harmful emissions compared to the production and combustion of fossil fuels used for on-site energy required by the net-pen system. The influence of the primary energy source on the life cycle contributions from the bag system was clearly illustrated in the sensitivity analyses in which the water pumps were powered by a generic Canadian electricity mix (Fig. 4 and Table 4). This scenario resulted in the net-pen system outperforming the bag system in terms of life cycle environmental impacts. Given this result, the geographic location of the bag system takes on an important role in determining the environmental performance of this system since in most cases, location is a key determinant of the type of primary energy inputs that will be readily available.

The latter also applies to the land-based flow-through system, which had the second poorest environmental performance of the four systems modeled despite the advantage of relying primarily on hydropower. The substantial amount of energy required to pump seawater up into the land-based tanks is problematic from an environmental performance standpoint. As was illustrated in Section 4.4, had this system been located in a region that did not have access to hydropower, its life cycle impacts would have increased substantially. Similar to the bag system, the flow-through system essentially eliminated escapes and interactions between farmed and wild salmon. It also released slightly fewer eutrophying emissions than the net-pen as a result of lower feed inputs per tonne. However, by not collecting and treating wastewater, both of these systems fell short on one of their potentially significant advantages over net-pen technology.

In terms of the life cycle environmental impact categories considered in this study, the land-based recirculating system had the poorest environmental performance of the four culture systems modeled by a considerable margin. By collecting and treating wastewater, and even sequestering some waste nutrients for reuse, this system did outperform the others in terms of eutrophication potential, in addition to eliminating the potential of escapes and interactions between farmed and wild fish. However, these advantages are tempered by the substantially higher life cycle impacts in all of the other environmental impact categories (Table 3 and Fig. 2). Most notable are the impacts that are directly linked to energy use, including abiotic depletion (the depletion of non-renewable resources), global warming potential, and acidification, all of which increased by over an order of magnitude compared to the net-pen system. For example, producing 1 t of live-weight fish in the recirculating system resulted in the release of over 28 t of CO_2 equivalents to the atmosphere, compared to just over 2 t CO_2 equivalents in the net-pen system.

5.2. Environmental costs of technology

Based on the results of the present analysis, a shift in production mode from conventional net-pen farming to closed-containment alternatives will result in a substantial increase in material inputs and energy use for every tonne of live-weight fish produced. This is a result of the increased inputs needed to build and maintain infrastructure, the increased energy inputs required to pump water and operate mechanical equipment, and also the generally lower production capacity of the closed-containment systems modeled in this analysis. This has serious implications for the proposed increased use of these alternative systems [22,23,64]. In order for these systems to have the capacity to be economically competitive with net-pen farming systems and other well-established seafood production systems, they will need to produce a large volume of fish. This will require the construction of larger closed-containment systems, or alternatively the construction of a greater number of small systems. In either case, the increase in material and energy demand involved with this expansion would be substantial, as would the associated life cycle impacts. This holds true even for the marine-based bag system, as despite its marginal advantage over the net-pen in terms of environmental performance in the present analysis, it cannot be assumed that the system would have access to hydropower in every site location should these systems be employed more widely.

One of the advantages of producing salmon in marine net-pens is that this form of aquaculture makes use of ecosystem services provided freely by the ocean. Ocean currents and tidal action help to maintain optimal growing conditions by providing a constant supply of fresh seawater, dissolved oxygen, and flushing of waste products. These advantages are greatly reduced or eliminated in a shift to closed-containment systems. By isolating the culture environment, these systems effectively restrict access to ecosystem services. The appropriate rearing conditions must then be maintained by technological processes. This includes the continuous pumping of fresh water into the culture environment, the provision of supplemental oxygen (both by tanks of liquid oxygen or oxygen generators), and in the case of the freshwater recirculating system, includes the addition of chemicals to maintain optimal water quality, the ozonation of water as part of a biofiltration process, and seasonal heating and cooling of the building to maintain optimum temperatures. Results of the present analysis indicate that all of these additional processes come at a very substantial biophysical "cost" (Fig. 5).

The environmental costs associated with the substantial increase in energy demand of closed-containment systems were particularly notable for the land-based systems, which showed substantially higher contributions to energy-driven impacts such as abiotic depletion and global warming potential (Table 3). The environmental cost of substituting technology for ecosystem services was even more pronounced for the recirculating system because of its dependence on electricity generated primarily from coal. The bag and flow-through systems were shown to have performed better largely because they were able to access electricity produced primarily from hydropower. This is due to the fact that hydropower does not generate the same levels of harmful

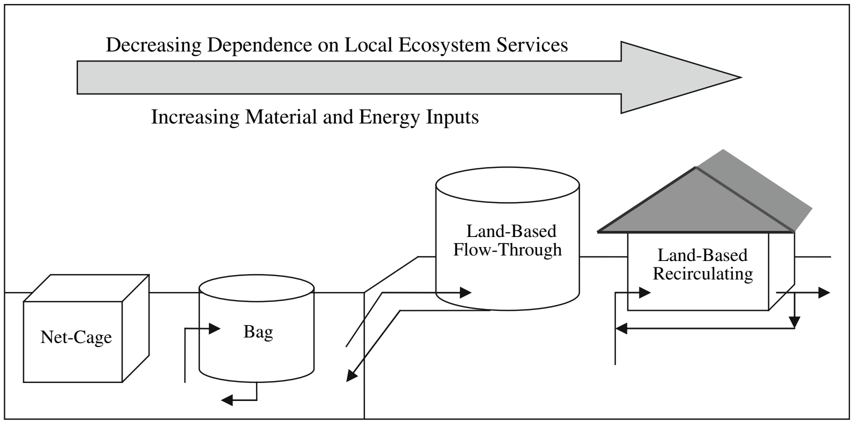

Fig. 5. The flow of material and energy inputs in relation to the dependence on ecosystem services.

emissions to air and water when compared with fossil fuel-based electricity generation [62]. It is important to note, however, that LCA does not encompass all environmental impacts of importance. Within the current context, the local ecological impacts associated with hydroelectric dams simply cannot be addressed by the LCA methodology. This includes the substantially negative impact that large-scale hydroelectric dams have on wild salmonid populations as a result of the alteration of habitats during dam construction, the alteration of flow regimes, and the continuous erosion of riverbeds upstream and downstream of the dam during operation [62,65]. Although LCA is currently “blind” to this type of impact, it provides a powerful reminder that all energy production comes at some environmental cost. The fact that the culture systems operating on hydropower performed well in this analysis should therefore not form a basis to argue that powering aquaculture systems in this manner comes at little or no environmental cost.

5.3. *Environmental problem shifting*

One of the benefits of taking a life cycle approach to analyzing the environmental impacts of any new technology is that it provides a broad enough perspective to help reduce the likelihood that application of this new technology will result in unintended problem shifting [34]. The implementation of closed-containment salmonid farming technologies would appear to represent a classic case of environmental problem shifting. These systems were designed specifically to isolate the culture environment from surrounding ecosystems in part to reduce the proximate ecological impacts that are typically associated with net-pen salmon farming. However, in doing so, they must substitute industrial energy-driven technological services (e.g. pumping water, providing supplemental oxygen, heating and cooling) to simulate the natural rearing conditions that are required by the fish. Consequently, material and energy demands increase along with the concomitant environmental impacts. While trading off potential reductions in local impacts on ecosystems for increased contributions to a range of global scale concerns may be justified, it should be undertaken with a conscious awareness of the tradeoffs.

6. Conclusions

Life cycle assessment was used to evaluate the environmental performance of a conventional marine net-pen system for culturing Atlantic salmon and to determine how the life cycle environmental impacts of salmonid farming would change with a shift in production mode to each of three proposed environmentally-friendly alternatives; a marine floating bag system, a land-based saltwater flow-through system, and a land-based freshwater recirculating system. Of the four systems modeled, the floating bag system demonstrated the best environmental performance in six of the seven impact categories considered (ABD, GWP, HTP, MTP, ACD, and EUT), followed by the net-pen, the flow-through system, and the recirculating system. The advantages of the bag system resulted from lower feed inputs per tonne, lower energy demand than the other closed-containment systems considered, and access to hydroelectricity as the primary source for on-site energy use. However, sensitivity analysis revealed that the life cycle impacts of this system can vary widely depending on the form of on-site energy used. The use of more fossil fuel-based electricity to power the water pumps resulted in a substantial increase in the life cycle impacts of this culture system, giving the net-pen an advantage over the bag system in terms of environmental performance in those instances.

The two land-based systems exhibited the poorest environmental performance of the four systems modeled, with the land-based recirculating system generating substantially higher life cycle environmental impacts for the categories considered. The greater energy-intensity of the land-based systems was the primary source of their increased life cycle impacts.

Overall, the results of this study reveal that while a shift to closed-containment technologies may reduce the set of proximate ecological impacts typically associated with conventional salmonid farming, their increased use may also result in substantially increased contributions to several other environmental impacts of global concern, including global warming, acidification, and abiotic resource use. It is beyond the scope of this study to determine which set of impacts should be of greater concern, however, these tradeoffs should be factored in to the ongoing discussion on how to improve the environmental performance of salmonid farming. Although closed-containment systems are currently being described and promoted as environmentally-friendly alternatives to net-pen farming, results of this study suggest that there is an environmental cost associated with employing this technology which should be considered in any further evaluation of their environmental performance.

Acknowledgments

The authors would like to acknowledge the generous financial support of Dalhousie University and the Lenfest Ocean Program at the Pew Charitable Trusts. Thanks are also due to those who provided data, in particular D. Roberts, R. Buchanan, R. Walker, and A. Clarke, and to N. Pelletier for development of the salmon feed model. The manuscript was greatly improved with the input of two anonymous reviewers. Any remaining errors or omissions are of course the sole responsibility of the authors.

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