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Perspective on the Technical Challenges Associated with Closed System Aquaculture for Grow-out of Salmon in BC

**Prepared for the Aquaculture Judicial Inquiry on
behalf of the BC Salmon Farmers Association**

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 PERSPECTIVE ON THE TECHNICAL CHALLENGES ASSOCIATED WITH CLOSED SYSTEM
 AQUACULTURE FOR GROW-OUT OF SALMON IN BC
 PREPARED FOR THE AQUACULTURE JUDICIAL INQUIRY ON BEHALF OF THE BC SALMON FARMERS
 ASSOCIATION

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Any questions concerning the information or its interpretation should be directed to David A. Jackson, P.Eng.

1. INTRODUCTION

Farmed salmon has been British Columbia's largest agricultural export for the last five years and the BC Salmon Farmer's Association (BCSFA) represents members who are responsible for the vast majority of this production.

In BC and throughout the world, farmed salmon is produced with Open Net Pen (ONP) technology. It is well known that many interest groups favour a complete replacement of ONP production with Closed System Aquaculture (CSA), believing the latter to be a more sustainable method of production with less environmental impact. BCSFA applauds the goal of progressively improving the sustainability of salmon production, and would like the Inquiry to be well-informed about the state of readiness of CSA technology and the various factors that could affect the relative sustainability merits of ONP and CSA. To that end, BCSFA engaged WorleyParsons to prepare this short report, based primarily on WorleyParsons' recent experience in conducting feasibility studies for a BCSFA member into the siting, design and implementation of both demonstration-scale and commercial scale CSA facilities for salmon grow-out on Vancouver Island. WorleyParsons is a global engineering services company with 32,900 employees in 41 countries and is rated as the number two design firm in the world¹.

BCSFA has been a global leader in the application of one particular type of CSA, namely Recirculating Aquaculture Systems (RAS), for the production of salmon smolts. In fact, BCSFA members have been early adopters of RAS technologies developed at the Freshwater Institute (FWI) in West Virginia and in Europe, to the point where more than 65% of smolts produced in BC are raised with RAS technology. For reasons that are explained in this report, RAS technology probably has the best chance, among the many varieties of CSA, of successful application to salmon grow-out. For that reason, this report will focus on RAS technology, recognizing that other forms of CSA are also available.

Submissions filed with the Inquiry to date may leave the impression that CSA has been, and is, immediately adoptable by industry as a replacement for ONP production. In particular, the paper "Global Assessment of Closed System Aquaculture"² submitted to the Commission does not provide evidence that CSA is ready for immediate commercial application to land-based grow-out of a commodity species like Atlantic salmon in BC. While CSA (specifically RAS) has exciting potential, the state of readiness of the technology is such that considerable technical and economic challenges remain and the relative sustainability merits of the two technologies (considering GHG emissions, for example) are unclear at this point in time. It is hoped this report will provide the Inquiry with an additional perspective on this matter based on engineering feasibility work focussed specifically on salmon grow-out in BC.

¹ Engineering News Record, 2010

² EcoPlan International, Inc., 2008



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Marine Harvest Canada, a BCSFA member, has developed plans to test the viability of RAS technology for salmon grow-out through the establishment of a pilot/demonstration facility at a location on northern Vancouver Island before the end of 2012. In an unprecedented level of cooperation with ENGOs, a Project Review Board (PRB) with wide representation from ENGOs, DFO, First Nations and industry experts is being convened to provide technical guidance, establish performance metrics and assess the results of the tests. These demonstration tests will be hugely influential in determining the practical role that RAS technology can play in the grow-out of salmon in BC.

2. CURRENT STATE OF CSA TECHNOLOGY

The state of technology for closed system aquaculture is well represented in peer-reviewed journals such as *Aquaculture*, and *Aquaculture Engineering* as well as various trade publications. The industry standard comprehensive reference “*Recirculating Aquaculture*”³, known colloquially as the “Yellow Book” first published in 1977 has been continuously updated, most recently in 2010. Of more direct interest to this paper are studies that address the state of technology readiness and potential viability of salmon grow-out.

2.1 Previous Studies

In 2008, the Coastal Alliance for Aquaculture Reform (CAAR), the Georgia Strait Alliance and the David Suzuki Foundation commissioned a “Global Assessment of Closed System Aquaculture”. This is a broad-scope study that presented an interesting survey of closed system aquaculture (CSA) employed for raising a great variety of finfish and other species around the world. It was not specifically focussed on salmon grow-out and did not identify instances of commercial-scale salmon grow-out.

The CAAR study correctly determined that the “*vast majority of commercial production of finfish in OECD countries is based on open systems*” and was not able to assemble statistics for CSA production. They also found that “*to date the most consistent and notable successes to date in commercial scale closed system aquaculture for food fish production have been achieved by systems using species tolerant of high density conditions and those which command a premium market price*”. “*Currently, most CSA production systems in the United States are small, less than 45 MT of production per year, providing fresh high quality product at premium prices to niche markets*”. This is still the case, and to date there are no examples of commercial production of market-size salmon using CSA. Whereas a typical net-pen farm can produce 2,500 MT/year, there is a huge jump in scale from niche CSA systems to commercial production of a global commodity product such as salmon. The unit direct operating costs for many of the CSA systems described in the report (in the range of \$7.5/kg or more) are well above the wholesale price for Atlantic salmon (in the vicinity of \$6/kg), implying that product would be sold at a loss unless it was priced at a significant premium.

The study also identified the need to balance the potential drawbacks of CSA (energy consumption and associated GHG emissions) as well as the benefits when exploring CSA options.

The study conclusion that “*(t)he number of sustained commercial operations illustrates that CSA is a viable means of commercially producing fish for harvesting*” needs to be understood in the context of qualifications also stated in the report that “*considerable debate remains as to the adaptability of CSA to the range of commodity species*”. In fact, none of the operations described in the report was of a scale that

³ Timmons and Ebeling, 2010



could viably produce commodity species such as Atlantic salmon without a price premium that would restrict the sale of product to a decidedly niche market.

In summary, the CAAR study provides an interesting broad perspective on CSA and illustrates how CSA has been successfully applied to the production of certain high value, tolerant species for sale at premium prices in niche markets. However, it provides little guidance on the issue of the potential viability of CSA production of a high-volume commodity species such as salmon in BC.

Fisheries and Oceans Canada (still colloquially known as “DFO”) prepared two reports relating to the potential viability of CSA for production of salmon in BC. The first study (DFO, 2008) assessed the state of CSA technology as it might be applied to salmon production. They cited over forty CSA systems around the world and found that *“none were producing exclusively Atlantic salmon and that many previous attempts to do so had failed.”* The study identified a number of uncertainties with regard to operating variables in salmon grow-out with CSA (including maximum fish density, water quality parameters, salinity effects, achievable growth rates, etc), set out a list of research needs and proposed some methodology for CSA trials.

DFO followed up with a feasibility study of CSA options for the BC Aquaculture Industry (DFO, 2010). This study developed business cases for salmon production with each CSA option, based on a defined configuration for each. The study concluded that of the ten CSA methods analyzed, only two (ONP and RAS) showed potential for financial feasibility. They determined that RAS was marginally profitable; however, given the low rate of return on investment and the high sensitivity to adverse market trends in comparison with ONP, a RAS system would not be an attractive investment opportunity. They recommended the next step to be a pilot or demonstration system to demonstrate the technical and financial viability under real world operating conditions which would generate data to support an accurate life cycle analysis comparison between ONP and RAS.

The results of the feasibility study described in Section 3 are broadly consistent with the findings of the more recent DFO study. The studies agree that RAS has the greatest potential for viability and achieves better biological isolation than, for example, most floating systems, which treat only the sediment-rich portion of their effluent. The DFO study outlined the major challenge faced by RAS for salmon production: the need for substantial improvements in unit production costs in order to make RAS production solidly viable. Consequently, the WorleyParsons engineering feasibility study focussed on ways to improve the unit cost structure through economies of scale, lower energy use, better equipment utilization and other measures.

2.2 Existing RAS Technology and Installations

Several dozen RAS systems are employed around the globe producing salmon smolt, and in British Columbia it is the dominant method of producing smolt. At the present time, there are no examples of commercial-scale RAS grow-out of salmon anywhere in the world. Although RAS is used extensively in Europe, Chile and Canada to produce smolt (typically 80–120 g), grow-out is accomplished by ONP production methods. There are plans to establish facilities to produce larger size fish (perhaps 350–

1,000 g) from smolt using RAS; however, none of these have yet been built⁴. RAS is also used in several locations, including BC, for production of brood stock; however, these are low intensity (low fish density) operations (often < 20 kg/m³) that while acceptable for production of high value brood stock, would not be capable of economically producing fish for market. As will be explained in this report, there is a substantial technical leap from either smolt production or brood stock production to full commercial-scale production of market size fish, using RAS methods.

The Freshwater Institute (FWI) in West Virginia continues ground-breaking work in the development of intensive fish culture methods with the pilot scale (150 m³ tank) grow-out of Atlantic salmon to a size of approximately 4 kg in a freshwater environment. It is understood that fish behaviour, health and quality has been very good at peak densities of about 40 kg/m³; however, growth rates underperformed expectations in the latter growth stages. This phenomenon could be attributable to lack of salinity, small tank size or other factors. As explained in Section 3, the fish density and growth rates that were demonstrated in these trials would not result in viable commercial salmon production; therefore some improvements on these parameters would be required. The feasibility work by WorleyParsons concluded that tanks of 1,400 m³ or more may be required for commercial scale production, a scale-up factor of more than 9 to 1.

At least one BCSFA member, Marine Harvest Canada, announced plans to establish a facility to test the viability of commercial grow-out of salmon using RAS technology. This project is described in Section 3. The Namgis First Nation near Port McNeill⁵ also announced plans to establish a demonstration scale grow-out facility. It is understood that both projects will employ a small number of modules of full commercial size RAS equipment, so as to accurately emulate a commercial system, which would consist of many more modules of the same design. So far as we can determine, these two projects would be the first salmon grow-out operations anywhere in the world that would use full-scale RAS equipment.

In summary, RAS technology for salmon grow-out is at the “demonstration” stage, where testing with commercial scale equipment and variable operating conditions is required to conclusively determine if grow-out using RAS is practical and economically viable using present technology.

2.3 Technology survey

In the process of conducting engineering feasibility studies for both demonstration and commercial scale RAS grow-out facilities, WorleyParsons conducted a survey of technology that could be applicable to intensive grow-out of Atlantic salmon. A Request for Qualifications (RFQ) was issued to a total of eleven firms that purport to offer integrated RAS systems for smolt production or grow-out of finfish species.

The firms surveyed included:

⁴ Personal Communications Dr S. Summerfelt of FWI and Paal Haldorson, MH Norway.

⁵ CEAA commencement announcement, June 15, 2011



- AKVA Group (Norway)
- AnoxKaldnes (Sweden)
- AquaCare (Washington, USA)
- AquaOptima (Norway)
- Aqua-tec Solutions A/S (Denmark)
- Atlantech (Canada)
- Billund Aquakultur Service (Denmark)
- Inter-Aqua Advance (Denmark)
- PRAqua (BC, Canada)
- Water Management Technologies (Louisiana, USA)
- Yanmar (Japan)

These firms represent a clear majority of the firms most active in supplying integrated RAS systems. A total of ten firms responded. In all cases, the information provided was somewhat generic in nature, with only one offering a solution customized to the specific application (grow-out of Atlantic salmon). None of the companies, were able to provide any project references for such an application. Most requested that the client provide a bioplan for the production system since the application was beyond their experience. Some offered to work collaboratively to help develop the production plan.

In due course, budgetary quotations were requested and received from several of these firms as well as many additional companies offering less specialized components such as oxygen generators, ozone generators, pumps, tanks and buildings, with the objective of helping establish accurate estimates of capital cost for a complete facility.

There was a remarkable diversity in configurations offered and divergent views on matters such as:

- the type of biofilter [Fluidized sand biofilter (FSB) , Moving Bed Bioreactor (MBBR), Submerged Bed Biofilter (SBB)]
- the sequence of operations
- the use of Ozone and / or UV light disinfection
- the method of introducing oxygen into the system (Low Head Oxygenation (LHO), Diffused Oxgenation, Pressure devices)
- the method of producing or supplying oxygen
- the method of particulate removal (drum filters, belt filters, bead filters, etc)
- the method of CO₂ removal (packed column stripper, diffused aeration)

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- segregated or non-segregated treatment of the culture tank dual drain effluent
- the size and shape of culture tanks

With such unexpected diversity to assess, a great deal of effort went into considering the various options and trying to identify a configuration that would best fit the application. To aid this effort, a process and economic model of a hypothetical 2,500 MT/yr production facility called RASbook was developed to help compare options and assess the financial viability. It was determined that none of the offerings was the ideal solution for the application and a new configuration (called MHC-RAS) was developed using primarily generic components available from multiple suppliers. This configuration has greater economies of scale and a lower energy requirement than previous configurations.

In summary, based on WorleyParsons' experience in conducting the technology survey, there is very little consensus in the industry with respect to the basic configuration for a salmon grow-out design, and an "off the shelf" integrated system for such an application is simply unavailable at this time. A bioplan and production plan must be developed from first principles and a system may need to be configured using offerings from several suppliers.



3. LEARNINGS FROM A RAS GROW-OUT FEASIBILITY STUDY

3.1 Scope

WorleyParsons conducted a feasibility study on behalf of a BCSFA member to examine the siting, design and economic feasibility of both a demonstration scale and full commercial scale land based RAS facility for production of market size salmon. The facilities were to be located at a suitable site on northern Vancouver Island.

As part of the design process, WorleyParsons completed a Siting Study, a review of current technology, a series of workshops with operating staff to define the design parameters, a production and economic model for the proposed facility and a preliminary design and cost for the proposed facility at the preferred site identified in the Siting Study.

This study addressed two scales of facility: a hypothetical Commercial grow-out facility with a production of approximately 2,500 MT/year as well as a smaller demonstration (Pilot) facility. The viability of land-based grow-out was assessed on the basis of the commercial system, whereas the Pilot is intended to thoroughly test the production configuration and operating assumptions made in the development of the commercial system concept.

3.2 Siting Study

A siting study was conducted with broad terms of reference to find suitable sites according to the following primary criteria:

- a) Adequate supplies of groundwater of suitable quality (surface water is considered to be a biosecurity risk)
- b) Access to saltwater of adequate quality, preferably from a salt water well
- c) Reasonable logistical characteristics (travel distances for staff, etc)

Having adequate supply and quality of water is paramount. Insufficient water supply has been cited as the predominant reason for the high rate of failure of intensive aquaculture enterprises to date (Timmons, 2010).

Calculations performed according to guidelines provided in the standard industry reference (Timmons, 2010), which cites a usage index of 100% water exchange per day plus makeup requirements, indicate that a 2,500 MT/yr production facility should have a water supply capacity of about 40,000 Lpm to fulfill normal process needs, cleaning and utility needs, emergency supply and allowances for well decline (actual average usage would be considerably less). This is a huge supply that would be available only in very few locations and there is a general feeling in the industry these indices are excessively conservative and that a modern, well designed RAS facility with a high level of mechanical reliability will need much less water. A more realistic estimate for a commercial facility would be 5,600 Lpm plus requirements for depuration, which would vary with method. It is understood that other grow-out design efforts currently

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underway are assuming that a water supply in the range of 4,000–8,000 Lpm (including depuration) would be adequate for a commercial scale facility⁶.

It is technically possible to design a RAS facility to operate with an even smaller water supply; however, the costs of treatment become exponentially higher as the quantity is reduced and at the present time, the marginal economics of RAS grow-out preclude such costs. For example, water makeup rates less than approximately 300 L per kg of feed applied necessitate (for a salmon smolt or grow-out operation) the addition of a biological denitrification process to the treatment system to control levels of nitrate. The addition of a non-aerobic biological component to a RAS system adds to system complexity and raises questions regarding biosecurity and unintended detrimental water quality effects.

Similarly, an almost ideal supply water quality is sought so as to avoid the costs and reliability issues associated with treating the supply water. The recent construction of a large \$46 million salmon hatchery for the Alaska Department of Fish and Game in Fairbanks, Alaska illustrates the importance of this consideration. Groundwater in the Fairbanks area has elevated levels of iron and manganese which must be removed prior to use in any aquaculture facility and the hatchery was duly designed with a water treatment system for removal of iron and manganese. Severe problems in commissioning and operating the water treatment system delayed the start-up of the hatchery by several months and required the installation of additional equipment costing millions of dollars⁷.

The requirement for saltwater is driven by the supposition that certain levels of salinity may be essential for optimum growth and health conditions for salmon grow-out. RAS performance that has been demonstrated to date with freshwater conditions has not been adequate for commercial viability. It is suspected that brackish water would provide the best performance; however, finding brackish water of the right quality and quantity that will maintain consistent salinity over long periods of production is very challenging. In any case, the optimum level of salinity is not known and could vary with fish size. Therefore, the siting study proceeded on the basis that independent sources of freshwater and saltwater (preferably naturally filtered seawater) that can be blended in any combination would be required for the project.

The Siting Study proceeded initially from a hydrogeological perspective, identifying sixteen areas on Northern Vancouver Island that had a reasonable probability of exhibiting the necessary combinations of groundwater and saltwater supply and quality. Some areas that, due to geological conditions, are prone to iron and manganese were excluded. The requirement for relatively large flows of groundwater and salt water naturally lead the study toward sizeable fluvial deltas along the coast. Unfortunately, conditions that

⁶ Personal communication – Dr Summerfelt

⁷ “Fish hatchery in Fairbanks opening delayed at least until May” The Associated Press – Jan 15, 2011.



are favourable for large supplies of high quality groundwater tend to be almost mutually exclusive of conditions that are favourable for sterile saltwater supply.

The siting study demonstrated that while there appeared to be several candidate sites in favourable locations along the coast of northern Vancouver Island with possible access to sufficient quantities of fresh, high-quality groundwater to service a pilot or commercial RAS facility, and where the operation of a RAS facility with the extraction of groundwater may be unlikely to adversely impact local environmental/social receptors or existing water users, no “perfect” site emerged that possessed all of the desired physical, chemical, environmental, and social performance attributes. From the pool of sixteen candidate sites (general areas, as opposed to specific legal parcels) analysed in the siting study, two high-priority (“Tier 1”) sites were identified that displayed a wide range of known attributes related to their potential suitability to host RAS pilot and commercial facilities.

In summary, the current combination of requirements regarding water quality and quantity and basic logistical constraints are surprisingly limiting when it comes to identifying suitable RAS sites. These constraints will be alleviated if it can be demonstrated that freshwater provides adequate growth rates or if product price will provide sufficient margin to employ additional technology to pre-treat imperfect water sources and reduce water requirements in the process.

3.3 Technical Challenges

Use of RAS systems for salmon smolt production has developed a considerable knowledge base for application of RAS technology to smaller Atlantic salmon (up to 120 g); however, the mass production of market size fish introduces new challenges and exposes other information gaps.

As identified in the DFO feasibility study (2010), a primary challenge will be to achieve reductions in unit capital and operating costs (relative to current RAS designs) that will be required in order to make RAS viable for salmon grow-out. Gains can hopefully be made through economies of scale (larger reproducible modules), onsite oxygen generation and reduced energy requirements. WorleyParsons modelling work indicated that larger tanks sizes (in the region of 20 m diameter) are required to have sufficient economies of scale; however, there is inadequate experience at the present time to know how dual drain tanks of this large size will perform with high fish densities in a grow-out situation. Hydrodynamic modelling as well as some period of field adjustments will likely be required before designs can be finalized.

Another technical barrier is achieving very high standards for mechanical and process reliability. Failures that kill fish cannot be tolerated. At the same time, RAS technology must be implemented at an unprecedented scale and be pushed to new limits in order to achieve the required reduction in unit production cost. Operating such a mechanically complex system close to its operating limits will require new levels of operator skill and higher levels of process monitoring and control than have been applied to date in aquaculture operations.

Salmonids raised in RAS systems are reputed to have a muddy flavour due to the presence of geosmin and MIK compounds. A depuration process, where pre-harvest fish are starved of food so that offending compounds are metabolized will hopefully address this issue; however, the proper parameters for depuration (salinity, temperature, duration, etc) are yet to be established.

Another technical barrier of high importance is simply the lack of knowledge in the industry regarding the optimum conditions for grow-out. At the present time, certain key data that would underlie the bioplan (such as maximum fish densities, the thermal growth coefficient at different salinities and fish sizes, etc) are not well known.

The following are some of the more important questions that are currently unresolved:

1) Physical System

- a) Which RAS process configuration minimizes overall energy demand and GHG generation, consistent with maintaining proper conditions for fish health and growth?
- b) To what degree can capital cost be reduced through economies of scale, facility design and project delivery methods?
- c) Can the latest RAS technology be adapted for a brackish or salt water production system and if so, how?
- d) Can RAS systems be designed to meet the exceedingly high reliability standard required for grow-out operations, if so, how?
- e) Can large dual drain tanks (20m) perform reliably, have uniform fish distribution and be self-cleaning in a grow-out operation?

2) Operating Parameters

- a) What is the optimum salinity level for grow-out and does this vary by growth class and depuration phase?
- b) What is the optimum temperature regime for fish growth subject to water quality, fish health and other system constraints, and does this vary by growth class and depuration phase?
- c) Can all target water quality parameters for fish growth and health be met at target loading rates and which are the limiting parameters?
- d) What survival rates can be achieved through complete elimination of all pathogens and minimizing stress?
- e) To what extent can the feed conversion ratio be optimized through improved monitoring of feed intake and maintenance of optimal growth conditions?
- f) What maximum fish densities can be achieved without significantly affecting growth and quality of the fish or their health and welfare and to what extent can this be aided by improved process control?



3) Product Quality

- a) What is the level of product quality and taste prior to depuration?
- b) What is the most effective depuration method (salinity, duration, temperature) and can it achieve typical industry standards for quality?

3.4 Economic Challenges

The DFO Study (2010) highlighted the economic challenges facing land-based grow-out methods. Of the various CSA options surveyed, only RAS was determined to offer the potential of a positive return. Even then, the return was so small and the downside risk so great that it would be unattractive to investors. Working against the recognized advantages of RAS methods (higher feed utilization, optimization of conditions for growth, shorter cycles, etc) is the substantially higher capital cost of land-based facilities. Whereas a 2,500 MT/yr net-pen farm might cost \$5 million⁸, a serviced RAS facility of equivalent capacity could cost in the vicinity of \$30 million (\$23 million according to the DFO estimates). The burden of financing this large investment is considerable and WorleyParsons modelling indicated that only high utilization production scenarios, with average and peak fish densities much higher than typical for smolt production, offer any potential for financial viability.

Fish density and growth rates are critical to the economic viability of RAS grow-out and the large investment must have high productivity to generate revenues to cover the financing costs. Whereas peak fish densities of 50 kg/m³ are common in smolt production, modelling shows that peak densities of up to 90 kg/m³ are required to achieve viability in a RAS grow-out facility. Even with a high utilization production scenario, some price premium for the land-based product is required to make the enterprise an investment-grade opportunity. Densities of up to 80 kg/m³ have been demonstrated in Atlantic salmon pilot-scale grow-out trials at FWI⁹ and some trials in Europe indicated that densities of 86 kg/m³ might be achievable in certain circumstances¹⁰, so there is some basis for optimism in this area; however, these operating parameters would push biological performance to the theoretical maximum and these high densities would need to be demonstrated in realistic operating conditions.

3.5 Demonstration Facility

The feasibility study concluded that, based on the current state of technology and knowledge relating to salmon grow-out, it is not possible to state that land-based salmon grow-out is economically viable. Only a demonstration project employing full scale equipment operating under actual conditions can answer this question. Fortunately, two such projects are planned for BC and have attracted funding from government

⁸ DFO, 2010

⁹ Personal communication Dr Summerfelt.

¹⁰ Hosfeld et al, 2009

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sources. It is understood that both projects will be conducted under the guidance and scrutiny of a broadly-constituted Project Review Board (PRB) that will scrutinize test methods and assess results.

These projects will be very important in closing the knowledge gap on salmon grow-out, generating data to complete an accurate life cycle assessment comparison between RAS and ONP and providing performance data upon which RAS investment decisions can be made.



4. COMPARING RAS AND OPEN NET-PENS – GLOBAL WARMING POTENTIAL

Much work has been devoted to the analysis of potential environmental impacts of ONP production and some attempts have been made to develop sustainability comparisons between ONP and CSA. An observation made in comparing these two methods is that while the potential environmental impacts of ONP are predominantly local, those of RAS are predominantly global, due to its higher energy requirements and GHG potential.

Ayer and Tyedmers (2009) reported on a life cycle assessment (LCA) comparison of several salmonid grow-out methods, including ONP and land-based RAS. This paper will not attempt to address the complex comprehensive comparison between ONP and CSA but merely provide some additional insight on one aspect of the comparison, energy use and Global Warming Potential (GWP) as it relates to land-based salmon grow-out in BC.

Ayer and Tyedmers compared four production systems (ONP, Marine floating bag, land based flow-through and RAS) on several LCA criteria. They calculated that ONP had lower life cycle contributions than RAS in six of the seven LCA categories considered, including abiotic depletion (ABD - effectively all non-living inputs), GWP, Human toxicity potential (HTP), Marine Toxicity Potential (MTP), acidification (ACD), and cumulative energy demand (CED). In contrast, RAS was found to result in lower eutrophication potential (EUT) than ONP. Since energy use and resultant GHG production is the largest factor affecting the comparison, the issue is examined here in more detail for the BC context.

The LCA analysis found that feed is the most important component of GWP in conventional ONP culture, while energy use dominated the GWP of the RAS system. The dominance of energy use in the RAS was due to a high energy intensity coupled with a high modelled emission factor for electricity consumption due to the assumption of a 77% coal-derived source. The RAS was also modelled to use more feed than ONP. The net result was a significantly worse overall score for the RAS on GWP as well as other energy-related indices. It should be noted that new feed formulations that have lower content of fish and other animal products could have substantially better GWP scores than is currently the case. Though this has the potential to improve the performance of all methods of production, its effect would be greatest in systems with the largest inputs of feed.

Given that the BC power supply mix is clearly different from the Canadian average, it is instructive to consider what impact this would have on the analysis. In addition, the configuration and energy intensity of an indoor BC salmon grow-out is expected to be different from that of the RAS modelled by Ayer and Tyedmers (2009), and this paper attempts to account for this also.

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It is not clear what energy mix is most appropriate to assume for a RAS facility in BC, or for that matter, any new industrial power user. BC Hydro publishes average GHG intensity by calendar year and the most recently published value is 28 kg CO₂-e/MWh¹¹, an attractive value reflecting the dominance of hydro in the BC power mix. This value varies literally with the weather, with dry years resulting in higher values as greater quantities of fossil fuel generated electricity are needed. This number does not factor in electricity imports to BC, and would somewhat understate the real emissions associated with electricity usage in BC because much of the imported electricity tends to originate from fossil fuel sources. A higher GWP of 76 kgCO₂-e/MWh associated with electricity consumption in BC was modelled in Ayer and Tyedmers (2009). This value assumes an energy source of 90% hydro and 10% natural gas, which accounts for why it is higher than the BC Hydro index, which had a roughly 96% Hydro source. The modeled results presented below used the Ayer and Tyedmers emission factor for the low-emissions case. It should be recognized that this is an “indicative” value and in a given year, the actual value could be higher or lower depending on the weather, the regional power balance and other factors.

Without the “Site C” hydro expansion project, incremental power supply in BC may have higher fossil fuel content. Some analysts will argue that any new project should reflect the source mix of incremental supply, rather than the average supply mix, in which case the index could be as high as 600 kgCO₂-e/MWh, reflecting predominantly fossil fuel use, a factor of 21 times the BC Hydro average index¹². The realistic value would seem to be somewhere in the middle; however, since there is no clear guidance on setting such an intermediate value, we simply present results for both extremes.

Table 1 below shows how the GWP varies with both production configuration and the assumed emissions factor. Several RAS configurations and one net pen configuration are considered along with emissions factors of 76, 260 and 600 kgCO₂-e/MWh.

¹¹ GRI Index Report, BC Hydro 2009

¹² IPCC NGGIP 2011



Five different RAS configurations were examined to account for the considerable variation which exists in terms of system layout, energy requirements, and on-site fuel requirements. Some common assumptions were made for all of the RAS configurations. An infrastructure GWP of 161 kgCO₂-e/tonne fish produced was assumed for all RAS systems based on the findings of Ayer and Tyedmers (2009). The system modeled in that study had a high amount of construction materials relative to the production volume, so 161 kg CO₂-e/tonne is likely overstating the value for most RAS facilities, and can be regarded as a worst case. The GWP associated with alkalinity adjustment (chemical addition) assumed the use of sodium bicarbonate being shipped 2,000 km by transport truck, and assumed sodium bicarbonate requirements based on a water recirculation rate greater than 99% and alkalinity content in the makeup water of 120 mg/L CaCO₃. The GWP associated with alkalinity adjustment could vary considerably depending on the source of product and the amount of sodium bicarbonate required; however the values used are fairly typical and provide a reasonable representation. Ayer and Tyedmers (2009) pointed out that if the bi-product organic waste generated in a RAS facility is reused as fertilizer it will offset the need to produce fertilizer by other means, thereby resulting in a GWP credit. This assumption was made in all of the RAS facility cases, and therefore a modest 'avoided burdens' GWP credit was included.

A feed conversion ratio (FCR) of 1.05 kg feed per 1 kg fish produced was modeled for all RAS cases, and a FCR of 1.27 was modeled for ONP, both based on published values from DFO (2010). If real world FCRs achieved in commercial operations end up being higher/lower than predicted, the associated GWP would increase/decrease. These values are therefore an indication of a general case, and might differ from results achieved in various real world facilities. The GWP associated with the hatchery production of smolt and the transport of harvested fish to market are both left out of the analysis because they are assumed to be equivalent for ONP and RAS operations within a BC context.

Referring to Table 1 the configuration "RAS: DFO 2010" is based on the RAS analyzed in the DFO 2010 study. The configuration "RAS: Current FSB Technology" is based on a typical modern RAS using a fluidized sand bio-filter (FSB), and assumes propane is used for on-site heating. The configuration "RAS: Ayer & Tyedmers 2009 NS" is the RAS analyzed in Ayer and Tyedmers 2009, which took operating data from an existing arctic char grow-out facility located in Nova Scotia. The configurations "MHC-RAS: Propane Heating" and "MHC-RAS: No On-site Fuel" are based on the configuration developed in the course of the feasibility study described in Section 3. The configuration "Net-pen: Ayer & Tyedmers 2009" makes use of the data from Ayer and Tyedmers 2009, albeit with a slight revision in the emission factor associated with feed, which was used to keep the analysis consistent with the other configurations. A value of 1,710 kg CO₂-e/tonne feed produced was used in all cases, based on 2007 Canadian averages for salmon feed as reported in Pelletier et al. (2009).

It must be noted that both MHC-RAS cases and the DFO case are "speculative", that is, they are based on concept designs developed in the course of the feasibility studies and the projected improved performance has not been proven in practice. Also, the optimized energy case requires substantial incremental capital investment and results in a more mechanically complex system.

Of the RAS configurations, "RAS: Ayer & Tyedmers 2009 NS" had the highest GWP. This is due to the high electricity use of 22,600 kWh/tonne fish produced, a high feed conversion ratio of 1.45 kg feed per kg fish (typical RAS values reported by DFO 2010 are 1.05), and a large amount of on-site fuel use for

heating. The configurations “RAS: Current FSB Technology” and “MHC-RAS: Propane Heating” had a higher GWP than “RAS: DFO 2010” and “MHC-RAS: No On-site Fuels” due mostly to the GHG emissions associated with on-site fuel use for heating.

In Table 1 it can be seen that the GWP associated with RAS facilities is greatly dependent on the emissions factor of the available electricity source. By contrast, net-pens are assumed to not directly use any grid electricity, and therefore have a modeled GWP that is independent of local electricity source. When electricity with a low emission factor of 76kgCO₂-e/MWh is assumed, the DFO RAS and the MHC RAS were found to be only slightly higher than net-pens in terms of GWP, while the other RAS facilities were notably worse than net-pens. For emission factors above 76kgCO₂-e/MWh, all RAS configurations are have substantially higher GWP values than net-pen, due entirely to the added GWP associated with electricity generation.

Table 1: The effect of energy blend on the GWP of various aquaculture configurations

Sensitivity Analysis: The effect of energy blend on GWP (kg CO₂-e/1000kg product)			
Production Configuration	BC Blend from Ayer & Tydemers 2009 (76kgCO₂-e/MWh)	Aggregated Canadian Blend 2009 (260kgCO₂-e/MWh)	Marginal Fossil Fuel in BC (600 kgCO₂-e/MWh)
RAS: DFO 2010	2,420	2,950	3,940
RAS: Current FSB Technology	2,910	3,760	5,330
RAS: Ayer & Tyedmers 2009 NS	5,870	10,000	17,700
MHC-RAS: Propane Heating	2,770	3,270	4,200
MHC-RAS: No On-site Fuels	2,430	3,010	4,070
Net-pen: Ayer & Tyedmers 2009	2,410	2,410	2,410

Table 2 provides a comparative breakdown of the GWP contributions of ONP with the “best case” for RAS, namely the (projected but not demonstrated) energy-optimized MHC-RAS configuration with an assumed emission factor of 76kgCO₂-e/MWh. Under this scenario, RAS and ONP are roughly on par. As noted, this best case is speculative and has not been demonstrated in practice.

Net-pens experience lower GHG emissions in the categories of electricity, infrastructure, chemical addition and nitrification. These gains are partially offset by the on-site fuel use, as well as higher feed requirements due to a modelled FCR of 1.27, which is much higher than the FCR of 1.05 achievable in



RAS systems (DFO, 2010). It can be seen that feed is the largest contributor to GWP under these two scenarios, so the higher feed requirements predicted for net-pens make a significant impact on GWP.

Table 2: Breakdown of the sources of GWP in open net-pens and the MHC-RAS using an electricity emission factor of 76kgCO₂-e/MWh

Global Warming Potential ((kg CO ₂ -e/t fish produced)		
	MHC RAS – No Onsite Fuels	Net-Pens
Feed	1,796	2,172
Electricity	237	0
Infrastructure	161	55.8
On-Site Fuel	0	185
Chemical Addition	94	0
Nitrification	215	0
Avoided Burdens	-70.6	0
Total	2,432	2,413

In summary, RAS systems are generally predicted to have higher GWP than ONP systems. Under many sets of assumptions, RAS systems are dramatically worse than ONP in this regard. The factors that most affect the comparison are the GHG emission factor assumed for the particular source of electricity, the energy intensity of the RAS configuration in question and the efficiency of feed utilization. Under a set of optimistic assumptions as illustrated in Table 2, RAS GWP can be roughly on par with ONP; however, this assumes a hypothetical RAS configuration that has not been proven in practice, a low emissions factor associated with hydro power and an excellent FCR. Only a RAS demonstration project employing full scale equipment under realistic operating conditions with carefully measured energy and feed inputs and a defined energy blend will allow determination of how much greater will be the GWP of RAS compared to ONP.

5. CONCLUSIONS

Recirculating Aquaculture System (RAS) technology is probably the most promising of the various Closed System Aquaculture (CSA) methods currently considered for application to salmon grow-out in BC. It is used extensively in the production of salmon smolts in BC and is reasonably well understood. However, there are significant knowledge gaps and technical hurdles when it comes to applying the technology to high intensity grow-out. No variety of CSA has been successfully applied to high-volume commercial grow-out of a global commodity species like salmon. Basic bioplan parameters (thermal growth coefficients, maximum fish densities, effect of salinity, etc) are poorly understood for grow-out sizes. No “off the shelf” system designs are available and there is little industry consensus with regard to the optimum culture and treatment system configuration for grow-out. Even allowing for the potential of a price premium on land-produced product, the economics of RAS for grow-out is challenging, necessitating high intensity production, economies of scale, improvement of existing designs and the development of operational experience and skill to be able to reliably operate the technology close to its operating limits.

In short the technology is at the ‘demonstration’ stage of development where pilot scale work, experience with smolt production and feasibility studies indicate some potential for viability but where “real world” testing is required to improve the knowledge base and determine an accurate business case for investment in commercial scale RAS grow-out facilities. The paper “Global Assessment of Closed System Aquaculture”¹³ submitted to the Commission does not provide any evidence that CSA is ready for immediate commercial application to land-based grow-out of a commodity species like Atlantic salmon in BC; that evidence will need to come from the planned RAS salmon grow-out demonstration projects in BC.

There is scope for further improvements to RAS technology to reduce its energy demand. This is an important consideration in any life cycle assessment comparison between RAS and open systems. RAS systems are more energy intensive than open systems, however, they generally use feed more efficiently and the resultant impact on GHG production depends heavily on assumptions about the energy source mix. Under some assumptions, the GHG footprint of RAS is substantially worse than for open systems; however, with energy optimization of RAS systems, additional investment in energy integration within RAS systems and an electricity supply with a large hydro component, the GHG footprints of RAS and open systems could theoretically be similar.

Two demonstration RAS salmon grow-out projects are planned for BC for 2011-2012, one by a BCSFA member. It is understood that both of these projects will be conducted under the guidance and scrutiny of a broadly-constituted Project Review Board (PRB) that will help ensure that the trials are properly designed and accurately assessed. These trials are the logical next step in developing and assessing RAS technology for salmon grow-out and will be hugely important in both advancing the technology

¹³ EcoPlan International, Inc., 2008



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readiness of closed system aquaculture and in resolving many questions in the debate between closed system and open system aquaculture.

6. CLOSURE

We trust that this report satisfies your current requirements and provides suitable documentation for your records. If you have any questions or require further details, please contact the undersigned at any time.

Report Prepared by

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