Fish Farming in Land-Based Closed-Containment Systems

Steven Summerfelt and Laura Christianson

The Aquaculture Innovation Workshop #5 – An International Summit on Fish Farming in Land-Based Closed-Containment Systems was hosted by The Conservation Fund Freshwater Institute, Tides Canada (TC), the Gordon and Betty Moore Foundation (GBMF) and the Atlantic Salmon Federation (ASF) at the National Conservation Training Center (NCTC) in Shepherdstown, WV, 4-6 September 2013. This international summit provided an opportunity for aquaculture producers, scientists, engineers, aquaculture industry suppliers, regulators and investors to communicate progress on the technical, biological and economic feasibility of culturing fish – particularly salmon – to food-size in land-based closed-containment systems.

Over 130 participants from industry (the largest contingent), academia, non-government organizations (NGOs), and government attended to share scientific results and commercial experiences, identify opportunities to advance the use of technology and address industry myths. High interest in this timely and relevant topic meant attendees traveled from far corners of the globe, with speakers representing Norway, Denmark, Australia, Canada, Chile, Israel, the Netherlands, Germany and additional attendees traveling from Ireland, Poland, Switzerland, South Africa, Sweden, and throughout North America. The Summit included land-based aquaculture producers, representatives from large international salmon farming companies, engineers from the design industry and representatives of groups intending to build closed-containment systems to farm food-size salmon.

As a collective group, the Summit attendees are pioneering the technologies necessary to increase finfish aquaculture production in a manner that is more environmentally sustainable and economically viable. A major outcome was that emerging aquaculture technologies were highlighted for attending senior-level decision makers in government, industry, the financial community and philanthropy. Across the diverse participants, this catalytic meeting brought together a community of stakeholders and created a focused communication space critical for increasing the adoption of land-based closed-containment systems using water recirculating aquaculture system (RAS) technologies.

The two-day Summit consisted of invited sessions discussing innovations and challenges surrounding food-fish production, particularly salmon, in land-based closed-containment systems. Session topics included:

- salmon health and performance in land-based closed-containment systems (4 presentations)
- eliminating off-flavor from fish produced in closed-containment systems (2 presentations)
- denitrification and microbiology (4 presentations)
- assessment of alternate production systems for salmon farming (3 presentations)
- closed containment project updates (6 presentations)
- lessons learned while engineering and building commercial RAS (3 presentations)
- creating value from the waste stream (2 presentations)
- design innovations and opportunities in land-based closed-containment systems (3 presentations, plus panel).

There was also a presentation on research advances towards more sustainable alternative Atlantic salmon feed by William Wolters from the U.S. Department of Agriculture Agricultural Research Service (USDA ARS) and an update on the Department's aquaculture research strategies and priorities by Jeffrey Silverstein (USDA ARS), the Department's National Program Leader in Aquaculture.

Salmon Health and Performance in Closed-Containment

A presentation by Bendik Fyhn Terjesen of Nofima, Norway opened this session with the new findings about the effects of water salinity and exercise on post-smolt Atlantic salmon in land-based closed-containment systems. Fish performance indicators can be significantly improved when Atlantic salmon smolt are cultured to 1 kg at salinities of 12 ppt when compared to full-strength seawater. This presentation was followed by a discussion from Jeff Richards (University of British Columbia, Canada) about the University of British Columbia's InSEAS Research program to determine optimal salmon rearing conditions in RAS. InSEAS new, replicate state-of-the-art water recirculating systems can be operated in a nearly closed-manner at various temperatures and salinities. Coho salmon and Atlantic salmon post-smolt performance studies are imminent, with temperature and salinity two of the initial variables to be studied at this new facility.

The final two talks in this session were from Christopher Good and Steven Summerfelt, both from The Conservation Fund Freshwater Institute (TCFFI, USA). Dr. Good discussed the effects of water exchange rate and water treatment processes on hormones (cortisol, testosterone (T), 11-ketotestosterone (11-KT), progesterone, and estradiol) in RAS containing sexually maturing Atlantic salmon. Findings of this USDA ARS-funded research suggest that, under the conditions of this study, the quantified hormones (except for T) do not accumulate in lower exchange water recirculating systems, and that, aside from 11-KT, the system's unit processes do not impact hormone concentration.

Dr. Summerfelt closed the session with a synopsis of TCFFI's several Atlantic salmon grow-out trials in land-based, freshwater, closed-containment systems. Last year, 23 mt of food-size Atlantic salmon were produced at the Freshwater Institute; this was an extremely large-scale research undertaking, albeit a tiny fraction of commercial production goals at sites like the 'Namgis First Nation's salmon farm (Canada) or Langsand Laks (Denmark). In TCFFI's most recent growout trial, Atlantic salmon were reared under near ideal water quality conditions to a mean harvest size of 4.3 kg by 22 months post-hatch and a mean harvest size of 5.6 kg by 27 months post-hatch. Feed conversion during the production trial averaged 1.07 and, importantly, no major negative fish health events occurred (no viruses, sea lice, or kudoa parasites) despite zero employment of vaccines, formalin, antibiotics, or pesticides. Overall mortality accounted for about 7% of the population during the grow-out production phase, which included fish culled due to fungus. These studies suggest it is technically and biologically feasible to raise Atlantic salmon to food-size in closed-containment systems, even in freshwater at locations remote from the ocean.

Eliminating Off-Flavor from Fish Produced in Closed-Containment Systems

Two presentations described technologies and practices to eliminate earthy/musty off-flavors sometimes encountered in RAS-produced fish. Niels Jorgensen (University of Copenhagen, Denmark) presented procedures for reduction of off-flavors caused by MIB and geosmin in rainbow trout from RAS in Denmark. John Davidson (TCFFI, USA) reported on three studies examining depuration procedures to mitigate off-flavor from harvest-size Atlantic salmon. The depuration process for these fish was optimized by using standard operating procedures that provided clean and relatively biofilm-free systems during a 7 to 14-d depuration period. Biofilter media should not be used within depuration systems due to off-flavor bacteria and compounds present in associated biofilms. In addition, pre-disinfection of depuration systems using 250 mg/L H_2O_2 appears to enhance off-flavor removal.

Denitrification and Microbiology in Closed-Containment Systems

Four presentations focused on the water quality issues of denitrification and microbiology within land-based closed-containment systems. Lars-Flemming Pedersen (DTU Aqua, Denmark) opened the session with a discussion of microbial interactions (particularly nitrifying bacteria) with RAS water quality. The session then shifted towards denitrification with Keiko Saito (University of Maryland, USA) describing anaerobic waste treatment to remove nitrate and biosolids within zero-flushing land-based closed-containment systems for marine warm-water species. Likewise, Jaap van Rijn (Hebrew University of Jerusalem, Israel) described the importance of an anaerobic treatment stage for removing nitrate, phosphate, and off-flavor compounds. Both scientists described actual facilities that use innovative technologies to operate with practically no water flushing or waste discharge. Although they presented different technologies, both scientists described processes used to digest and hydrolyze biosolids (i.e., manure, waste feed, sloughed biofilm) within the RAS to generate organic acids that serve as a carbon source to fuel heterotrophic denitrification. These technologies mitigate nitrate accumulation without flushing the system with new makeup water.

Dr. Saito also described how the University of Maryland process could be used to produce hydrogen sulfide to drive chemo-autotrophic denitrification. Volumetrically the anaerobic digestion basin described by Jaap van Rijn might equal approximately 20 percent of the total RAS volume and, in addition to nitrate removal, phosphate is deposited within this basin largely as hydroxyapatite [$Ca_5(PO_4)_3(OH)$]. Moreover, geosmin and MIB are strongly bound to the anaerobic sludge in the basin and the sludge's internal biological activity removes these off-flavor compounds. In the final denitrification talk, Laura Christianson (TCFFI, USA) described nitrate removal using relatively low-cost and simple woodchip bioreactors. Such bioreactors have been used to treat agricultural tile drainage but are now being trialed for treatment of RAS discharge in TCFFI research funded by the USDA ARS and Tides Canada. The woodchips provide a surface area for the growth of heterotrophic bacteria that utilize the wood's carbon to fuel denitrification.

Assessment of Alternate Production Systems for Salmon Farming

Brian Vinci (TCFFI, USA) and Trond Rosten (SINTEF, Norway) co-presented a comparative economic and environmental analysis of land-based versus net-pen salmon production for a 3,300 mt/y Atlantic salmon model production facility. This volume is approximately 1 percent of the Atlantic salmon consumed in the U.S. annually. The land-based system was based on grow-out trials conducted at TCFFI, whereas the net-pen model was based on conservative estimates using data sets from Norway and an investment plan for establishment of a 3,300 mt/y production (head-on gutted; HOG) open pen facility (small-scale open-pen farm). Findings indicated the cost of production was approximately equal for land-based and net-pen production at US$ 4/kg of head-on gutted product. Fixed capital investments associated with building facilities were greater for the land-based system, but the required site license costs in Norway brought the overall costs of the two options more in line. The 10-year net present value analysis showed that rates of return were approximately equal (15 percent) under likely scenarios where land-based produced salmon achieved a price premium. A life cycle assessment indicated that land-based production would have a larger carbon footprint than net-pen production if the former were sited to use electricity provided by a typical US mix of fossil fuels. However, if fossil fuels are replaced with hydropower, the carbon footprints of the two production options were approximately equal. Net-pen salmon production in Scandinavia followed by airfreight export to the US had a slightly larger carbon footprint than land-based salmon production in the US using fossil fuels. The environmental value of escapee prevention, fish pathogen exclusion, and disease minimization was not quantified, but could potentially benefit a land-based system. It is likely that a variety of technologies, including hybrids of the options compared here, will be used in the future.

Following this comparative analysis, Andrew King (University of Tasmania, Australia and University of St. Andrews, Scotland) presented an evaluation of production expansion options for the Tasmanian salmon industry. The use of land-based closed-containment systems for at least a portion of the Tasmanian production period could reduce production costs and risks associated with existing production methods.

Svein Martinsen (Nekton AS / Smola Hatchery and Smolt Farm, Norway) closed the session with an assessment of floating closed-containment Atlantic salmon farming systems. His company

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LEFT, FIGURE 1. *Hoop building installation in April 2013 at the 100 mt land-based steelhead model aquafarm at Taste of BC in Nanaimo, British Columbia (Photo: Steven Summerfelt/The Conservation Fund).* RIGHT, FIGURE 2. *The 'Namgis First Nation's "Kuterra" land-based salmon farm uses five 500-m3 dual-drain culture grow-out tanks connecting to a central water treatment system (Photo: J.R. Rardon).*

is investing in a floating bag technology to rear Atlantic salmon smolt from 100 g to 1 kg. This technology aims to draw water to pass through the bag from far below the water surface to minimize sea lice infestations and provide a healthy and large post-smolt to be stocked into net pens.

Updates on Land-Based Closed-Containment Projects

There were six presentations about existing land-based closed-containment salmon and steelhead production facilities and one presentation detailing a yellowtail kingfish facility (the latter by Andries Kamstra, Imares Institute, Holland). Steven Summerfelt opened with an update to briefly summarize the status of over a dozen land-based closed-containment salmon grow-out farms around the world. Jim Terry (SweetSpring Salmon, USA) described the production of Coho salmon at Aquaseed's SweetSpring Salmon in Rochester, Washington (production capacity >100 mt/y), and Steve Atkinson (Taste of BC, Canada) presented on his Land Based Steelhead Model Aquafarm (Fig. 1) in Nanaimo, British Columbia (production capacity >100 mt/y). Both freshwater facilities were designed and supplied by PRAqua/In-Situ (Nanaimo, British Columbia, Canada) and are similar (except at a smaller scale) to the system operated by the 'Namgis First Nation, described below. SweetSpring Coho salmon are already being marketed, and Taste of BC steelhead will begin to reach the market in spring 2014.

Chief Bill Cranmer of the 'Namgis First Nation, Eric Hobson, and Jackie Hildering (all part of K'udas Limited Partnership, Canada) teamed to share with the Summit about the 'Namgis First Nation's "Kuterra" Land-Based Salmon Farm (Fig. 2), which is fully owned by the 'Namgis First Nation (Vancouver Island, near Port McNeil, BC). The first phase of this farm is now operational and is expected to produce over 450 mt/y of Atlantic salmon with initial sales expected in spring 2014. Project support from two charitable foundations has helped advance the notion that "land-based, closed-containment" is an economically profitable method of raising Atlantic salmon in a way that does not negatively impact the environment. "Save Our Salmon" is the initiator of the Project, and Tides Canada is the lead funder and a Project advisor. The project was designed by PRAqua/In-Situ and uses five 500-m^3 dual-drain culture tanks tied into a single grow-out module water treatment system. The facility also contains a separate depuration system (operated as a partial water reuse system) and an isolated quarantine system used to culture new batches of smolt for approximately four months. The water recirculating systems use low-head oxygenation units at each culture tank and a centralized water treatment area that incorporates microscreen drum filters, a forced-ventilated cascade aeration column, and fluidized-sand biofilters. The centralized water treatment area is able to effectively reduce the elevation of the equipment while pumping the recirculating water in two directions (i.e., to the LHO/culture tanks and the biofilter/aeration column).The facility also uses a central feeding system and a central fish pump, grading, and counting station to simplify fish handling. Site infrastructure has been installed to allow for expansion to 2,500 mt/y, once the economics of the first phase have been demonstrated. Fixed capital for this facility was $8.5 million. Production costs have been estimated at $4.77/kg of gutted fish. All salmon will be marketed in partnership with Albion Fisheries Ltd (Vancouver, Canada) under the brand name "Kuterra."

Bjarne Hald Olsen (Billund Aquaculture Service AP, Denmark) presented an update on Atlantic Sapphire – Langsand Laks (Fig. 3) and also discussed RAS design innovations and opportunities for new technologies. Langsand Laks, built at a former fish farm in Hvid Sand, Denmark, was one of over 114 RAS worldwide installed by Billund. Depending on site conditions, Mr. Olsen reported a 1000 mt/y salmon grow-out module could be installed for less than approximately $10 million in fixed capital investment. The Langsand Laks growout building is 3300 m^2 (120 m × 275 m; not including hatchery and smolt production), and eyed eggs are purchased from Iceland approximately four times per year. These fish are raised to post-smolt (>200 g) to stock into the grow-out system that contains 6100 m^3 of tank volume at 7-15 ppt salinity. All culture tanks have been installed in one large system. The central water treatment area uses microscreen drum filters followed by submerged fixed-bed, moving-bed and trickling biofilters, with an apparent capacity to treat waste from 3000 kg feed daily. Following these processes, water is pumped to a head tank where it gravity flows through oxygenation columns before returning to each culture tank. The single center-drain culture tanks are made from pre-cast panels with a high-quality, smooth concrete finish. Each tank is flushed approximately every 45 minutes with recirculating water. They stock post-smolts into the grow-out system, first into 8.5 m diameter tanks, then 10.2 m diameter tanks, and finally 14.2 m diameter grow-out tanks for a total of about 10 months until harvest. Several purge tanks are plumbed to operate either on flow-through or water from the grow-out recirculation system. Densities are allowed to reach 85-100 kg/m^3, depending upon life stage in the growout facility. Fish are removed from these large and deep (6 m) culture tanks using a purse seine to pull fish to the pump intake followed by portable hoses and a large vacuum pump. Fish are pumped to a dewatering box (water flows back to the RAS) and onto a hand-sorting table before they enter the next tank. Harvested fish will be hauled live to the processor when harvest begins at the end of 2013 or early 2014. The total grow-out period is expected to be less than 24 months (from egg hatch) to harvest a 4 to 5 kg salmon.

German Merino (Universidad Catolica del Norte, Chile) presented trends for Atlantic salmon production in land-based systems in Chile. He provided a detailed review of the rapid expansion in the use of RAS to produce Atlantic salmon smolts and even broodfish. Continued refinement in technologies has improved system performance and reduced overall electrical operating costs in later-generation RAS.

These first projects, particularly the ‘Namgis First Nation’s salmon farm and the Taste of BC steelhead farm, will begin to identify the fish production costs, market potential, and overall economics of salmon produced to food-size in land-based closed-containment systems. Quantifying and communicating the economic viability of raising salmon in closed-containment facilities is critical to the success of this industry. For these reasons, these two farms aim to be completely transparent and all the information collected during the first three production cycles will be available to all interested parties.

Lessons Learned While Engineering and Building Commercial RAS

Ivar Warrer-Hansen (Inter Aqua Advance A/S, Denmark) opened the session with an interesting case-study on challenges in construction and operation at extremely remote RAS locations, such as Finmark, Norway. Gary Robinson (GRV Inc., Canada) discussed a comprehensive retrospective assessment of construction costs for the first 400 mt/y Atlantic salmon grow-out module at the ‘Namgis First Nations. Mr. Robinson identified several areas where savings could be made in concrete construction and where economies-of-scale were realized in unit processes, such as tanks, pumps, and filters. He also itemized areas where improvements would realize savings when the ‘Namgis build their second of five planned grow-out modules (total 2500 mt commercial scale).

Creating Value from the Waste Stream

Summit attendees had great interest in reuse benefits associated with waste streams from land-based closed-containment fish farms. Norman McCowan (Bell Aquaculture, USA) discussed his success in this arena due to Bell Aquaculture’s innovative and revenue-creating conversion of fish processing offal and thickened fish manure (Fig. 4) into marketable organic fertilizers and soil amendments. Aquaponics was another hot topic with Thomas Losordo and Huy Tran (Pentair Aquatics, USA) providing an interesting case study about Urban Organics, an aquaponics facility in Minneapolis, Minnesota.

RAS Design Innovations and Opportunities in Land-Based Closed-Containment Systems

Marius Haegh (Krugerkaldnes/Veolia, Norway), Thomas Losordo (Pentair Aquatics, USA), and Bjarne Hald Olsen set-

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LEFT, FIGURE 3. *Submerged filters (left), moving bed biofilters (middle) and trickling filters (right) in the central water treatment area at Langsand Laks, Denmark (Photo: Steven Summerfelt/The Conservation Fund).* RIGHT, FIGURE 4. *Bell Aquaculture LLC (Albany, Indiana, USA) uses four gravity thickening settling units (each 4 m dia x 5.5 m deep) to capture and dewater biosolids in their RAS facility discharge before this flow is further treated in a created wetland (Photo copyright © 2014 Bell Aquaculture LLC™ — All Rights Reserved).*

the-stage for the panel discussion with presentations on RAS design innovations and opportunities for new technologies. They were then joined by Eric Hobson, KC Hosler (PRAqua/In-Situ), Nick Pranger (Aquaculture Enterprises), Ivar Warrer-Hansen, and Andrew Wright (technical advisor for Tides Canada) for a panel discussion moderated by Steven Summerfelt. Major points included:

- Panelists largely agreed that existing land-based closed-containment technology is adequate to produce food-size salmon. However, improvements are still required to reduce the fixed capital and electrical costs for these systems.
- The most important factor for expansion of a new technology in an existing industry (e.g., salmon farming to food size) is the economics of the technology. Because businesses operate with the single primary goal of profit, they will embrace new technologies that contribute to maximizing profit.
- Broader implementation and improvement of denitrification technologies will help reduce water flushing requirements, practically eliminate waste discharge, reduce heating costs, and allow these facilities to be more easily sited. In addition to the denitrification technologies described above, membrane biological reactors have tremendous promise and are becoming more cost-effective given their wide adoption in other industries.
- Although oxygenation and carbon dioxide stripping technologies have improved, further improvements would help reduce energy costs and potentially provide for a healthier fish environment. For example, achieving low carbon dioxide limits in the culture tank, such as 12 mg/L, clearly begins to increase energy costs geometrically. A better understanding of the water quality limits for different life-stages of Atlantic salmon (and other fish) is required.
- Improved technologies to dewater biosolids need to be adopted. Dewatering to filter cake consistency allows biosolids to be more readily converted into a marketable product, especially when they are generated in brackish or seawater systems.
- Nutrients must be reclaimed and not wasted. Developing markets for new products, such as organic-listed liquid fertilizers, composts, and other horticulture products, will be important to help improve the environmental sustainability and revenue potential of these fish farms.
- Selling salmon from land-based closed-containment systems into niche, premium markets is an early strategy to maximize revenue, but increased production will eventually place the salmon into the general farmed salmon market.

Panelists also remarked on the importance of training opportunities for personnel operating and managing large, land-based, closed-containment facilities. The rapid growth in land-based closed-containment facilities for Atlantic salmon smolt production has created a notable labor shortage. Chile has now shifted more than half of Atlantic salmon smolt production to land-based closed-containment systems. Expectations from Norway suggest that Atlantic salmon smolt production is moving away from flow-through systems and that over half of all of the smolt produced could come from land-based closed-containment systems in over a decade. Similar growth in RAS production facilities is occurring elsewhere, but not at the magnitude seen in Norway and Chile. This existing industry could be a good source of talent, at least to fill certain key positions, but more formal training programs must be implemented

Conclusions

The presentations highlighted how land-based closed-containment systems can increase farmed fish production in systems that practically eliminate water pollution, minimize water use, improve freshness and safety, reduce business risk, and are economically competitive with other established fish production technologies. In addition, land-based closed-containment systems use water recirculation technologies that can meet point-source effluent discharge regulations and reclaim the nutrients that would normally be wasted. The ability to site these facilities in many locations means they can provide a fresh product, reduce shipping costs, and capitalize on cheap electricity when such locations are available.

At the conclusion of the Summit, Eric Patel, a Tides Canada advisor, provided a wrap-up that summarized the tremendous progress since the First Aquaculture Innovation Workshop (NCTC, January 17-18, 2011) and key advances that are required. The First AIW included only 33 participants from just the US and Canada, whereas this Fifth AIW had four times as many attendees representing six times as many countries. At the First AIW, workshop organizers knew of no commercial land-based closed-containment systems growing salmon to food-size, although there were several projects about to begin. In contrast, there are now at least nine land-based closed-containment farms stocked with salmon to be raised to food-size. Excitingly, total production will approach 5000 mt annually when these facilities have reached their full production levels, and there is talk (often covered by the trade press) of potentially 10,000 mt of additional production.

It is clear that confidence in these technologies is rising rapidly and that investor interest has been stimulated, but that many are waiting to see industry success before moving. Private investment in land-based closed-containment fish farms is growing, and projects now range from $1.5 to $30 million in terms of capital investment. There are several more projects like the 'Namgis First Nation's Salmon Farm in the pipeline in North America and many more around the world to produce salmon to food-size. Each of these projects will produce an economic stimulus and jobs in rural communities during facility construction, throughout the supply chain, and during fish production. These innovations will allow fish farm expansion in North America, Europe, and around the world to increase farmed fish production with minimal environmental degradation.

The next Aquaculture Innovation Workshop will be held in Vancouver, British Columbia, October 27-28, 2014.

Notes

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The program, participant list and most presentations are available for download at: tidescanada.org/salmon/aquaculture-innovation-workshops-and-reports/