Open Ocean Aquaculture

Bulletin of the Aquaculture Association of Canada
111-2 (2013)

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de l'Association aquacole du Canada

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Cover photo courtesy of Ocean Farms Technologies Inc., Searsport, Maine

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Open Ocean Aquaculture

Tim Jackson and Susan Waddy, editors

Tim Jackson

Introduction

As one workshop participant put it, "Offshore aquaculture is like the Olympics, every 4 years someone organises a workshop to talk about it!" This trend was remedied between 2005 and 2007 with a series of 3 workshops organized by a group of Canadian and American government, academic and industry representatives interested in moving the open ocean aquaculture yardsticks a little further towards commercial reality. At that time, with the University of New Hampshire's Open Ocean Aquaculture Program, progress by a number of U.S. cage technology developers and the policy development work toward the presentation of 2007's National Offshore Aquaculture Act to the U.S. Congress, it felt like the eve of the commercialization of open ocean aquaculture in American coastal waters. In Canada, the Atlantic Canada Fish Farmers Association (ACFFA; then the New Brunswick Salmon Growers Association) was early in a 5-year study to assess the economic and technical feasibility of moving salmon aquaculture into a higher energy environment. A number of new Canadian companies were starting the development of net pen and supporting technologies which were generating interest. Working together, it was felt that Canada would bring to the table its extensive practical marine finfish farming experience and the U.S. would bring its significant aquaculture engineering and offshore technology development expertise into a complementary critical mass—to say nothing of the increasing number of emerging firms on both sides of the boarder. Thus the three workshops, a small one in St. John's, NL, a 65 participant-strong workshop in Durham, NH and the last with 100+ participants in St. Andrews, NB.

A diverse agenda of presenters would include the high-level economic case for offshore aquaculture, how U.S. offshore aquaculture policy was developed, the lessons to be learned from the regulatory compliance experience in existing deep or exposed marine finfish aquaculture sites, and an inclusive lineup of possible technologies and technological considerations for open ocean aquaculture.

The wrap-up of the St. Andrews workshop involved a series of breakout groups agreeing on high priority recommendations under the themes of Technology, Policy and Economics, and Environment. Those recommendations were:

> **Technology**—to validate feasibility of open ocean rearing technology at a commercial or near-commercial scale through a model or pilot farm initiative. Participants agreed that this was needed to generate confidence in the insurance and financial/investment communities. It would also serve to establish environmental performance and develop appropriate monitoring regimes.

Policy and Economics—to assess two approaches for developing a policy/strategy for open ocean aquaculture: proactive planning or reactive incrementalism. These approaches might be tested through the pursuit of a demo/pilot farm project.

Environment—to pursue development of an eco-regional (i.e. North Atlantic or Atlantic – U.S. Eastern Seaboard) monitoring and modelling program to inform the development of environmental quality standards and metrics for open ocean aquaculture. Participants agreed that ground truthing for such a program could be based on the extensive environmental monitoring data already collected for a variety of aquaculture sites in high or approaching high energy environments.

Although none of these projects proceeded exactly as envisioned and an offshore aquaculture policy remains unresolved in the U.S., there has been progress. Canadian and U.S. companies such as AEG Innovative Solutions (AEG), Open Ocean Systems, and Ocean Farm Technologies have made progress in the demonstration of their containment technologies. The ACFFA concluded its study and is finalizing their data analysis. There has also been very recent popular and trade media coverage speculating once again about the opportunity presented by offshore aquaculture. However, no specific offshore aquaculture workshop has convened since 2007. Has the "Olympic" cycle come back around again?

This publication of the Aquaculture Association of Canada contains papers based on presentations from the 2007 St. Andrews *Canada-U.S. Sustainable Open Ocean Aquaculture Workshop* as well as reports on the aforementioned study by the ACFFA and testing on the net pen system designed by AEG for high energy aquaculture sites. I thank all of the authors for their contributions to this issue.

Acknowledgements: The workshops that were held would not have been possible without the significant support of the Canadian Consulate in Boston (in particular, Jacques Ruel and Sarah Nobel). The St. Andrews workshop also received significant support from the Aquaculture Association of Canada, Fisheries and Oceans Canada, the Province of New Brunswick, and the U.S. National Oceanic and Atmospheric Administration.

Tim Jackson

2005-2007 Workshops Co-Chair (with Dr. Rich Langan, University of New Hampshire)

Past-President, Aquaculture Association of Canada

Industrial Technology Advisor, National Research Council Industrial Research Assistance Program

Economics of Offshore Aquaculture in the United States

John Forster

The economics of offshore aquaculture will be determined by factors that have little to do with whether aquaculture is offshore, nearshore or onshore. While supply and demand trends look positive, lack of future supply will leave a gap in the market that will be filled with alternatives, most likely nutritional supplements. The aquaculture part of the seafood value chain comprises only 25% of total sales, most of which relates to feed, juveniles, and other costs that have little to do with where aquaculture takes place. The future success of offshore aquaculture depends on developing economic solutions to specific questions of capital cost and operating logistics. History suggests that where the opportunity is big enough, as it clearly is for seafood, the necessary solutions will be found. In turn, this suggests that the United States should develop its public policy accordingly.

Since very little seafood is presently produced by offshore aquaculture in the United States, discussion about its economics must, necessarily, focus on the future. This will be governed by what happens in global seafood markets as regards supply, demand, competition and costs.

Future seafood supplies will come from two sources—capture fisheries and aquaculture. Landings from the world's capture fisheries are static and no increase is expected (Figure 1).

Figure 1
World Fisheries and Population Trends
Source: NOAA Fisheries, J Cho, personal communication.

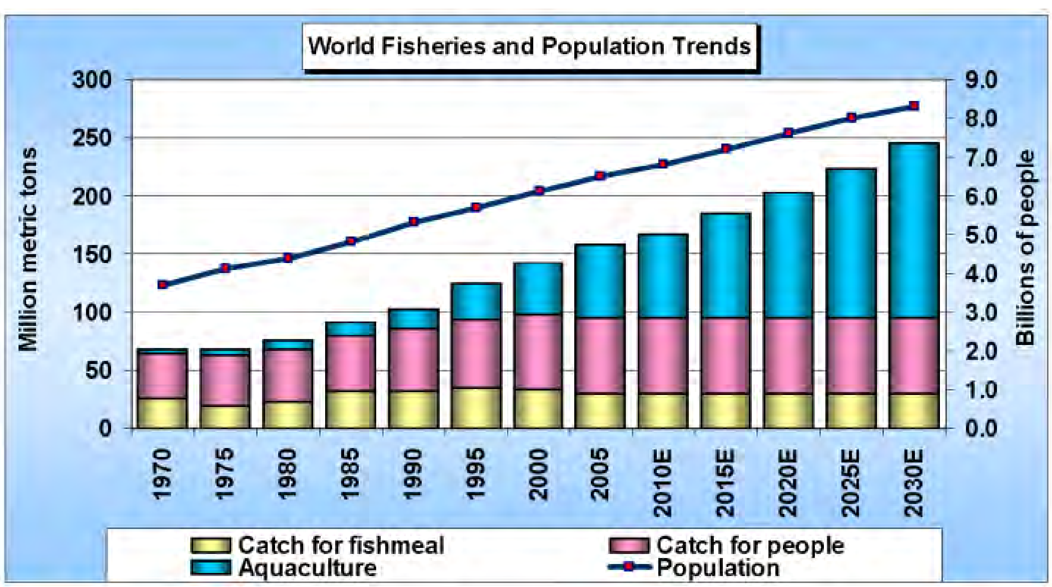

Table 1. Increases in global aquaculture production by weight and by percentage. Source: NOAA Aquaculture, J. Cho, personal communication.

Year	Total Production metric tons ('000's)	Increase in Production metric tons ('000's)	Rate of Increase %
1980	7.3	2.1	6.4
1985	11.4	4.1	8.7
1990	16.8	5.4	10.1
1995	31.2	14.4	11.2
2000	45.7	14.5	9.2
2005	63.0	17.3	6.8

Production from aquaculture is increasing and in percentage terms this has been the fastest growing sector of world agriculture in recent years (Table 1).

The projections for future global aquaculture production (Figure 1) assume a flat rate of production increase of about 3.5 million metric tons per year, which is what was achieved between 2000 and 2005. However, to assume that this rate of increase can be sustained may be over-optimistic. It is equivalent, for example, to creating 2.3 new global salmon farming industries every year for the next 25 years. While there is no denying the achievements of the past, it is suggested that most of the easy development options for aquaculture have now been taken, and from here on expansion will be more difficult.

If this is right, it will have profound impacts on the seafood industry and on the potential for offshore aquaculture, since other trends in the global economy point toward continued expansion of seafood demand. The number of people and their relative affluence is increasing in many countries, and history shows that increasing affluence leads to increased consumption of animal protein; especially seafood protein in some Asian countries. At the same time, ageing populations in western countries are inclined to eat more seafood and less red meat, encouraged by a continuing stream of information that supports the health benefits of seafood consumption. It seems probable that the world is headed into a period of significant seafood under supply.

Generally, this must be good news for all aquaculture, including offshore aquaculture, since it will lead to higher prices. In the United States this trend will be further accentuated by the decreasing value of the U.S. dollar and the increasing costs that exporters of seafood to the U.S. have to incur in shipping, especially for the air freight of fresh products.

However, such optimism should be tempered with the caution that seafood shortages will also leave a market gap, as people find themselves no longer able or willing to pay higher prices for the seafoods of their choice, while still wishing to avail themselves of the nutritional benefits of marine oils. Market gaps are always filled and in this case two outcomes seem probable.

First, seafood buyers and distributors will revise their attitude to frozen seafood, since this offers numerous opportunities for cost savings throughout the value chain. In turn, this will make it less expensive for producers overseas to ship products to the U.S. thus continuing to expose domestic producers to global competition.

Second, demand for fish oil pills and omega-3 fatty acid fortified foods will increase. The reality is that there is not enough and likely never will be enough seafood available to meet future global demand. Moreover, much of what is available is not rich in marine oils and sooner or later consumers will realize this. 'Two servings of seafood per week' provides vague and even misleading nutritional advice, if its purpose is to encourage people to consume adequate levels of these valuable nutrients. Eventually, this will become clear and governments will then be under pressure to make sure that their citizens have access to the nutrients they need. The only feasible solution is supplements and, as they become generally accepted, they will provide a new and formidable competitor for global seafood suppliers.

A future offshore aquaculture industry in the U.S. will therefore have to be vigilant about keeping costs down so that it can provide consumers with seafood products that remain affordable. In this respect, such an industry has two advantages that may prove to be significant.

First, it may be possible to locate offshore farms reasonably close to the markets they serve. As offshore farming technology develops, this may also allow for concentration of activity within a defined area that will make it possible to operate efficiently. It is possible to envisage, for example, a future offshore fish farming company with, perhaps, 20,000 metric tons of production spread among several farms within a 100 square mile area and located within relatively easy reach of its markets. At this level of production such a company would also be able to justify investment in onshore feed manufacture and fish processing, so that its operations and sales activities would be both integrated and streamlined. Cost savings that result from such efficiency might be more than enough to compensate for higher costs in other areas such as the cost of labor, especially as regards the supply of fresh products, which, despite probable future repositioning of frozen seafood, are likely to continue to command a premium.

Second, there is a plausible case to be made that because of better water quality offshore fish performance will be better. Since feed is the largest cost in most finfish farming and looks set to become even larger as prices of feed commodities rise, even a small improvement in performance is significant. Also, since the U.S. is a primary producer of the ingredients used in fish feed, there are likely long-term advantages to U.S. growers of being able to source raw materials domestically.

So, these are reasons to be optimistic about the prospects for offshore aquaculture in the U.S. However, it must still maintain a focus on keeping costs down in order to create value. A factor that is often overlooked in this respect is the fillet yield (the proportion of whole body weight that is edible fillet meat) of species that are selected for aquaculture. U.S. consumers increasingly demand that seafood products offer convenience. For finfish this means offering skin-off, pin bone out fillets and, therefore, a fish like salmon that yields up to 60% of whole weight as fillet has a substantial production cost advantage over a species such as cod, for example, that yields less that 40%.

Also, since costs magnify as seafood products move through the value chain because markups are usually calculated as a percentage of cost, a product that enters the chain at a high price will attract correspondingly higher costs as it moves through it. When it is still possible to buy fresh chicken breast meat at $1.99/lb, fresh fish at $12.99/lb[(1)] looks awfully expensive, especially if, in future, equivalent nutritional value can be obtained by taking a fish oil pill with the chicken or feeding chickens so that the meat contains omega-3 fatty acids.

[1] This was Costco's Pacific NW price for fresh halibut in 2007.

These and other variables including the relative strength of the U.S. dollar, environmental and trade regulations, possible future carbon taxes and the purchasing power of people in developing economies will all interact to determine the viability and success of U.S. offshore aquaculture. Primary producers can do little to manage these forces other than to try and ensure that their products are cost competitive throughout the value chain.

Governments, on the other hand, must plan for the future and allocate resources accordingly. In the context of U.S. offshore aquaculture, this means making space available in the U.S. EEZ (Exclusive Economic Zone) for aquaculture to develop. Since this is contentious, allocation decisions must be supported by rigorous justification of the costs and benefits and, given the wide range of variables involved, this is difficult. A suggested approach is to create a 'System Dynamic Model' that would include sub-components that model each of the variables involved and which then interact with each to show the consequences of government actions or changes in assumptions. This would provide a more informed and perhaps less contentious basis for government decision making than is presently available.

The U.S. imports 80% of its seafood. In this respect it is as dependent on foreign seafood as it is on foreign oil. As the global economy evolves, it is possible to envisage a situation where Americans will no longer be able to afford to import the seafood they want and will depend for their seafood supply on domestic onshore and offshore aquaculture. Presently, this is a possibility that cannot be substantiated by anything other than informed speculation. A model that could be used to support or refute such speculation could be a powerful tool in arguing the case that the U.S. offshore aquaculture industry must be given the space it needs in the nation's waters if it is to deliver on its promise.

Author

John Forster (e-mail jforster@olypen.com), Forster Consulting Inc., Port Angeles, Washington, is an aquaculture consultant with a special interest in the application of experience from the farmed salmon industry to new aquaculture species. He is a director of four aquaculture companies and serves on NOAA's Marine Fishery Advisory Committee.

Building the Technological Bridge to Open Ocean Aquaculture

M. Chambers, R. Langan, B. Celikkol, W. Howell, R. Swift, K. Baldwin and J. DeCew

Open ocean environments around the globe present both opportunities and challenges for aquaculture development. North America, with its enormous seafood economy, scarcity of acceptable sites in protected waters, and leadership in technical innovation, is well suited for offshore development. Wind and wave conditions in the open ocean preclude the adoption of proven technologies for nearshore culture; therefore, new engineering approaches must be developed to insure structural integrity, operational capacity and worker safety. In addition, economic uncertainties of offshore farming must be resolved for development to take place at a meaningful scale.

The University of New Hampshire's Atlantic Marine Aquaculture Center has been at the forefront of developing the necessary tools and knowledge to move the aquaculture industry offshore. Mathematical modeling, scale model testing and field verification of new mooring and cage designs have greatly advanced the understanding of these systems in exposed sites. Remote feeding, telemetry control, operations and husbandry of cold water finfish and bivalves have been demonstrated at their submerged test platform 10 km offshore.

The Center's experiences over the past decade in managing an experimental offshore farm have made it clear that automation of many routine operations including cleaning, inspection, feeding and harvesting is needed to reduce cost and risk to personnel. Therefore, user-friendly cage systems that minimize diving and are capable of being harvested in 3 m seas will be necessary. In addition, service vessels will need to be designed with greater efficiency and mechanization to reduce staff and liability.

Figure 1
A 500 m^3 Aquapod cage being deployed.

Introduction

What is it that offshore fish farmers are trying to do? Ultimately, they want to make money by raising a seafood product. So to do so, they need to deliver a healthy, nutritional and affordable product to the consumer. They must maximize production efficiency by maintaining stock security, enhance fish performance, minimize labor requirements and insure worker safety. At the same time, they need to exercise environmental stewardship and achieve regulatory and environmental compliance.

In developing a business plan, the right components must be in place for a successful offshore farm. First of all, proximity to commercial port facilities must be taken into consideration. The site has to have characteristics that are conducive to the species of choice. Optimal conditions would include current speeds averaging no less than 20 and preferably no more than 50 cm/second. A depth ranging from 30 to 50 m is preferred to avoid concentrated deposition of wastes on the seafloor beneath the cages. Other parameters such as wave climatology and seasonal temperature profiles must also be known. If you can only access your site once per week due to high wave conditions, then this limits your ability to maintain, feed and harvest product.

Open Ocean Containment Systems

A wide variety of containment systems for fish culture have been developed for nearshore, protected environments. More recently, systems have been developed to endure greater exposure to open ocean conditions. The open ocean systems have adopted a submersible approach to escape storm and wave conditions, which at some locations can exceed 9 m. Several cages that are proving themselves in these extreme environments include the Ocean Spar Sea Station™, Aquapod[(1)] (Fig. 1), and OCAT (Fig. 2). These systems though, require alternative feeding systems that can deliver feed hydraulically below the surface (Fig. 3 and 4) as opposed to the industry standard of pneumatic feeders.

Figure 2 Deployment of a 100 m^3 OCAT cage at the Port Authority in Portsmouth, NH.

Figure 3
Deployment of a 20 ton, auto feed buoy at the AMAC test facility.

Figure 4
Aquaculture Engineering Group 100 ton feed buoy.

So how can a containment structure help farmers achieve their goals of making money? This can be achieved by the following factors:

1. **Fish Performance, Health and Welfare**
   - Maintain maximum volume in waves and currents
   - Appropriate shape and configuration for the species
   - Afford sufficient water replacement (flow)
     – per size, configuration and resistance to bio-fouling
   - Achieve precise depth control
   - Easily configured for automated feeding
   - Allow for prompt and efficient removal of mortalities
   - Ability to treat fish stock
   - Allows for efficient and low stress harvesting

2. **Stock Security**
   - Structural integrity of the frame
   - Transparency to waves and currents to reduce drag
   - Integrity of permeable barrier
     – resists abrasion/damage by equipment, humans, predators and fish
   - Maintain bio-security
     – does not harbor parasites or disease organisms
   - Accommodates technology for enumeration and biomass estimation

3. **Minimize Labor Requirements**
   - Cleaning is either not needed or is fully automated
   - Barrier requires reduced time for inspection and maintenance
   - Sampling and harvesting are fully automated

4. **Insure Worker Safety**
   - Design and construction that can accommodate user-friendly automation to reduce or eliminate the need for diving for routine operation and maintenance. (e.g. inspection, cleaning, harvesting and mort removal)
   - Easy (safe) ingress and egress
   - Visual and verbal communications

5. **Regulatory and Environmental Compliance**
   - Prevent/minimize escapement and consequences of escapement on native species
   - Reduce benthic organic loading from cage cleaning
   - Capture and recycle uneaten feed
   - Reduce the need for treatments and therapeutins
     – eliminate parasite “reservoirs”
     – stress-free conditions
   - Reduce attraction to predators and scavengers
     – automated removal of mortalities
   - Accommodate culture of an extractive species
     – seaweeds and shellfish

Open Ocean Feeding Systems

How do you feed your farm on a daily basis in the open sea? Commercial feeders of the day are designed for near shore or semi-exposed sites, not the open ocean.

UNH recognized this problem back in 2000 and initiated the design and development of remote, fully automated feeders. These feeders have progressed to the latest system that can hold up to 20 tons of feed [2] (Fig. 3). The new buoy is designed to withstand harsh winter storm conditions with seas greater than 9 m. This system is moored on a robust, four point mooring, adjacent to the experimental farm and delivers feed hydraulically through a network of underwater HDPE hoses. These hoses are integral with the submerged grid system.

How can an automatic feeding structure help farmers achieve their goals of making money? A feed platform will:

1. Provide consistent, daily feed rations to the farm during all weather conditions
2. Utilize feed recycling
3. Provide a stationary platform for:
   a. communication
   b. remote control
   c. biological monitoring
   d. environmental monitoring
4. Increase growth, survival and get product to market sooner
5. Reduce labor and safety issues
6. Provide video surveillance and radar alarms for farm management

Recommendations

In summary, the desirable attributes for a fish containment system would be robust, durable and automation ready. This would include an integrated feed distribution, mort removal and harvesting system. The system should consider compatible design/geometry for the specific species, resist bio-fouling and maintain volume under all circumstances. The cage should be breach resistant, predator proof and provide a safe and stress-free environment for the fish. It is also important to have the ability to control the depth of the cage to protect fish against storms and place them in temperature profiles to achieve optimal growth. The containment system should be able to be serviced (e.g. stocking, harvesting, inspection, mortality removal) from a surface vessel in wave conditions of 3 meters. Finally, systems should consider integrating a multi-trophic culture component for extractive species. This will serve as an secondary product for sale as well as reduce the carbon footprint of the farm by utilizing all the outputs from the fish and feed.

Desirable attributes for auto feeding systems include a stable, robust structure that can withstand the high energy environment of the open ocean. A surface platform will allow for remote communication, control and monitoring of the farm. The buoy should be readily supplied with fuel and feed and distribute feed to cages that are at the surface or below surface. Alternative power sources such as wave, current, wind and solar power should be harnessed and integrated into the feeding system.

Farms of tomorrow may include single point moorings that can be used in deeper water and have less of an impact on the ocean environment. Tension leg moorings have been demonstrated in the Mediterranean that could also be considered for exposed sites, thus reducing the footprint of the farm. As new engineering technologies come forth, mobile fish farms may be developed (Fig. 5) that could navigate in deep waters close to large market centers around the United States.

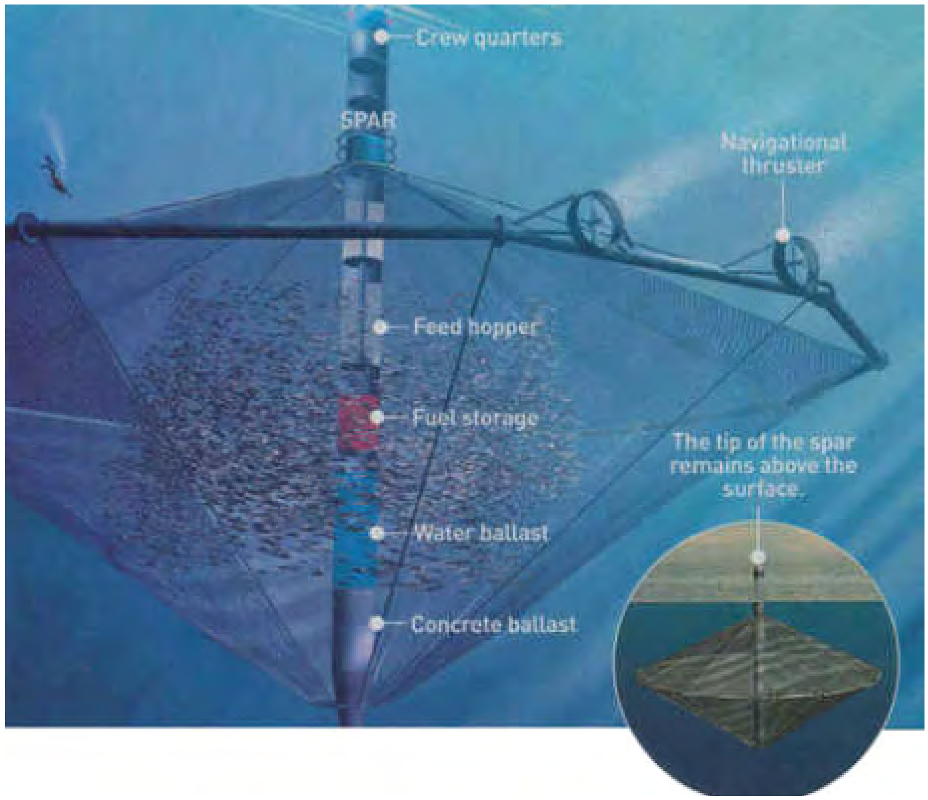

Figure 5

A conceptual ocean drifter designed by MIT and Ocean Spar.

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Authors

The following authors are located at the University of New Hampshire, Durham, NH 03824. **Michael Chambers** (email: Michael.Chambers@unh.edu) is Project Manager of the Atlantic Marine Aquaculture Center, Jere Chase Ocean Engineering Lab. **Richard Langan** is Director of the Atlantic Marine Aquaculture Center, 130 Gregg Hall. **Barbaros Celikkol** and **Rob Swift** are Professors of Mechanical Engineering, Kingsbury Hall. **Hunt Howell** is a Professor in Zoology in Spaulding Hall. **Ken Baldwin**, Director of Ocean Engineering and **Judson DeCew,** Research Project Engineer, are also located in the Jere Chase Ocean Engineering Lab.

Integrated Systems to Allow Safe, Efficient and Cost-Effective Aquaculture Operations in the Open Ocean Environment

Christopher J. Bridger and Phillip R. Dobson

Modern finfish farming, such as that operating in Canadian waters to raise Atlantic salmon, began a little over 35 years ago in Norway. Norway continues to play the "model farm" role and Canadian aquaculture finfish companies are inundated predominately with Norwegian technology that was developed for the relatively benign Norwegian fjord environment. While these technologies work well in Norway they tend to be generally sub-optimal for use in the more robust Canadian environment.

In 2002, AEG was incorporated to develop technology and management solutions that are capable of safe, efficient and cost-effective operations in medium- and high-energy environments while remaining cost-competitive for low-energy environments. The AEG product portfolio is driven by innovation, while our design philosophy requires that all AEG Solutions must meet five sustainability criteria that ensure products have a focused design and are socially acceptable, cost-effective, eco-friendly, and robust for survival particularly in higher energy environments.

Project Rationale and Objectives

AEG was incorporated in November 2002 to develop innovative solutions—AEG Solutions—to limitations impeding further sustainable growth of the finfish aquaculture industry worldwide. AEG Solutions were originally designed for use predominately in high-energy open ocean environments and individual products have been professionally engineered and model tested at the National Research Council Institute for Ocean Technology in St. John's, NL in simulated high-energy conditions prior to fabrication and field-testing of commercial-scale prototypes. These technologies can be integrated within a single commercial operation to allow safe and efficient aquaculture in open ocean conditions (Figure 1) and include:

- The AEG Feeder is designed to provide water-borne delivery of feed thereby maintaining the feed delivery pipes below the active ocean surface. The AEG Feeder is capable of feeding using manual control, automatic 'meal feeding' individual cages, or automatic 'pulse feeding' to feed 28 cages simultaneously.
- AEG Containment Systems combine surface logistics strategies common in the aquaculture industry with subsurface mooring connections that are increasingly integrated in novel 'offshore' cage designs and submersion capability incorporated where conditions require it.

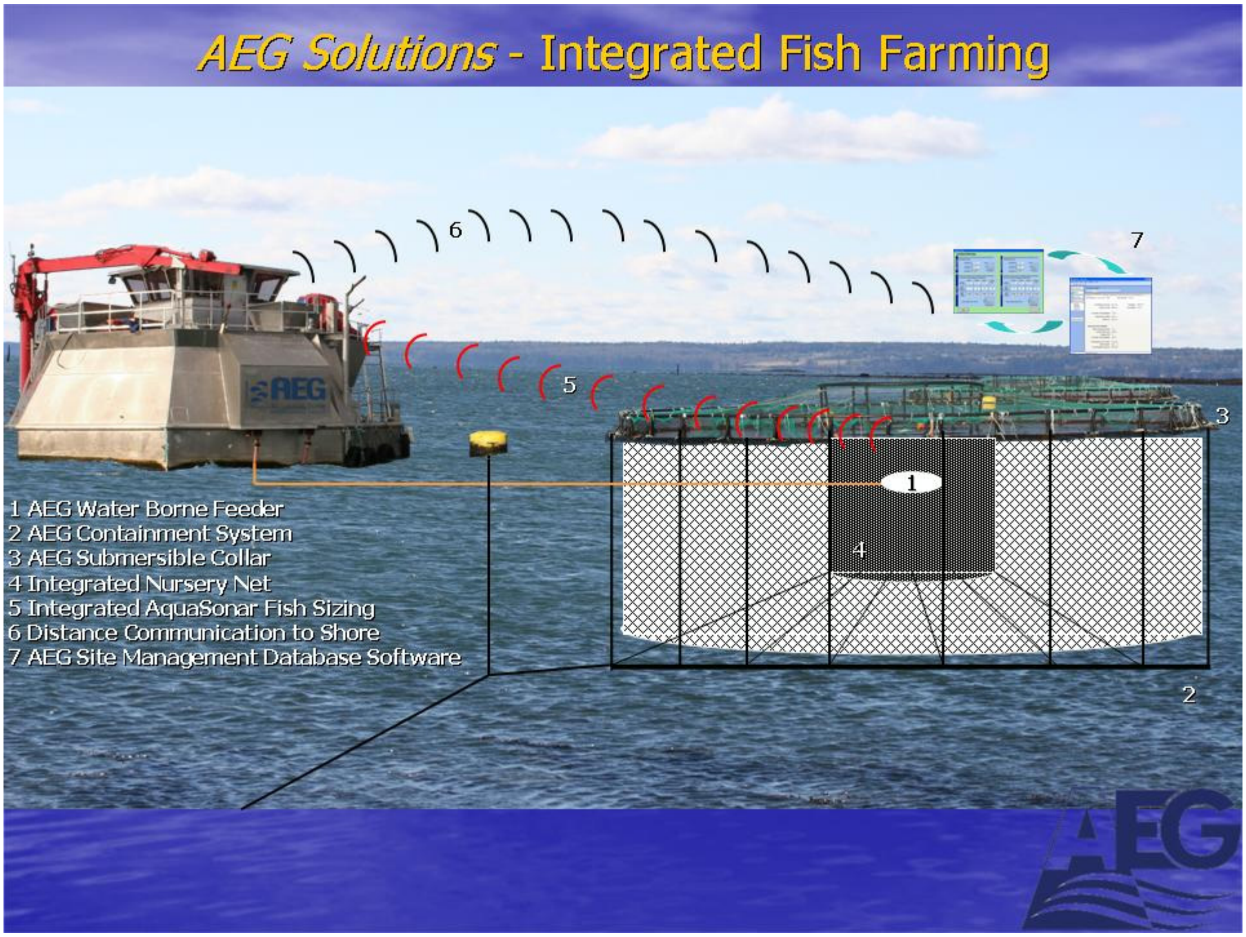

Figure 1

Integration of AEG Solutions deployed on the high energy project site in St. Mary's Bay, Nova Scotia.

- An advanced site data management software program—Neptune—for direct use with the AEG Feeder.

Location of the Project

AEG integrated its individual technologies on a commercial aquaculture site in St. Mary's Bay, NS near Tiddville north of Petite Passage along the southeastern shore of Digby Neck (Figure 2). The nearest wharf for site maintenance is 3.22 km northeast of the site in Little River. The site offers many challenging attributes that demonstrate the full potential of AEG Solutions to raise fish in higher than normal energy including very high energy—50 knot winds, 4 m waves and 1.8 knot currents—on a fairly regular basis having a very long fetch from the NE (up St. Mary's Bay) and SE-S-SW (mid-Atlantic exposure) directions. The site also regularly experiences ice flows in February, which has inflicted severe site damage and fish loss on the site during previous attempts to grow fish.

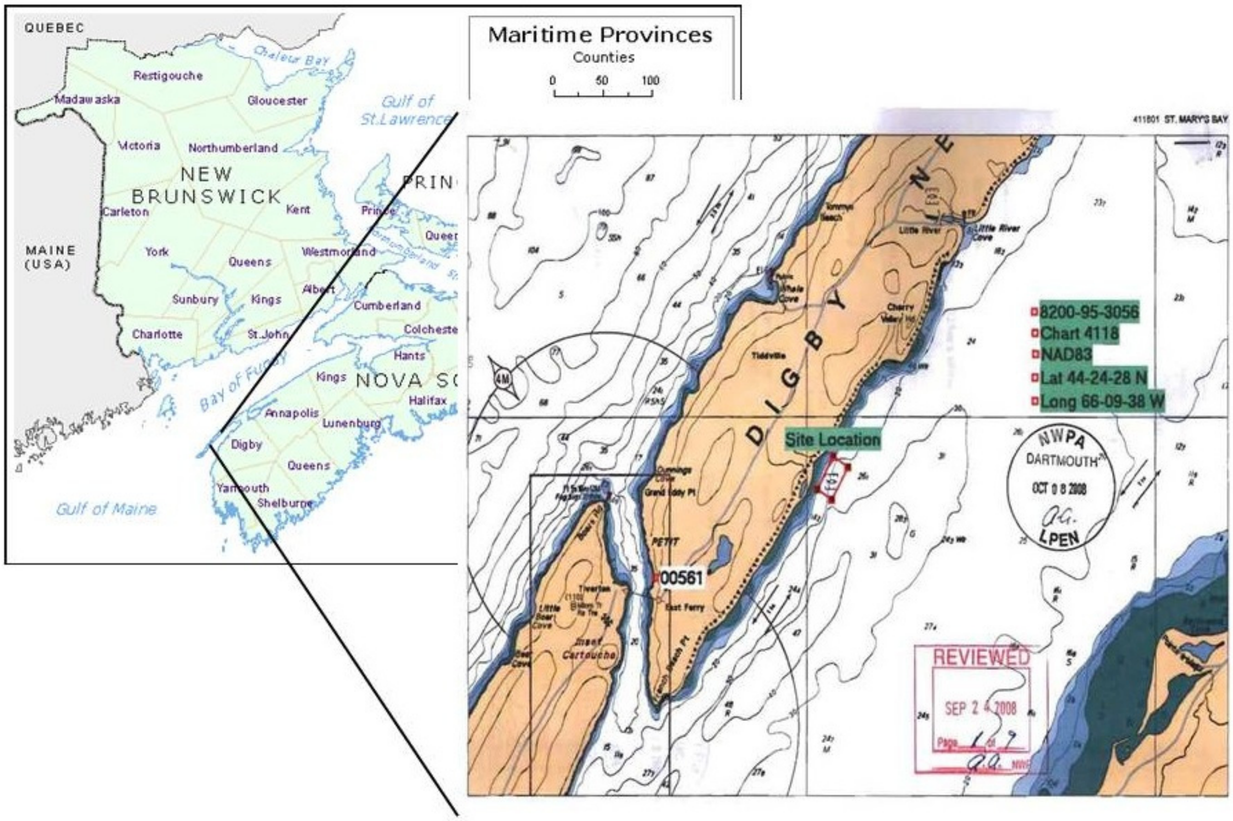

Figure 2
Location of the AEG project site in St. Mary's Bay, NS.

Site Set-up and Fish Entry

More than 250,000 steelhead trout were delivered to the site in fall 2009. The initial saltwater entry in October resulted in higher than expected mortality. As a result, the entry of the majority of the trout was delayed and SuperSmolt® was applied in an attempt to increase saltwater survival. This effort did not work and total entry mortality was upwards of 35%, leaving less than 150,000 trout for continued grow-out on the site. The mortality rate began to decline in the first quarter of 2010 following entry until eventually settling to an acceptable commercial rate below 0.6% per month by April 2010. This declining mortality rate in January, February and March 2010 during the harshest weather conditions on this high energy site is in large part attributed to the use of internal nursery nets to initially contain the fish stock.

Site Performance

Feeding

The AEG Feeder uses an innovative water borne feeding technology that is less aggressive on feed pellets compared with air blowers, thereby minimizing feed breakage and subsequent costs and environmental loading (see a video at http://www.youtube.com/user/AEGSolutions/videos).

The AEG Feeder measures the water temperature daily and allows feeding an entire site simultaneously with no requirement for day-to-day crew intervention or use of cameras. The AEG Feeder software allows automatic feeding based on established commercial feed tables that considers cage-by-cage biomass and measured water temperature. The biomass is adjusted based on calculated incremental fish growth coupled with fish removal as mortalities, harvest or other site management decisions occur. Feed rates are further adjusted based on a percent of the calculated feed table provision to maintain an assumed food conversion rate (FCR). The cages are also visually monitored on a bi-weekly basis for waste feed using a collection cone in the bottom centre of each cage.

A significant advantage of the centralized and fully automatic AEG Feeder with distance control is that fewer feeding events/days are lost due to foul weather. Trout were consistently fed using the AEG Feeder during the life of the project; however, the site manager noted feed days would have been lost due to inclement weather had the crew been required to visit the site each day. Figure 3 clearly shows the advantages of the AEG Feeder in this regard compared with feeding using feed boats or even other centralized feeders available globally. Note that lost AEG Feeder days towards the end of June and throughout July, August and September were related to adjusting the feed rates as the fish began to belch feed after reaching 1 kg in size and the water temperature increased. These same days would have been lost by crew feeding, but not recorded as such, as the weather on these days was fine to visit the site. Likewise, most AEG Feeder lost feeding in November and December was intentional to allow starvation for fish harvest. Again, similar days would have been lost using crew feeding if in fact the fish were at the target harvest size.

The average monthly feed rate for both cages was initially set at more than 100% of the feed table in the first quarter of 2010 as is typical while the fish are

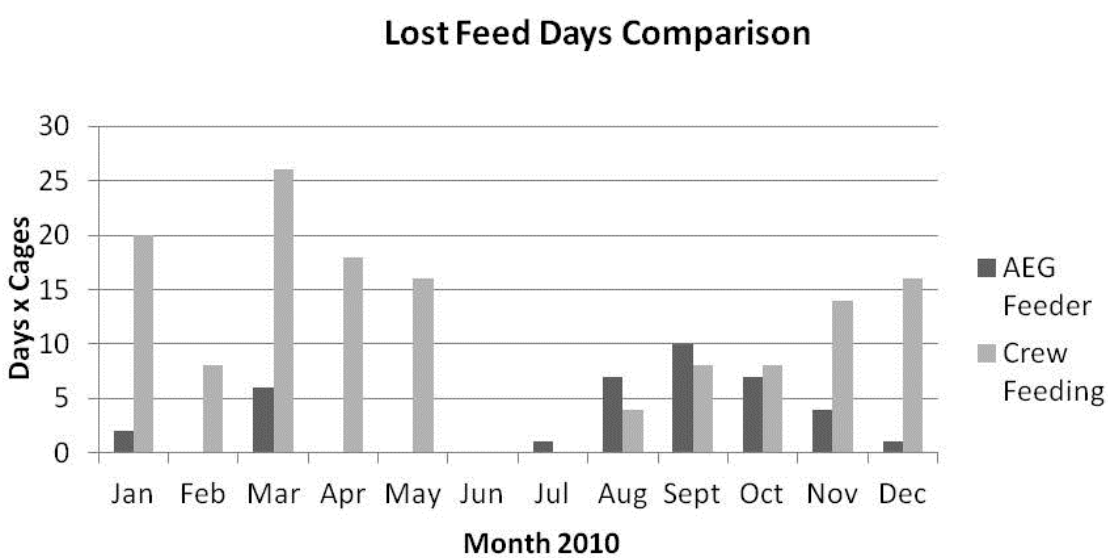

Figure 3
Comparison of lost feed days using the AEG Feeder with distance control versus crew feeding using feed boats or centralized feeders that require onboard management.

small. This rate was lowered to 100% as the temperature and growth increased in spring 2010. In early July, the trout began to belch feed creating an orange film of fish oil on the water surface as the water temperature warmed and the average size approached 1 kg. This can be a common occurrence when raising trout and widely accepted to be associated with use of specific feed ingredients. Typically, farmers continue to feed their stock at about the same rate when feed belching occurs, in an attempt to offset the loss of feed and the site FCR suffers dramatically. We managed the site with daily communication with the site manager and gradually decreased the feed rate to 40-60% of the feed table to eliminate the feed belching. The feed rate was maintained at 70-80% of the feed tables in the last quarter of 2010 as the trout reached the average target harvest size by mid-November.

The site FCR for the entire grow-out period was under 1.2. This compares with the typical trout FCR of 1.3-1.5 while raising the stock to an average target harvest live weight of up to 2.15 kg. This lower FCR is attributed to better overall feed management afforded by the AEG Feeder, effectively managing the feed belching issue, elimination of feed breakage during the feeding process with water-borne feeding, and maintaining a healthier stock of fish with nets that are consistently cleaned and therefore allowing well oxygenated water to flush through the cages.

Growth

The majority of the trout were entered in mid-December at an average weight of 91 g. The average target harvest live weight was 2150 g. Early projections had the stock reaching this average weight before the end of August 2010. However, this projected date was delayed to November 2010 (11 months following entry) due to the feed belching issue—which was experienced, but not anticipated, in July/August 2010 and required that the feed rate be dramatically reduced to keep the belching under control. Obviously reducing the feed rate had a profound negative effect on fish growth and the time required to reach target harvest weights.

Fish Health

Fish health was constantly monitored during the grow-out cycle. On a couple of occasions the Nova Scotia provincial veterinarian visited the operations to monitor fish health and sea lice load. One of these visits coincided with an increase in mortality in June 2010. Fish samples taken at this time found that the trout were carrying a *Vibrio* species that is specific to trout and not covered by the salmon vaccination. This might be the reason for the increase in mortality at this time but the issue was rather muted as the mortality rate declined to normal levels by July 2010. Sea lice were never a concern during the grow-out cycle and absolutely no pesticides or antibiotics were used during the grow-out. These fish health results further illustrate the capability of integrated AEG Solutions to provide superior fish welfare to maintain a healthy and stress-free stock even in the high energy conditions on the site. It may also be assumed that the high energy conditions contribute significantly to fish health in a positive way if the equipment allows the fish to survive in those conditions.

Harvest

Harvested fish were processed and marketed as either dressed with head-on (DHO) or fillets. In all cases, the fish were graded 100% premium. This in itself is quite encouraging given the ample opportunity for product downgrade through mechanical damage after experiencing numerous significant storm events during the grow-out, and with the present sea lice issue within the local salmon industry. Having no mechanical damage to the outside of the fish is a testament to the capability of the AEG Containment System to hold and raise fish on very high energy sites in the absence of net bagging and subsequent external damage to the fish stock. Avoidance of sea lice is likely related to the location of the site in isolation from other operators and the fact that trout were raised and not Atlantic salmon.

Harvested fish size was graded in two ways based on whether the final product would be DHO or fillets. Table 1 outlines the processing results for DHO product.

Table 1

Summary of harvested trout that were size graded for dressed head-on (DHO) processing and sales.

Size Grade	Total DHO (lbs)	Average DHO (lbs)	Fish (%)	% DHO (lbs)
2-4 lbs	24,603.56	3.02	26.89	18.83
4-6 lbs	88,609.48	4.59	63.77	67.81
6-8 lbs	17,451.57	6.18	9.33	13.36
	130,664.61	4.32		

The remainder of the trout were graded based on ± 3.5 lbs to produce fillets that were 1 to 2 lbs each. Fillet yield of 65% is quite respectable for trout and was consistently acquired due to the attention of the plant manager and the thick fillet provided by trout raised during the project. Upwards of 200,000 lbs of fillets were produced from the trout filleting. These fillets were all quite consistent in quality characteristics such as firmness, shape, size, gaping and color. All fillets were also given a premium grade with the color consistently given a rating of 27 to 29 as seen in Figure 4. This consistent flesh color is attributed to the capa-

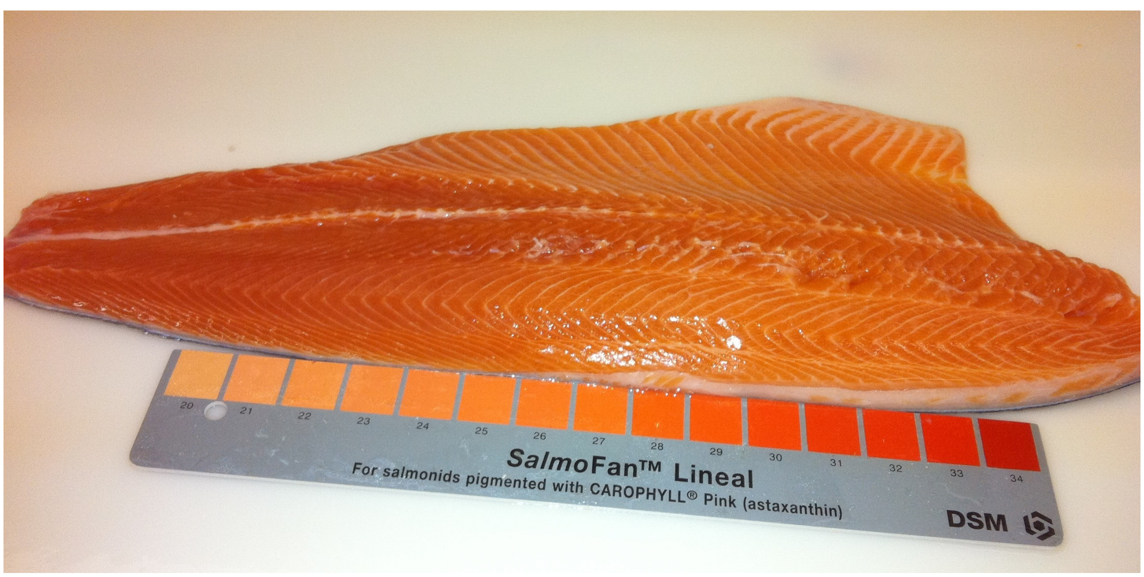

Figure 4

Trout fillet color quality resulting from project activities in St. Mary's Bay, NS.

bility of the AEG Feeder to provide feed over an extended daily feeding period exceeding 4 hours each day, thereby ensuring that all fish were fed each day regardless of a dominance hierarchy established within the stock.

Economic Analysis

Operational cash flow benefits associated with use of an AEG Feeder compared with crew feeding is abundantly clear following this project. Using an AEG Feeder will provide more than $867,000 in additional profit compared with using traditional crew feeding in feed boats in a single grow-out to raise 800,000 trout to a target harvest weight of 2.5 kg (5.5 lb). The majority of this difference comes from a much higher total feed cost using crew feeding due to the higher FCR, using many more vessels to feed and maintain the site, and a higher labour cost to feed the fish using at least three feed boats. Clearly the return on investment from integrating an AEG Feeder within commercial operations is quite appealing. In fact, the purchase price for an AEG Feeder having sufficient capability and capacity to raise these 800,000 trout should be recovered within a single grow-out cycle.

Our economic analysis does not consider further gains associated with a better market price from not using pesticides, antibiotics or antifoulants; a more consistent product quality for the market due to better overall feed provision and management; and, fewer lost feeding days using an AEG Feeder compared with crew feeding. This latter aspect is very difficult to enumerate but certainly having lost feed days will delay harvest accordingly and therefore add costs from having to operate the site for additional time. Further, the analysis does not fully evaluate gains coming from integration of other AEG Solutions used during the project (e.g., lower mortality rate and product downgrades while using AEG Containment Systems).

Conclusions

Project results provide clear indication that deployed AEG Solutions will have a positive impact on operational efficiency, equipment reliability, feed management, product quality, fish welfare, and cost effectiveness. These results are encouraging to continued product development and optimization. This is particularly the case as sites having higher energy in the open ocean environment become the only new sites that are available.

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Authors

C.F. Bridger and **P.R. Dobson**, AEG Innovative Solutions Inc.,
73A Frederick St., St. Andrews, NB.

Aqualine Net Pens and Moorings for Canadian Aquaculture Farms

Joe Hendrix

Since 1980 AQUALINE AS of Trondheim, Norway has worked with fish farmers throughout the world to develop a tough and reliable net pen and mooring system for raising fish. All the equipment AQUALINE supplies has been certified by the Norwegian aquaculture standards in NS9415 with the objective of providing equipment for long life and sustainable farming practices. All net pen designs use steel brackets, connector bars and sinker tube suspension chains for strength and HDPE heavy wall float tubes for flexibility and flotation that work together to incorporate extra safety features to prevent total float ring collapse and fish escape.

The current generation of AQUALINE Net pens are truly Open Ocean Aquaculture equipment designed to meet the requirements of challenging offshore sites and heavy weather conditions. AQUALINE, as a certified supplier of net pens and mooring equipment, has an engineering department with the most advanced tools to analyze dimensions plus site parameters to design the fish farmers growing system to produce the best results. By introducing the sea currents, wave heights plus tides into the computer modeling program, it calculates forces the net pen system will be subjected to and creates the margin of safety necessary within the system design. Many years of experience with the AQUALINE staff and cage assembly crew produce net pen and mooring systems that grow fish for the most successful aquaculture companies around the world today.

The fish farmers of the Canadian Atlantic Provinces and British Colombia are now opening new sites with challenging environments for raising fish. AQUALINE plans to provide the net pens and mooring systems that will produce fish in an environmentally friendly manner for the Canadian and American aquaculture industry.

Author

Joe Hendrix represents AQUALINE AS in the Americas for market development and cage site surverys (e-mail jhendrix1706@aol.com).

Characterizing Cage and Mooring Responses on Low, Medium and High Energy Aquaculture Sites in the Bay of Fundy

Alex R. Hanke, Betty House and Christopher Bridger

Salmon farming activities in the Bay of Fundy region have been ongoing since 1978. The first sites to be developed were located in reasonably protected bays and passages but increasingly higher energy sites have been developed as the commercial farming activities of the region continued to expand. This expansion has continued with no clear input from a science based approach (i.e., correlations between oceanography and engineering) but rather using more of a trial and error approach based on personal experience. The goal of this project was to develop oceanographic/engineering methodologies to incorporate within fish farming activities and, especially, to deploy higher energy sites and to develop new cage/mooring approaches and technologies. This project aimed to create a general knowledge base associated with the relationships between the oceanographic conditions at low, medium and high energy marine sites and the associated response of cages and moorings.

Project Sites

The project area encompassed the southern New Brunswick coast of the Bay of Fundy, south of Saint John to the coast of Maine and including Passamaquoddy Bay. This project was led by the Atlantic Canada Fish Farmers Association and as such project personnel had an opportunity to choose applicable sites from the inventory of all member companies. The chosen project sites included: Man O'War for the low energy site; Hardwood Island for the medium energy site; Penn Island and Orange Cove for medium-high energy conditions; and Duck Cove representing high energy sites. A weather station was also established on the tip of Point Lepreau. This paper will focus on results from the high energy site of Duck Cove (Figure 1) but all project results can be acquired on request from the Atlantic Canada Fish Farmers Association.

All of the sites used similar mooring configurations to hold the deployed cages, which followed the general circular floating HDPE pipe design. Differences occurred between the sites with respect to the number and type of anchors, the number and diameter of float pipes, and the dimensional characteristics of the pipe, rope, etc., based on the site conditions and past experience of the farm personnel.

The project was conducted between January 2008 and March 2009 when the monitoring equipment was deployed at five principal locations: Man O'War, Hardwood Island, Penn Island, Duck Cove and Point Lepreau.

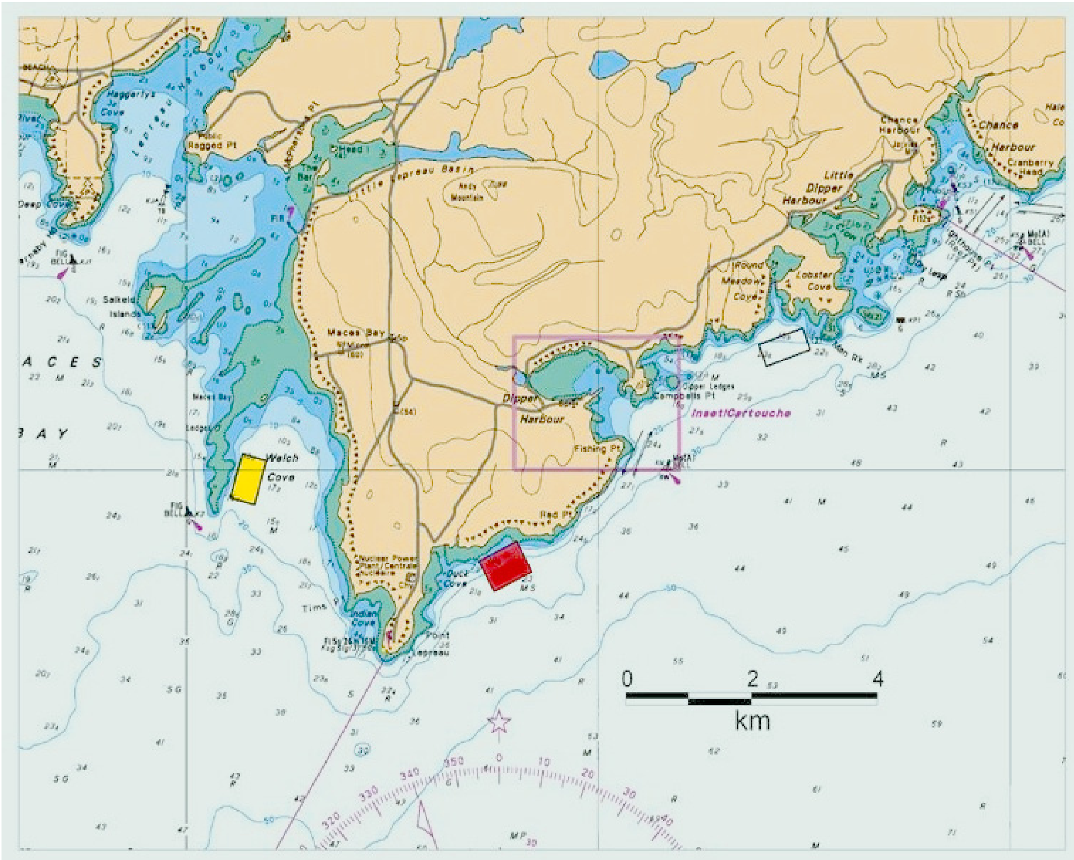

Figure 1
Location of the Duck Cove high energy site (red).

Transfer Function Modeling

A primary objective of this study was to develop models that can characterize loads that can be anticipated on cage site equipment (e.g., mooring lines) using inputs from the ocean environment. This information could then be used to appropriately size cage components or would lead to alternative mooring and cage designs to suit the site specific conditions. Further, the ability to use oceanographic inputs from existing but distant data buoys as a substitute to requiring site specific data collection was of interest to help offset otherwise expensive and time consuming data collection in the immediate vicinity of each and every high energy site that will be developed.

Load measurements were recorded at the Duck Cove high energy site. Climatic (wind speed and direction) and oceanographic data (wave height and direction, current speed and direction) were also collected in the immediate vicinity of the site to develop a feed forward neural network model relating measured loads to geographically local inputs. A similar exercise was completed to relate the same measured loads but using geographically distant inputs collected from the Gulf of Maine Ocean Observing System, Jonesport, Maine oceanographic data buoy (NOAA 44027 located at 44.273N; 67.314W).

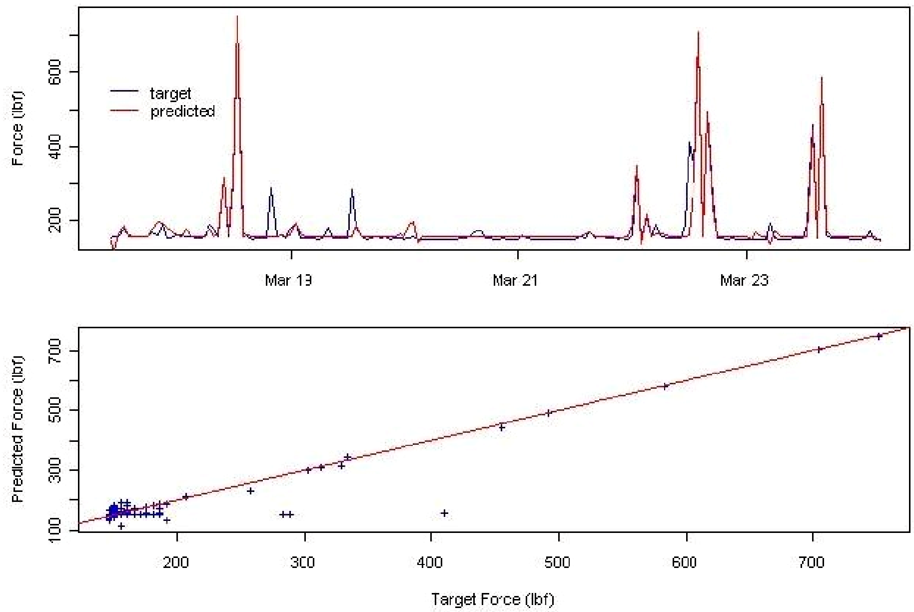

Figure 2

Results from a feed forward neural network analysis to predict mooring line loads using geographically local inputs.

Top panel: actual and predicted loads for a subset of the data.

Bottom panel: estimated versus actual loads.

The most parsimonious model to fit the data was based on wave height and current speeds. There was a relatively good fit between the predicted and observed loads when using geographically local inputs (Figure 2). In this case, the timing and magnitude of all but the smallest peaks are comparable to the observed data. Unfortunately this was not the case while using geographically distant inputs where the results indicate a poor fit of the observed and estimated loads (Figure 3).

Although this is still a work in progress, it is evident that a relatively simple feed forward neural network can be effective in predicting mooring line loads provided the input data originates from a location that is geographically close to the aquaculture site of interest. Both the timing and magnitude of the predicted load events were similar to the observed data when the inputs were from a geographically local source. Inputs from a distant source failed to predict all load events and only produced a load comparable in magnitude to what was observed when the input signal was strong. The maximum distance between the collected oceanographic data and aquaculture site location to provide a reliable prediction of loads is unknown from the project activities and requires additional study to determine this variable for modeling purposes.

Wave Power Dissipation

The energy in a wave is dissipated when it encounters a moored structure such as a cage site. The amount of energy generally absorbed by the site equipment

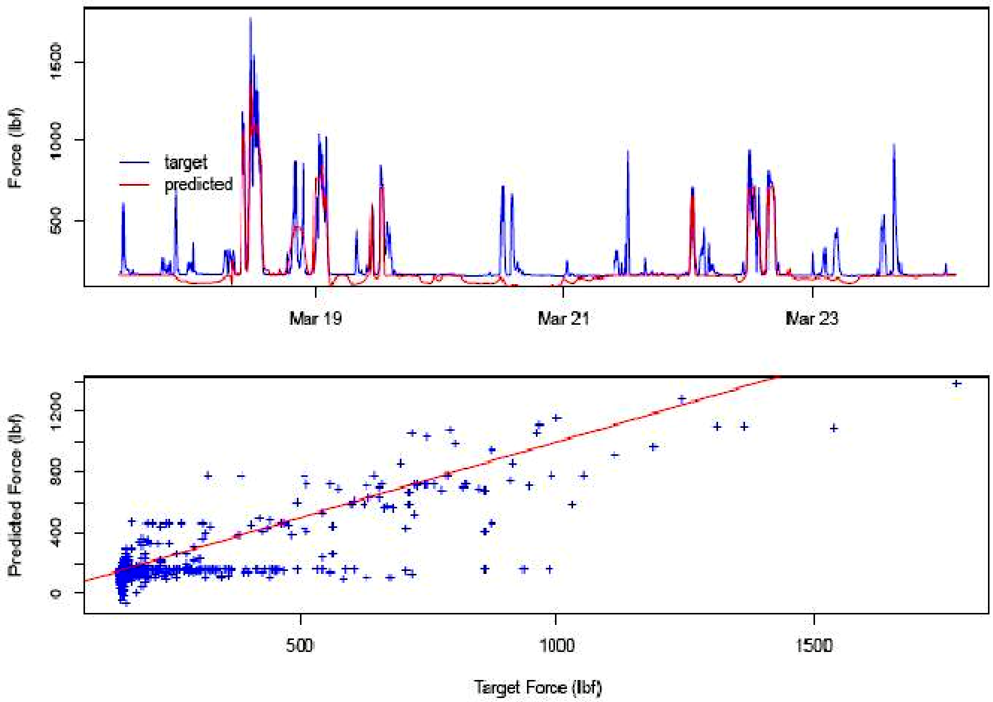

Figure 3

Mooring load predictions based on a feed forward neural network using geographically distant inputs.

(i.e., cages, moorings, etc.) can be determined by comparing the power associated with an incoming wave with that of a wave that has passed through the site.

Duck Cove represented the most energetic conditions within the study area. The severity of the current and wave environment on the site was measured using two WorkHorse Sentinel self-contained Acoustic Doppler Current Profilers (ADCPs) with WAVES packages. One ADCP was positioned offshore of the cage system in 22.6 m of water while the other ADCP was positioned inshore of the cage system in 17.3 m of water.

The expected wave height at the location of the inshore ADCP but in the absence of the cage system was calculated according to US Army Corps.(1) The difference between this calculated wave height and observed data collected with the inshore ADCP reflects the general interaction of the offshore waves with the cage system and therefore the wave energy transferred to the cage system. Note that consideration was given to the effect of shoaling but not refraction, friction or percolation when calculating the expected wave height.

Four major wave events were analyzed in this manner to determine wave energy transferred to the fish farm but only one of these is depicted in Figure 4. The 200 hour time series captures a storm event and illustrates the effect that the cage system may have on significant wave height. The force associated with the waves in this same storm event is also depicted in Figure 4. Note that the calculations of wave energy density were all based on significant wave heights and do not represent the extreme maximum case that the fish farm equipment will be exposed to and should be designed for.

Floating structures such as an array of aquaculture cages will dampen wave heights. The lost height of the wave represents energy captured by the cage array. Ideally, the cage array will allow waves to pass through it unimpeded, but in reality the wave heave and drift forces are reduced by the drag from cage components such as the net or by the work done lifting it vertically and by resistance to movement horizontally caused by the elasticity of the mooring lines.

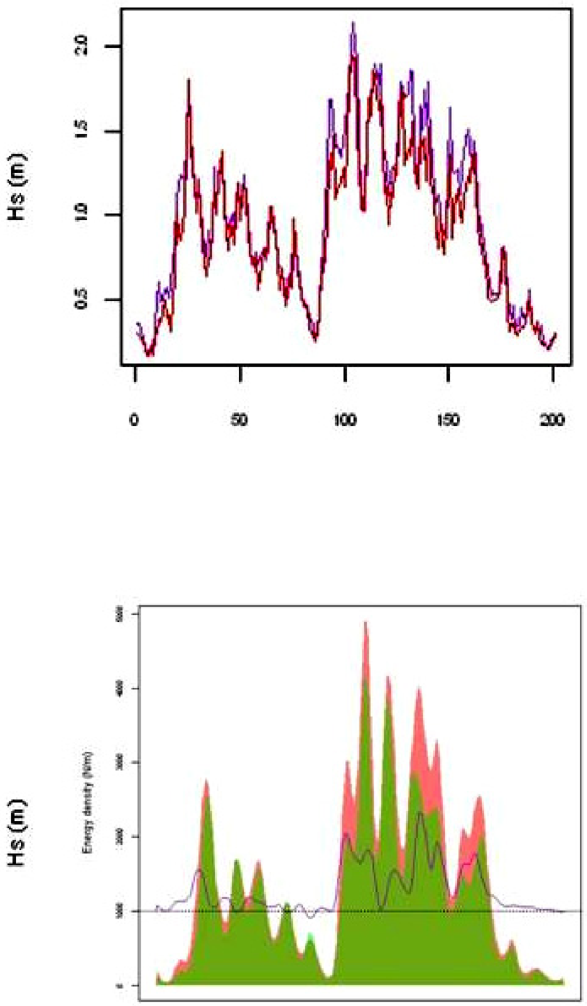

Figure 4

Wave height reduction caused by the presence of a fish farm over a 200 hour time series.

Upper panel: expected (purple line) versus observed (red line) significant wave height after passage through the fish farm location.

Lower panel: Loess smoothed energy density time series based on the expected and observed wave heights. The overlapping series is red when the expected density exceeds the observed, blue when the observed exceeds the expected and green otherwise.

No energy loss due to bottom friction or refraction was assumed in this brief examination of the wave energy density change caused by aquaculture cages. Additionally, the effects of wind on the parts of the cage above the water line are ignored. The energy loss from wave breaking was not important and the effects of shoaling and refraction were small. The force absorbed by the cages varied with the tide and the period of the incident waves. The cages tended to ride the swells and knock down shorter period waves with a transfer of force exceeding 1000 N/m of wave front.

Occasionally, wave heights inshore were greater than offshore. Wave diffraction and reflection from the coastline and coastal features could account for greater wave heights measured at the inshore sensor than those expected based on data from the offshore sensor. The amplitude of the reflected or diffracted wave interacts with the amplitude of the incident waves to produce standing waves larger than the incident waves. Incident waves with a long wavelength tend to reflect from the shore without breaking beforehand and thus have a greater likelihood of building big standing waves. Although there was a tendency for the wavelengths to be longer when the observed wave heights exceeded expectation, the relationship was confounded by the incident wave angle and diffraction-reflection off coastal features.

This method of estimating the force absorbed by the cages gives realistic values for the system as a whole but stops short of identifying the stresses on specific cages or components of a cage. These estimates can be viewed as being conservative as cages and their components are unlikely to experience the forces to the same degree even when the system is extremely well tensioned and balanced. It is recommended that measurements be taken from individual cages and cage components to be sure that the number and size of mooring lines, for example, are capable of absorbing the expected forces, rather than make over-simplifying assumptions about how the force is distributed.

Conclusions

Understanding the relationship between oceanographic and meteorological inputs and cage or mooring responses will support planning, operating and monitoring of high energy aquaculture sites. Additional data analysis and further development of the feed forward neural network model is ongoing to provide a basis for assessing the effect of the ocean climate on deployed aquaculture structures.

It is hoped that collected performance data for conventional installations at present locations can highlight the strengths and weaknesses of conventional installations in a range of environmental conditions as well as serve as a baseline for comparison with installations using new technology. Use of the developed neural network might allow new marine sites to be developed and new technologies tested with some sense of the risks involved and increasing the chance for success through appropriate system design.

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Authors

Alex Hanke, Atlantic Canada Fish Farmers Association, 226 Limekiln Road, Letang, NB E5C 2A8 (now with the Fisheries and Oceans Canada, Biological Station, St. Andrews; email alex.hanke@dfo-mpo.gc.ca). **Betty House**, Atlantic Canada Fish Farmers Association, and **Christopher Bridger**, AEG Innovative Solutions Inc., 73A Frederick St., St. Andrews, NB E5B 1Y9.

Thierry Chopin

Prospects for Integrated Multi-Trophic Aquaculture (IMTA) in the Open Ocean

Thierry Chopin, Shawn Robinson, Gregor Reid and Neil Ridler

As the demand for seafood is rising worldwide and the availability of appropriate sheltered nearshore sites is more and more reduced, the aquaculture industry is looking at expanding into more exposed and open ocean locations. Open ocean development will not be unlimited, however, as the vast oceanic systems have their functional and resource limitations. It will be important to develop the right design of open ocean aquaculture operations, that includes extractive species to carry out the biomitigating functions of the systems. It is expected that, because of economies of scale, the open ocean farms of tomorrow will be larger than the present nearshore farms. Higher levels of waste will be generated due to their inherent assimilative inefficiencies. Instead of taking the position that hydrodynamic conditions in open ocean environments will be appropriate for dispersion and reduced environmental impacts (but at a significant cost of lost food), the aquaculture sector should capitalize on the by-products of fed aquaculture to recapture what is food and energy for extractive aquaculture and engineer efficient integrated multi-trophic aquaculture (IMTA) systems.

The challenges will be numerous from the biological, environmental, economic, technological, engineering, regulatory and societal perspectives. Appropriate extractive species will have to be selected based on their biology and the culture methods and harvesting technology will have to be adapted to exposed conditions. High value-added markets will be needed to justify their culture within expensive infrastructures, as they generally have a lower value than fish. The profitability of open ocean IMTA systems will have to be demonstrated. Early bio-economic models of nearshore IMTA indicate that economic diversification and reduction of risks are keys to increasing the profitability of these systems over finfish monoculture. The same arguments can probably be used for open ocean IMTA operations. Moreover, if the environmental, economic and societal services and benefits of IMTA are properly estimated and internalized, they will provide significant incentives for cultivating extractive species. These species could be considered for nutrient trading credits in the global economy, as the aquaculture sector moves to become more efficient and sustainable, possibly by becoming a partner with the large wind power generation and biofuel projects of the future.

Introduction

The global seafood market is at a crossroad. While landings by capture fisheries have leveled off, and many fish stocks have reached their plateau or collapsed, demand for seafood has been rising steadily, leading to the rapid expansion of aquaculture.[1] A significant increase in aquaculture output will require expansion into more exposed, open ocean, locations, as the relatively sheltered nearshore sites appropriate for aquaculture, such as in the Bay of Fundy, have already been developed and not many others are available.

Moving to the open ocean has also been considered as a means for moving away from environmental and public perception issues in the coastal zone, already sought out by many stakeholders. This move, however, should not be seen as an "out of sight, out of mind" attitude, as open ocean developments will also be under scrutiny by a more and more educated public. Even though wastes will be more diluted through larger dispersion fields, it is likely that these operations will need, economically, to be much larger than farms in nearshore waters. This implies more wastes will be generated, particularly when one considers that animals are generally poor converters of food into somatic tissues. The solution to nutrification should not, as has been the case throughout history in most western countries, be dilution. Even if greater residual currents, deeper water and lower nutrient baselines are anticipated to reduce impacts from open ocean operations through wider dispersion plumes of nutrients, as compared to similarly-sized nearshore operations, there is a point when open ocean ecosystems will eventually reach their assimilative carrying capacities. We thought the sea was so immense that we did not need to worry about fisheries limits, and this is not the case. We thought the "Blue Revolution" of aquaculture development was benign, and this is also not the case. Why should we think that open ocean aquaculture, the "last frontier", will be without its own borders/limits? Moreover, our rudimentary knowledge about linkages between open ocean and nearshore systems could also result in unpleasant surprises.

This suggests that mitigating approaches should also be used in open ocean operations. Thus, conversion into other crops of commercial value, not dilution, should be applied to open ocean development as well as to nearshore environments.[2] Trophic diversification is required from an environmental and economic perspective, with "service species" from lower trophic levels (mainly seaweeds and invertebrates) performing the ecosystem balancing functions while representing value-added crops. Various approaches have been suggested to improve the deficiencies of the "Blue Revolution".[3] One such responsible practice is the development of flexible integrated multi-trophic aquaculture (IMTA) systems for a greener "Turquoise Revolution". The IMTA concept is based on an age-old, common sense, recycling and farming practice in which the by-products (wastes) from one species become inputs for another: fed aquaculture (fish or shrimp) is combined with inorganic extractive (seaweed) and organic extractive (invertebrate) aquaculture to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and societal acceptability (better management practices). IMTA is also a practical approach that provides additional revenues, as food and energy (which represent approximately 60% of the operating costs of nearshore finfish farms) can be recaptured and converted into crops of commercial value, instead of lost by dilution in a finfish monoculture.

Open Ocean IMTA—Realities and Constraints

It is important to clarify that open ocean, or offshore, aquaculture is not a question of distance from the coast, but one of moving from sheltered to more exposed habitats, which in some parts of the world can be found within less than 3.7 km (2 nautical miles) from land, whereas other aquaculture sites 18.5 km (10 nautical miles) offshore, but in inner seas, are still experiencing conditions described as sheltered.

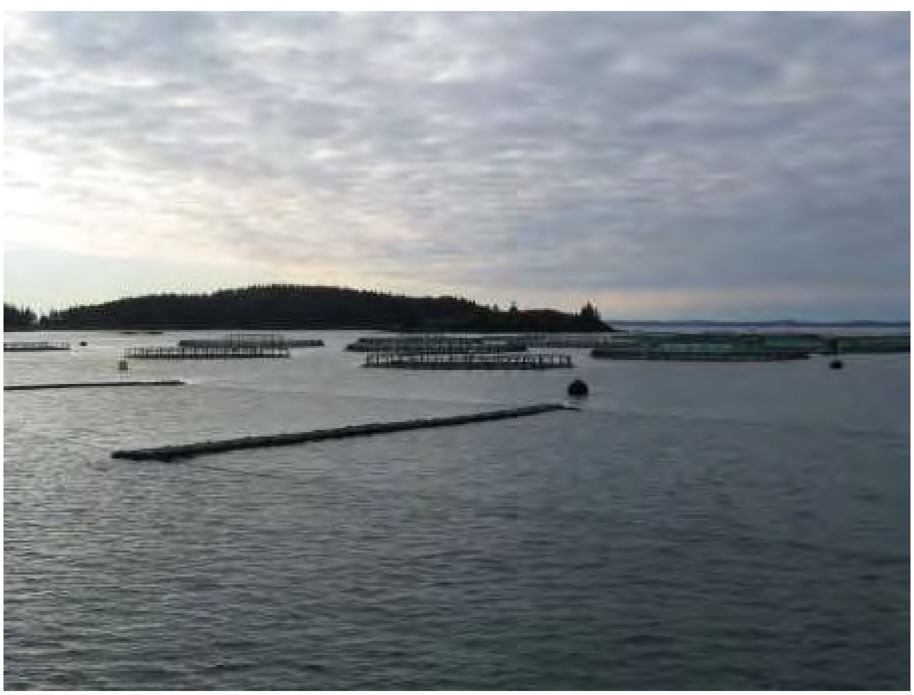
Over the last 20 years, there has been renewed interest in IMTA systems in the western world.[4] They, however, have remained at the experimental or small commercial scale (Fig. 1). It is difficult to extrapolate from limited nearshore IMTA experience to the unknown of open ocean IMTA commercial operations. Open ocean large-scale multi-trophic sea-ranching and suspended cultures do exist in China,[5] but their relevance to western socio-economic models is questionable.

At the present time, designs of finfish open ocean operations can be grouped into two categories: submerged and surface operations. In the first scenario, the distribution of nutrients will be different from that at shallower nearshore sites. The bulk of the nutrients will be released at a relatively greater depth. Organisms of the organic extractive component can be submerged to some extent, but seaweeds being photosynthetic organisms need to remain relatively close to the surface (based on light availability). If open ocean sites do not experience upwellings, such ascensional movements will have to be engineered. Surface open ocean designs will be simpler and more efficient regarding the functioning of the extractive species. Moreover, designs involving a one-point mooring system will enable the extractive species to always be in the zone of nutrient dispersion. In Canada, the first into the open ocean aquaculture field will probably be the salmon industry, so engineering will have to be developed to accommodate this effort.

Open ocean waters may have lower nutrient concentrations than nearshore waters and the presence of the fed component should improve the growth of the extractive species, which would otherwise have difficulty there in large amounts, due to the relative lack of food and energy. This will certainly be highly geographically specific. For example, mussels have grown quickly in open ocean operations off New Hampshire,[6] and have very high meat yields, suggesting they are not food limited.

Contrary to fish, which are pelagic, most extractive organisms are benthic and are often either attached to a substrate or living within it. The success in aquaculture is to make these organisms attach to artificial substrates: attachment or entwining by holdfast to ropes and nets for seaweeds, by byssus to ropes or socks for filter feeders such as mussels, or by burrows for polychaetes. An important aspect for open ocean IMTA to determine is if such organisms will be able to withstand the hydrodynamic forces at these sites. This has rarely been tested and demonstrates the need for specialized equipment.[7,8]

Figure 1. Small commercial scale IMTA site in the Bay of Fundy, Canada, where seaweeds (*Saccharina latissima* and *Alaria esculenta*, front), blue mussels (*Mytilus edulis*, first line of cages) and salmon (*Salmo salar*, other cages in the background) are cultivated **(photo by T. Chopin).**



The inorganic extractive component: seaweeds

For open ocean systems, the primary goal will probably be the maximization of seaweed areal yield and not nutrient reduction efficiency (which is a more typical approach of land-based recirculation systems). Therefore, a significant fraction of the dissolved nutrients may remain in the seawater, but there will still be a net removal of nutrients when the seaweed biomass is harvested.

Most seaweed culture methods have been designed for sheltered conditions (suspended ropes, suspended nets or off-bottom monolines).[(9)] Moving to exposed conditions will require a complete rethinking of the culture techniques, infrastructures and possibly species. Materials of higher resistance and improved anchoring systems will be needed. Selective thinning of the seaweed biomass is a common harvesting method that implies frequent visits to the sites; in the open ocean context this will have logistical implications.

Even if increased water transparency (reduced turbidity) in open ocean waters permits culturing seaweeds in deeper waters, they will still be cultivated near the surface and over a relatively large area, as seaweed cultivation is almost a two dimensional system using a small vertical dimension of the water column as compared to fish and organic extractive organisms.

The organic extractive component: filter and deposit feeders

Pilot projects have demonstrated the technical feasibility and rapid growth rates for blue mussels (*Mytilus edulis*) grown in open ocean environments.[(6,10)] The deployment of mussels in the deeper, less turbulent environment found in open ocean conditions resulted in thinner shells and more meat.[(10)] Mussels deployed at a summer flounder (*Paralichthys dentatus*) open ocean cage site had an average growth rate of 1 mm/wk and meat yields (percent cooked meat weight divided by total cooked weight) ranging from 44 to 58%.[(6)] These are encouraging results and suggest mussels would be good candidates for open ocean IMTA operations.

Modelling results from nearshore IMTA systems show that while filter feeders are excellent biomitigating organisms for the extraction of small organic particulate matter, deposit feeders will also need to be added to the systems for better efficiency at recapturing the food and energy entrapped in the larger particles.

With the development of open ocean IMTA in waters of considerable depth, the cultivation of bottom deposit feeders could present challenges making that component economically prohibitive if they are grown on the sea bottom. Mid-water systems of suspended trays, or other artificial reef structures, below the fish cages will need to be developed and will require significant effort in engineering design and testing. As with the inorganic extractive component, equipment and infrastructure for the organic extractive component will need to be rethought and dimensioned to the conditions prevailing in open ocean situations.

Open ocean, biofouling and the IMTA advantage

A key issue that will have to be considered with open ocean cage culture systems is biofouling. Open ocean sites will not remain monocultures. Similar to their nearshore counterparts, organisms will settle and grow on the structures. This colonization concept has been amply demonstrated on offshore oil and gas platforms in the North Sea and off California.[(11-16)] These platforms have been described as some of the largest artificial structures in the marine environment,[(14)] and as such can carry significant loads of species that have settled from drifting larval forms. One platform was estimated to shed over 1 m^3 of mussels per day, through normal processes, that supported large numbers of sea stars on the bottom.[11]

Open ocean aquaculture sites will also create large structures on which drifting species attach. Biofouling will add to the stress loads on the structures by increasing the friction coefficients, hampering the inspection of the components and potentially accelerating the corrosion of some of the structural elements, hence creating physical damage to some parts.[15] For remote open ocean aquaculture sites that will not be visited for daily inspection, this could have some important operating consequences. The oil and gas industry, having faced these issues over the last few decades, has developed various antifouling strategies (*e.g.* cathodic systems) that will have to be adapted to the open ocean aquaculture industry.

Some studies have demonstrated that the succession of species settling on offshore oil and gas platforms are the same ones that settle on nearshore aquaculture cage sites.[11,15,16] The blue mussel is the dominant species and occupies most of the surface area of the structures. Sea anemones, such as *Metridium senile*, often eventually dominate the lower levels with various tube worms. Some of our observations on the IMTA system in the Bay of Fundy show that high densities of intentionally grown mussels can significantly reduce the settlement of other pelagic larvae (likely through ingestion). High densities of intentionally grown seaweeds can also significantly reduce the settlement of other algae on ropes (likely for the simple reason of being first to occupy the substrate and excluding the others by winning the early competition for space). These observations emphasize the point that if something is going to grow on your culture structures anyway, you might as well design the system for it to happen with species of commercial value to try to turn a biofouling nuisance into an IMTA advantage.

Species interactions and potential role of IMTA in disease reduction

Another biological issue to be considered is the interactions between species at the sites. Like offshore oil and gas platforms, open ocean aquaculture infrastructures will act as predator refuges for various species of fish and invertebrates, making them similar to fish aggregating devices (FADs) used in commercial fishing operations.[12] If disease agents are present, this will represent one vector that will need to be checked and hopefully controlled, perhaps through the use of vaccines.

Interestingly, recent studies[17] and our own unpublished data indicate that carefully chosen species in an IMTA setting have the potential for some disease control. Mussels are capable of reducing loads of the infectious salmon anemia virus (ISAV) in the water. Consequently, appropriately placed mussels around salmon cages could act as a possible biofilter for disease reduction or prevention.

Economics of open ocean IMTA

Economic feasibility studies on open ocean IMTA are rare. Some cost estimates have been made for a finfish/mussel system off New Hampshire, USA;[18] they are, however, based on hypothetical data with little allowance for risks and their management, which will be critical in determining profitability. Economic feasibility studies on nearshore IMTA are limited.[2,19,20] They demonstrate that integrating mussels and seaweeds with existing salmon monocultures can increase the profits of salmon farmers. This increase in profitability is compounded over time and grows with increased production and stocking densities.

IMTA is also an excellent tool for reducing and managing risks. A diversified portfolio of species will increase the resilience of the operation by absorbing price fluctuations of one species or the accidental catastrophic destruction of another. While some extractive species (*e.g.* mussels) may have a lower market price than fish species, especially in western-type aquaculture which favors carnivorous fish, others may be more valuable (*e.g.* scallops and polychaetes). However, the volumes that can be cultivated are often lower, resulting in a lower gross profit. To compensate for the higher costs of cultivating extractive species within high-tech open ocean infrastructures, their use and applications in high valued-added markets—such as in direct human food consumption (sea vegetables), nutraceuticals, cosmetics, bioactive compounds—will have to be systematically sought out.

If the costs of environmental degradation could be recognized and quantified, then the value of extractive species would increase and their "environmental and societal services" could be factored in, giving an advantage to farmers implementing IMTA. If there were limitations to nutrient emission, a farmer could expand finfish production if extractive species were also farmed, based on a system of nutrient (nitrogen, phosphorus, etc.) trading credits, similar to that of carbon trading credits, which would internalize the nutrient discharge mitigating properties of the extractive species. Better estimates of the environmental and economic benefits of IMTA to society could represent significant incentives for its implementation.

Discussion

Open ocean aquaculture will be an expensive venture. Its profitability remains to be demonstrated, especially when facing increasing prices for energy, fishmeal and fish oil; the high costs of engineering, construction, and reliable safety and monitoring systems; the cost of a specialized labour force; and risk uncertainties and the even lower commodity prices fish will reach (reduced profitability margins have already been experienced by the nearshore industry). Niche markets may justify the high fixed costs of open ocean aquaculture, but whether finfish such as salmonids can be cultivated profitably in open ocean systems remains to be proven.

IMTA could add to the profitability of open ocean systems through economic diversification and risk reduction. To reduce the entry costs and share the costs of developing technical solutions, open ocean aquaculture, including IMTA, should team up with other sectors considering open ocean development, such as the development of wind energy generation. In fact, the infrastructures developed for these other open ocean ventures could be amenable to becoming the pivotal anchoring systems of IMTA.

Open ocean aquaculture should, in fact, consider the IMTA option from the beginning if it does not want a repeat of what happened with intensive finfish nearshore aquaculture, where criticism necessitated the development of

Figure 2. Large commercial scale IMTA of kelps (*Saccharina japonica*), scallops (*Chlamys farreri)* and oysters (*Crassostrea gigas*) in Sungo Bay, Shangong Province, China (photo courtesy of M. Troell).

biomitigating practices such as IMTA. Including IMTA at the early stages, and not as an afterthought 30 years later, will lead to creating appropriate designs for environmental sustainability, economic stability and increased societal acceptability. As mentioned above, the bulk of nutrients will be at greater depth with submerged fish cages. Designing current turbines could create local upwellings, bringing nutrients closer to the surface; they could also double as electricity generators for the sites (also supplemented by wave, wind and solar power). Wave-energy breakers could also be designed around aquaculture sites to provide protection and to channel local currents to the turbines.

The spatial scale covered by the extractive species, particularly the seaweeds, will have to be large in IMTA open ocean systems (Fig. 2). This aspect has not really been addressed so far, nor have solutions been developed. Combining IMTA farms with wind power generating farms could be a means for reducing their cumulative footprint. Gigantic projects for the production of biofuel with terrestrial crops have been proposed in several countries, but the implications have not been clearly thought out. The price of some staple food crops used in traditional agriculture has already risen considerably due to competition for their uses as energy crops. To reach the American government's target of 30% displacement of gasoline with biofuels by 2030 using corn or switch-grass would require over 40.5 million hectares (100 million acres) of farmland,[21] equivalent to 1.7 times the total area of the provinces of New Brunswick, Newfoundland, Nova Scotia and Prince Edward Island (*i.e.* Atlantic Canada), or a little more than the state of California. Issues of irrigation on a planet already suffering from water availability problems, and of competition for land or deforestation occurring to make room to cultivate crops for biofuel production, have been ill-approached or ignored. Using organisms already living in water could be the real answer to address the above interdependencies, which have not been perceived or have been ignored so far. Kelps are, in fact, amongst the fastest carbon assimilators on the planet, with yields of up to 44.5 tons/hectare (18 tons/acre) compared to 11.2 and 24.7 tons/hectare (4.5 and 10 tons/acre) for corn and switch-grass, respectively.[21,22] The conversion efficiency of kelps is promising (0.43 g ethanol per gram of kelp carbohydrate).[23] The aquaculture sector should consider being involved in the elaboration of these large biofuel projects as a valuable partner, already having a lot of know-how and experience with regard to cultivation and infrastructure development.

Beyond the biological, environmental, economic, technological, engineering and regulatory issues of such developments, the basic question will be that of societal acceptance. Are we ready to industrialize the "last frontier" of this planet and consider not only the challenges of the physical forces at sea (wave exposure, winds, currents, depth, etc.) but also those of shipping routes, fishing zones, migration routes for marine mammals, recreational uses, and then finally deal with the concept of zoning some portions of the oceans (marine spatial planning) for large multipurpose integrated food and renewable energy parks (IFREP)?

As Jules Verne wrote more than 130 years ago, "tout ce qui est impossible reste à accomplir" (all that is impossible remains to be accomplished)...!

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Authors

Thierry Chopin (tchopin@unbsj.ca) and **Neil Ridler** are at the University of New Brunswick, P.O. Box 5050, Saint John, N.B. Canada E2L 4L5. **Shawn Robinson** and **Gregor Reid** are at the Department of Fisheries and Oceans, 531 Brandy Cove Road, St. Andrews, N.B. Canada E5B 2L9.

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