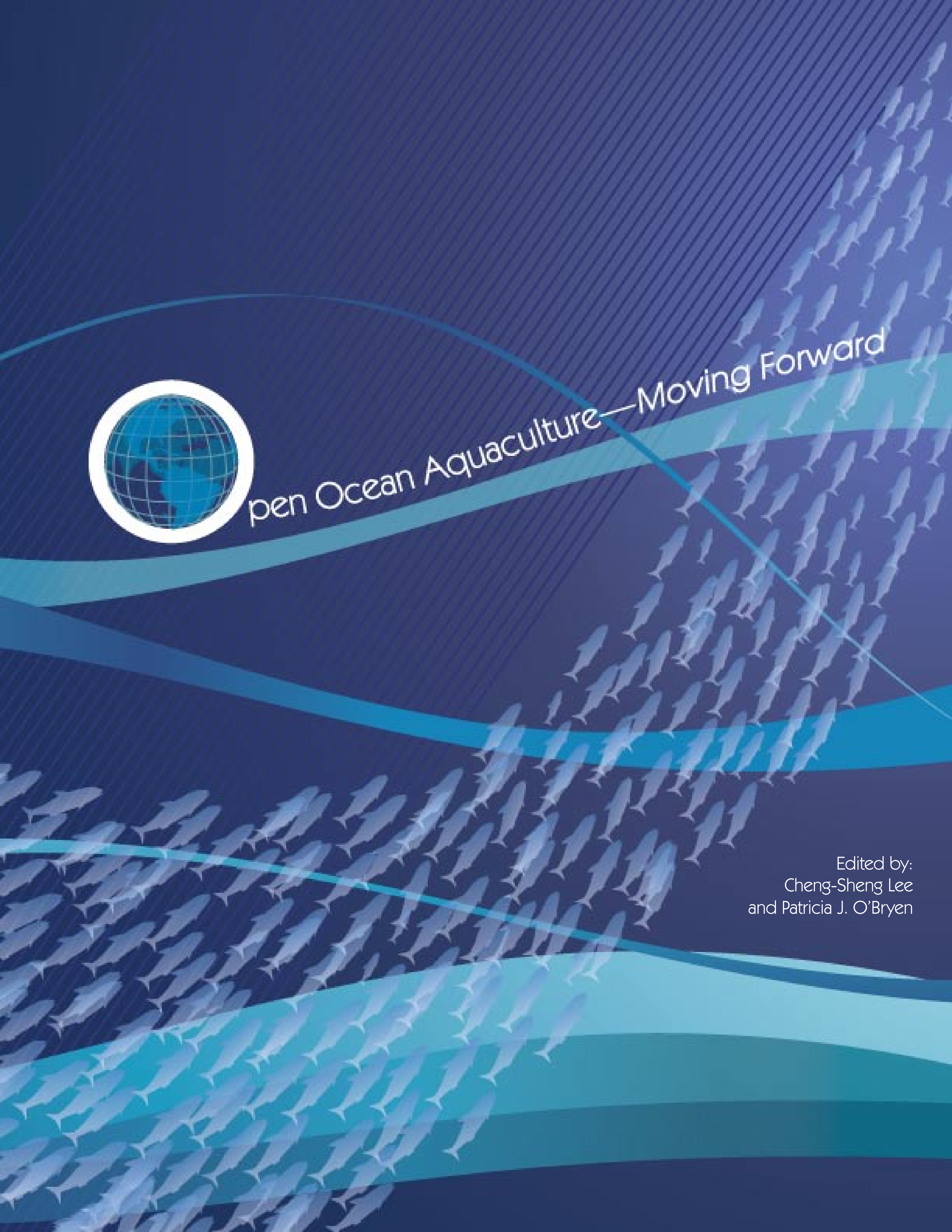

Open Ocean Aquaculture—Moving Forward

Edited by:
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Published by:

Oceanic Institute
An Affiliate of Hawai`i Pacific University

Oceanic Institute
41-202 Kalanianaole Hwy.
Waimanalo, HI, 96795

Preface

A workshop, "Open Ocean Aquaculture—Moving Forward," organized by the Aquaculture Interchange Program (AIP), was held in Honolulu, Hawaii, October 23-25, 2006. The objective of this workshop was to review and assemble information on operating open ocean aquaculture in various parts of the world and to develop a strategy for moving forward with the concept while maintaining current environmental conditions. In particular, every effort was made to avoid going over the same topics and issues covered previously in other workshops and meetings on offshore (open ocean) aquaculture. For faster dissemination of the information gathered at this workshop, it is posted on the Internet.

The invited international experts gave presentations at the workshop and discussed the business aspects of commercial-scale open ocean aquaculture, the environmental parameters to be monitored, the effectiveness of various monitoring tools, and the next steps for meeting the challenges to managing aquaculture in the open ocean. This report consists of extended abstracts of the papers presented, a summary of the discussion sessions, research needs, and suggested strategies for moving open ocean aquaculture to the next level. I thank the invited speakers for their contributions. I would also like to thank the Office of Oceanic and Atmospheric Research (OAR) of the National Oceanic and Atmospheric Administration (NOAA, Grant #NA05OAR4171169) for its funding support of AIP at the Oceanic Institute, Hawaii, which made it possible to conduct this workshop and publish this report.

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Contents

The Role of Offshore Aquaculture in Ecosystem-Based Approaches to Coastal Management

1

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The National Oceanic and Atmospheric Administration (NOAA) National Sea Grant College Program has been funding marine aquaculture projects since the inception of the program in 1968. Early funding emphasis was on disciplinary studies such as nutrition, pathology, genetics, systems engineering, and life history studies of promising candidate species for aquaculture. In the early 1990s, additional focus was placed on developing production systems that had the best potential for application in the environmentally conscious United States. These aquaculture technologies included recirculation system technologies, offshore aquaculture, and marine fisheries enhancement. Sea Grant funded several symposia on these subjects and proposed increases in funding through the NOAA budget process and this helped to further focus the research efforts for the NOAA based program.

The first Sea Grant sponsored workshop on the topic of offshore aquaculture was held at the University of New Hampshire in 1995. This time period coincided with the collapse of fisheries in northeastern United States. Fishermen and processors were desperate to find an alternative source of seafood. Because of the tremendous interest in the topic of offshore aquaculture, a second meeting on the promise and technology for offshore aquaculture was held in Hawaii in 1997. A third Sea Grant sponsored workshop was held in Texas in 1999 and a fourth was held in conjunction with Canada at St. Andrews, New Brunswick. All of these meetings were well attended by representatives from many nations from around the world.

NOAA Sea Grant began the National Marine Aquaculture Initiative in 1999 and this program has continued through 2006. In this 8-year period, NOAA Sea Grant has competed approximately $14 million of federal funds and funded a broad range of projects including a considerable portion of offshore aquaculture projects. Funding for the individual years of support varied, depending upon Congressional budget marks. The loss of funds in 2002, 2003, and 2005 caused NOAA to reduce or discontinue funding to projects that had already begun. This variability indicates the uncertainty of the national opinion about offshore aquaculture resulting in the reduced the level of effort for key industry technologies.

A progression of research topics through the years, with initial projects starting in 1999, focused on policy, regulatory, and environmental issues as well as life histories and technologies of new candidate species for marine aquaculture. In 2000, additional projects were added to expand the work on regulatory, policy, codes of practice, and Geographic Information Systems (GIS) issues. With the increase of funding in 2001 to $5.6 million, more than 20 projects were funded. The policy, regulatory, and environmental projects were continued and new projects on more species for culture, the use of alternative sources of protein meal, and demonstration of offshore and recirculation technology were begun. In 2002, funding was reduced by 60%, so ongoing projects were partially funded waiting for additional funds in 2003 to round out the projects. In 2003, all funds were lost for the program. All projects had to be terminated, with serious impacts on the end results of the research. In 2004, Congress provided only $700,000 for the program. NOAA called for projects to maintain the environmental monitoring studies on ongoing offshore projects. In 2005, all funds were lost again. In 2006, funding jumped to $4.6 million and it was decided to fund as many projects as possible for a full 2-year period from the 2006 funds rather than depending on year two funding from the 2007 budget. Thus, only 11 projects were funded in 2006; but if full funding was obtained for 2007 there would be additional projects started in that year. Table 1 provides a listing of projects for 2006.

Lead State	Principal Investigator	Affiliation	Project	2006-2007 Grant
California	Mark Drawbridge	Hubbs-SeaWorld Research Institute	Yellowtail as a Model for Marine Aquaculture	$505,553*
South Carolina	Craig Browdy	South Carolina Department of Natural Resources	Commercialization of Bait Shrimp Farming Based on Specific Pathogen-Free Stocks	$500,000*
Florida	Daniel Benetti	University of Miami	Demonstrating Technological and Economic Feasibility of Cobia	$400,000*
Hawaii	Charles Laidley	Oceanic Institute	Hawaii Offshore Aquaculture Research Project	$400,000*
North Carolina	Wade Watanabe	University of North Carolina Wilmington	Commercialization of Black Sea Bass	$400,000*
South Carolina	Theodore Smith	South Carolina Department of Natural Resources	Aquaculture Development and Fishery Enhancement of Cobia	$356,337
Washington	Daniel Cheney	Pacific Shellfish Institute	Alternative Shellfish Production Methods	$285,583
New Hampshire	George Nardi	GreatBay Aquaculture	New Technologies for Cod Culture	$248,952*
North Carolina	Craig Sullivan	North Carolina State University	Genome Mapping for Selective Breeding of Striped Bass	$202,578
Texas	Delbert Gatlin	Texas A&M University	Improved Diets for Warmwater and Coldwater Marine Fishes	$199,103
Florida	Larry Brand	University of Miami	Assessment of Environmental Impacts of Offshore Cage Culture	$150,000*

Table 1. NOAA-funded projects for 2006.

* Some project money to come from 2007 if available.

Despite the problems with funding for the program, a large number of marine aquaculture publications from the United States have appeared in statistics published by the Food and Agriculture Organization of the United Nations (FAO 2004). In 2004, the United States had 28 of the 97 publications representing the top 15 institutions in the category of marine aquaculture.

The impact of the research programs can also be seen in the establishment of new companies for offshore aquaculture and in the increase in seafood supplies. Two companies for marine fish production now exist in Hawaii and two more are in the permit process. In Puerto Rico, one company is producing cobia *(Rachycentron canadum)*, another just received the permits to begin operation, and another company is in the permit process. In New Hampshire, two companies have started up the production of blue mussels *(Mytilus edulis)* based upon the work of the New Hampshire offshore aquaculture project. In Hawaii, the production of moi *(Polydactylus sexfilis)* jumped from 0.91-1.37 metric tons (2,000-3,000 lbs.) per year to 15 metric tons per year as a result of the first offshore aquaculture company there. In Puerto Rico, the production of the single cobia farm of 5 metric tons equaled about 40% of the wild catch for that species in the southeast United States.

Even more importantly, the availability of moi and cobia in their respective regions invigorated the seafood supply line, providing communities with seafood supplies of top quality, traditional species. In Hawaii, farm-raised moi are served in many of the top tier restaurants. Visitors can enrich their vacations by trying a new fish representative of the locality.

Many countries around the world are moving toward the concepts of ecosystem based management. The new offshore aquaculture technology effectively opens up large areas of ocean to improve seafood supplies and to provide improved locations, ecologically, for the conduct of aquaculture. In terms of ecological function there are two types of aquaculture: extractive aquaculture, where the species being cultured serve to remove nutrients from the water (filter feeders and algae) and fed aquaculture, such as fish and shrimp, in which nutrients are added in the form of feeds. Coastal managers make use of this knowledge to consider aquaculture within models for improving ecological balance.

Addition of nutrients can be beneficial or detrimental, depending upon amount and location. Biological communities depend upon nutrients and they adapt to different levels of nutrients. Higher nitrogen levels lead to higher processing rates for nitrogen (Livingstone 2000). Carrying capacity for nutrients depends upon the combination of physical, chemical and biological factors. Offshore locations, because of their stronger currents, greater depths, and better mixing, have a greater carrying capacity for nutrients. Nutrients in offshore locations can stimulate fisheries. This can be seen in areas of upwelling of nutrients off of Peru, the U.S. Pacific Coast, and other locations where there are productive fisheries. NOAA based research has shown that natural biological communities in offshore locations quickly adapt to additional nutrients and fish and invertebrate communities increase as long as the nutrient does not cause negative effects on physical factors such as low dissolved oxygen or a build up of sulfides in sediments to unhealthy levels. All locations have a carrying capacity for nutrients. Five fed aquaculture farms may be acceptable but ten farms may be too many. This can be determined through experience and constant monitoring of environmental conditions. Research is being funded by NOAA on determining which environmental factors are the best indicators.

The development of management models for coastal ecosystems depends upon knowledge of the ecological roles of the biological communities, both wild and those represented by aquaculture.

This information must be coupled with additional data on the inputs of nitrogen from human sources such as agricultural run off, aquaculture, domestic waste treatment plants, and atmospheric deposition. It is also necessary to know the removal rates of nitrogen as a result of biological activity.

Several studies have provided some estimates of the removal rates of nitrogen for different biological communities. Production of seaweeds and animals compliment one another (Chopin 2002). The 4.8 million tons of marine algae produced annually by China removes 60-100,000 tons of nitrogen upon harvest (Fei 1998). One type of seaweed, Porphyra (nori), responds to higher levels of phosphorus and nitrogen in the environment by absorbing more (Fei 1998). Individual bivalves, which filter particles including phytoplankton, detritus, silt, and clay, can filter 1 to 4 L per individual per hour (Jorgensen 1966). Quahog clams were estimated by Rice (2001) to filter 21% of the tidal volume of the Providence River in Rhode Island, United States, on each tide, thus increasing light penetration. Hard clams excrete about 9 mg NH_3 per kg of soft tissue per day, but for every kg of shellfish meat harvested, about 16 g of nitrogen are removed (Rice 1999). This knowledge allows modeling.

NOAA maintains technical exchange programs with international partners:

- United States/Japan Cooperative Program in Natural Resources (UJNR) Aquaculture Panel
- United States/China Living Marine Resources Joint Coordination Panel
- United States/Korea Joint Coordination Panel, Aquaculture Sub Panel

These programs have been long term, and they provide U.S. researchers and those from the participating countries with an opportunity to exchange information on aquaculture science and technology of mutual interest. Activities include scientific symposia, exchange of scientists between countries, training of students in a broad range of topics, literature exchange, and development of web pages concerning the activities of the exchange programs. These web pages can be found on the web through the NOAA Central Library.

Discussions with NOAA's international partners have shown that they are also moving toward ecosystem based management for aquaculture. This universal move to looking at coastal ecosystems in a more holistic way prompted NOAA to bring its international partners to Hawaii in April of 2005 to discuss the role of offshore aquaculture in integrated coastal and ocean management. Representatives from Canada, China, Japan, Korea, the United States, and Vietnam presented country scenarios for ecosystem based coastal aquaculture, and were joined by participants from other countries and international organizations to discuss the dramatic effect offshore aquaculture is having on the management of coastal zones. China is rezoning some bays to move fed aquaculture activities offshore while employing filter feeders and macroalgae at appropriate levels to improve water quality. The European Union is using GIS based models to help place offshore aquaculture in proper context with other coastal uses. Canada is testing multi-trophic marine aquaculture or polyculture to minimize environmental impacts. The United Nations Development Programme has asked for assessment of aquaculture and fisheries in the Yellow Sea and the draft copy includes offshore technologies and ecosystem based management. South Korea has put a moratorium on nearshore and onshore aquaculture pending legislation that will facilitate offshore technologies. NOAA is supporting coastal ecosystem models incorporating GIS, benthic impacts, feed characteristics, and hydrography to predict impact of offshore aquaculture facilities. NOAA is also proposing a major study on coastal management that includes offshore technologies.

Possible benefits of offshore aquaculture technology include the following:

- Allows placement of ecological function at appropriate locations in coastal waters.
- Allows fishery managers to set different quotas for wild stocks for recovering fisheries and ecosystems.
- Allows alternative sources of seafood products when National Marine Protected Areas are created.
- Allows market planning and timing for selected seafood products thus contributing to expanded markets.
- Provides commercial quantities of popular species that are not available in the retail or wholesale markets today.
- Provides alternative source of tropical reef species that cannot be harvested commercially (contributes to coral reef community stability).
- Provides a larger scale of production to meet expected market demands.
- Opens up true open ocean/offshore areas for aquaculture, allowing countries and coastal managers to optimize the value of ocean resources while preserving ecological sustainability.

It is widely acknowledged that fish supplies from traditional capture fisheries are unlikely to increase substantially and that projected shortfalls in fish supply will probably be met mainly from expansion within the aquaculture sector (FAO 1997).

Recent statistics published by the Food and Agriculture Organization of the United Nations (FAO 2006) indicate that world aquaculture is now contributing 45.5 million metric tons (43%) of fish consumed. The actual amount of edible fish from wild fisheries is about 60 million metric tons. Aquaculture production is nearing that of wild fisheries. To supply world seafood protein demand, world seafood production is predicted to add 40 million metric tons by 2030, based on present per capita consumption.

In the opinion of this author, the development of offshore aquaculture is a revolutionary technology that begins to open up open ocean locations for aquaculture and expansion of seafood supplies. The more dynamic conditions of the offshore environment provide a better carrying capacity for the processing of nutrients, and this factor makes the open ocean a more appropriate location for fed aquaculture activities. Inshore locations are better for extractive forms of aquaculture that can process and balance nutrients coming in from human sources. Acceptance is growing for the concept of using the natural ecological functions of cultured species to place ecological function in the ecosystem that can lead to improving water quality and overall ecosystem health.

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2

Offshore Aquaculture in the United States: Opportunities and Challenges

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The U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), is focused on creating domestic seafood supply to meet the growing demand for all seafood products. Currently, over 70% of the seafood Americans consume is imported, and at least 40% of those imports are farmed seafood. Domestic aquaculture can be an effective option to reduce dependence on seafood imports, provide jobs for economically depressed coastal communities, and increase regional food supply and security. As it develops, offshore aquaculture will be one component of the broader NOAA Aquaculture Program, which currently addresses coastal and onshore marine shellfish and finfish farming. NOAA's Aquaculture Program also includes stock enhancement research and hatchery activities that support commercial and recreational fishing, endangered species restoration, and habitat restoration.

Currently, there is not a regulatory process for permitting aquaculture in U.S. federal waters – that area which extends from the outer boundary of U.S. coastal states to the 200-mile (322 km) limit of the Exclusive Economic Zone. This regulatory uncertainty is widely acknowledged as the major barrier to the development of offshore aquaculture in the United States. To solve the problem, the federal government, as part of the Administration's U.S. Ocean Action Plan, proposed legislation to establish a regulatory structure for offshore aquaculture in the United States. The National Offshore Aquaculture Act of 2005 (Act), which was introduced in the U.S. Senate in June 2005 as § S. 1195, will facilitate the approval of marine aquaculture operations in federal waters where there is great potential for aquaculture production.

The Act provides for the development and implementation of strong environmental protection measures. Issue-specific details about the permit requirements for offshore aquaculture will be addressed in the regulatory design process once Congress enacts the proposed legislation. In drafting regulations, the U.S. federal government is likely to draw on industry best management practices, codes of conduct, and regulatory examples from U.S. states and other countries with experience in marine aquaculture. The regulatory design process will include stakeholder consultation and a strong role for industry, states, coastal communities, fishery management councils, and conservation organizations.

One area of particular concern of resource managers is the risk of spread of infectious diseases from farmed animals to wild animals. Information was provided in the presentation on how this issue will be addressed by NOAA in cooperation with its federal partners.

3

History, Current Status, and the Future of Open Ocean Aquaculture Permitting and Leasing in Hawaii

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It is a necessary conclusion that ultimately the scientific insights into the impacts of open ocean aquaculture must be turned into policies, laws, and regulations governing industry development. Hawaii established a state law in 1986 to allow leasing of state marine waters for aquaculture and ocean energy purposes. Due to legislature concerns, however, the final statute only had limited applicability for small research projects (Corbin and Young 1997). Hawaii amended its state law in 1999 to correct these problems and encourage large-scale commercial aquaculture use of offshore waters (Cates et al. 2001). A coalition of state, university, and private sector interests engaged the public and supported this far-reaching change in the state legislature because: hatchery technology for mass rearing of local species was available; growout technology suitable for local open ocean conditions was commercially available; a federally funded, large-scale demonstration of cage culture, gathering real data, was underway (Ostrowski et al. 2001); experienced ocean interests were ready to invest in commercial aquaculture projects; and there existed strong state and public support for aquaculture for economic development.

Ocean leasing authority is legally vested with the Hawaii Department of Land and Natural Resources (DLNR) that manages all state marine waters out to 4.83 km (3 miles). Chapter 190D, Hawaii Revised Statutes, Ocean and Submerged Lands Leasing, as amended, established as state policy that marine waters could be leased by DLNR for commercial aquaculture and it defined a process for permitting and leasing ocean space, which included the surface, water column, and substrate.

Three major permits are required by an offshore aquaculture project in Hawaii marine waters, two from the State and one from the Federal government (DOA and DLNR 2006). The Conservation District Use Permit (CDUP) from DLNR is a conditioned permit that describes the conditions of use of the ocean resource including: species, operational parameters, degree of exclusivity, location and site layout, emergency response considerations, and management plans. The application requires an Environmental Assessment be carried out. The National Pollution Discharge Elimination System/Zone of Mixing Permits (NPDES/ZOM), issued by the State Department of Health, govern discharges from cage aquaculture facilities and they create an approved area around the facility where the state receiving water standards can be legally exceeded. Extensive water quality and substrate monitoring is required as a condition of the permit. In the United States, there is also exemption from these discharge permits for facilities producing less than 45,454 kg per year.

The Federal permit is issued by the U.S. Army Corps of Engineers (USACE), a national agency in charge of very large-scale water control projects. Inclusive in USACE authority is issuing a Section 10 Permit required of structures placed in navigable waters of the United States. The process for receiving this permit includes consultations with appropriate agencies on protected species, sensitive habitat, and coastal developments.

Once all the permits are received, the DLNR can issue a long-term lease for the proposed ocean site. The complex lease document includes key provisions, such as term (15 to 20 years), rent (fixed cost per acre [0.4 ha] or 1% to 1-1/2% of gross sales), a performance bond to address project removal, and ability to assign the lease to another party. Importantly, the DLNR can direct lease to the applicant for aquaculture, without the need for a public auction.

Hawaii currently has two operating commercial open ocean projects, Cates International, growing the Pacific threadfin *(Polydactylus sexfilis)*, and Kona Blue Water Farms, growing the greater amberjack *(Seriola rivoliana)*. Three more projects are pending, focusing on the Pacific threadfin, greater amberjack, and yellow fin tuna *(Thunnus albacares)* (DOA and DLNR 2006).

The Hawaii permitting and leasing process is accepted by government and the public because it involved knowledgeable and respected entrepreneurs, it required an Environmental Assessment, full disclosure on applications, and extensive community outreach, it was a transparent process and open to the public, and it used an adaptive learning approach to difficult environmental impact issues. It was also crucial that important issues, i.e., exclusive use, multiple use conflicts, native species, performance bond for project removal, and reasonable terms and rates to encourage investment, were addressed up front in the process. In the future, the state hopes to improve the site selection process through use of a computerized, interactive Geographic Information System to map and select sites (Young et al. 2003).

Based on experience to date, Hawaii's goals for open ocean aquaculture development are 10 successful commercial farms in 10 years, generating $100 M in sales annually. The major challenges going forward are: new species availability and large-scale hatchery technology for all species, accessibility to support infrastructure in harbors, the complexity of the permitting and leasing process, the high initial project costs, and the marketing of large volumes of product per harvest (DOA and DLNR 2005).

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4

Farming Deep, but Aiming High. Economic Incentives and Ecological Imperatives in Open Ocean Fish Farming

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Offshore fish farms are highly capital intensive, and operational expenditures are inherently greater than for conventional inshore cage culture systems. Research and development costs offshore are exorbitant, and the risks to investment are very real, and uninsurable. To attract investment, recapture these higher costs, and return an appropriate profit, open ocean ventures must look to a willingness on the part of the consumer to pay a premium for open ocean grown products.

Stronger consumer acceptance and higher price points, however, can be achieved only if open ocean aquaculture comes to be widely perceived as environmentally sound, healthful, and sustainable in the generational sense. This therefore creates a direct link between economic incentives and ecological imperatives in the nascent offshore fish farm industry. It is no longer enough to simply be out in deep water. Open ocean aquaculturists must be seen to be holding themselves to higher environmental standards.

These principles and their corollaries are examined using Kona Blue as an example. The company's branding efforts have successfully highlighted the appealing attributes of Kona Kampachi™ and its offshore farm operations. There has been a strongly positive response from conservation interests, the local community, and consumers to the company's emphases on transparency, ongoing improvement in its practices, and informed, open discussion of the issues.

The major environmental concerns with open ocean aquaculture were identified in the presentation. These include impacts of surface operations on the view plane, privatization of ocean space, long-term sustainability of fish meal and fish oil supplies, the potential impact of escapees on wild stocks, disease transference and the effects of therapeutants, nutrient enrichment effects on water quality and the surrounding ecosystem, depletion of wild stocks from collection of fingerlings for ranching, rational and compassionate management of predators, and the wholesomeness and healthfulness of the product. The validity of each of these concerns was examined. Rather than refuting these issues, or dismissing their potential impacts, it was suggested that these concerns be addressed in an open, rational discussion. Kona Blue's experience in the strongly eco-centric community of Kona, Hawaii indicates that misperception and misinformation are often the greatest enemies. Honest, objective analyses help to allay misplaced or unfounded fears.

Kona Blue's approaches to resolving these issues were discussed. Some cannot be immediately resolved, but are instead best addressed through incremental, ongoing refinement of practices in the hatchery or offshore. More aggressive approaches are needed for other problems. Research priorities were identified.

Integrated Offshore Aquaculture for Industrialization in Korea

5

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Due to the high demand for live fish, Korea already retains an advanced infrastructure for production and transportation for live fish consumption. With its considerable production costs, however, as well as prevalent consumer anxiety relating to environmental pollution and diseases, the conventional (inshore) aquaculture method has been proven to be inefficient from a commercial point of view.

Since the inception of Noah Net Technologies' offshore aquaculture venture in Korea two years ago, great progress has been made in establishing a business model to implement the offshore aquaculture technology in the aquaculture industry. For starters, the technology has proven to be very effective for withstanding typhoons and red tides, yet there are many aspects that still need improvement to successfully implement offshore aquaculture technology. The following are all issues that need to be addressed for such success:

- Improve the auto-feeding and mooring systems to withstand rough sea conditions and harvesting and logistic technology for live fish.
- Develop a cage that will submerge to a depth that is more ecologically stable. It would also be helpful to be able to increase the size and capacity of the cage.
- Develop a technology and species to polyculture by using thermocline for a double layer cage that submerges 10-30 m.
- Develop a comprehensive real time monitoring technology that will integrate monitoring of fish and their environment.
- Develop a feed technology that will be highly effective against diseases and that will increase the immune system of the fish against various diseases.

Through collaboration with other research labs, Noah Net Technologies would like to determine an appropriate feed formula for its offshore site based on its biomass. The company is also seeking useful industrial data relating to the above mentioned issues with cages, offshore equipment manufacturers, and ocean engineering companies to develop more productive operations.

6

Development of Offshore Aquaculture in Europe

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More that 30% of Ireland's farmed salmon production comes from Class 3 offshore sites. In northern Europe, Irish salmon farmers have pioneered finfish production in these sites, with a wave height of 1 – 2 m and moderate exposure to the full rigors of the North Atlantic Ocean's winter weather. The experience, gathered over 30 years of operating in this harsh environment, has led to developments in cage design, feeding technology, and husbandry practice. More recently, offshore cage farming has developed in the Mediterranean, where the culture of sea bass, sea bream, and bluefin tuna occurs in offshore sites in a number of countries.

Key issues in terms of wear and tear on equipment, the loss of feeding days, with consequent loss of production and workdays due to bad weather and the increased costs of operating offshore were documented in the presentation. These issues were set in the context of the benefits in terms of environmental stability, greater carrying capacities, and the perception of better fish rearing conditions.

The offshore environment has potential for increased biomass productivity with fewer user conflicts. Finding solutions to balance the difficulties of increased capital costs and other operating challenges is the key to ensuring that the offshore environment is utilized as a productive aquaculture zone in a sustainable fashion.

The further development of offshore aquaculture in Ireland, and worldwide, is conditional on the development of equipment and methodologies designed specifically for the offshore environment. European initiatives to promote the development of appropriate offshore technologies and systems include post-doctoral studies on offshore technologies, establishment of the International Council for Offshore Aquaculture Development (ICOAD), and promotion of the Offshore Aquaculture through a Technology Platform (OATP).

A post-doctoral programme on the development of offshore aquaculture technologies is funded by the Marine Institute (Galway, Ireland). The initial findings of these studies is that there is substantial development interest in new cage types capable of withstanding forces of waves and wind in the offshore environment. Trials are currently underway for many of these. The current focus of attention is on auxiliary systems used in offshore aquaculture in high energy sites. These include sensor systems, feeding systems, control systems, communications systems, and cleaning systems.

Ireland has recognized the opportunity that offshore aquaculture presents and has taken a course of action to identify and investigate potential offshore sites. This action was also a key recommendation of the 2004 Farming the Deep Blue Conference held in Limerick. These short-listed sites will be ready-to-go and investment is to be sought for their development. Key to this activity is also the requirement to be able to tap into international experts, be they in cage manufacture, wave dynamics, or international finance. To further this aspiration and another key recommendation that international alliances be built to forward this aim, the ICOAD is registered in Ireland with a permanent Secretariat drawn from the Irish membership. The intention is to seek membership for ICOAD in a global context and then look to generate alliances which can form regional nodes. ICOAD can serve as an international focal point for the development of offshore aquaculture and will aim to seek to accelerate and galvanize the process through coordination and the provision of information exchange, communication, and collaboration.

ICOAD exists as an internationally based council comprising individuals, companies, and institutions with an interest in developing offshore aquaculture. Its mission statement reads as follows:

> ICOAD will promote and facilitate, through all means possible, the development of suitable technologies and methodologies for successful aquaculture operations in the offshore zone. The ultimate aim is the creation of a major offshore aquaculture industry, which produces a significant proportion of the total world fish requirements in an economically and environmentally sound manner.

Drawn initially from experts brought together during the Farming the Deep Blue Conference, ICOAD is open to anybody or any organization interested in the Council's purpose. ICOAD is established as a center of expertise and is proposed to act as a funding facilitator in an information sharing environment. It is participant centered and will allow partnership, collaboration, cooperation, and synergy between participants. It is envisaged that seven regional executive committees will oversee global activity, while an international executive committee drawn from the regional executive will provide steerage to the regional committees. ICOAD sub-structures, communities of practice, and access levels will be determined as the Council evolves.

The objective of the Offshore Aquaculture through a Technology Platform (OATP) is, "To investigate the opportunity and usefulness for the aquaculture industry of promoting offshore aquaculture through a technological platform." The general methodology of the approach is to form a consortium of service providers, manufacturers, aquaculture practitioners with offshore experience, research and development organizations and agencies from the sector that will pool the available knowledge and experience by the most efficient and practical methods available. The goal is to ensure that the stated objective above is addressed accurately, comprehensively, and efficiently. This will be achieved by:

- A survey by way of a bespoke questionnaire, administered by direct interview. The survey is to cover all members of the consortium and additional stakeholders in the E.U./European Free Trade Association (EFTA) region.
- Informal seminars in key regions to identify key areas for future discussions.
- An interim report for circulation in advance of international workshop.
- International Workshop over two days for partners and stakeholders.
- A final report, with recommendations and a roadmap of the way forward. The report is to reflect the proceedings of the workshop and the views of the partners on the functions of a technology platform in achieving the goals set out above.

The main objective of this proposal is to investigate the opportunity and the usefulness for the aquaculture industry of promoting offshore aquaculture through a technology platform. In the course of carrying out a thorough evaluation, the project will achieve a number of clearly defined goals, which will of themselves have a measurable impact beyond the achievement of the stated objective of the project. These impacts will include the following:

- Develop a widely based consensus on Research and Technological Development and Innovation (RDTI) priorities in the Offshore Aquaculture sector. This will inform strategic planning at various levels including E.U. National and corporate. Feedback will be efficient, thorough, and immediate through the gateway of the participants and partners in the project.
- Raise the overall investment in the offshore aquaculture development sector (in terms of E.U., Member States, private funding, and venture capital) by showing a common vision of the potential and the intermediate steps required to achieve it.
- Strengthen networks and encourage the development of clusters and centers of excellence. In particular, the facilitation of cluster development between public and private organizations and across disciplines in this sector, which is very much in an early development phase and is as yet quite fragmented in nature, will be of critical benefit to realizing future potential.
- Identify, and objectively catalogue, areas of current strengths and weakness, and gap areas where there is a lack of capability or expertise within the European Research Area.
- Assist at a regional level in identifying and addressing challenges and in particular opportunities in this developing sector.
- Identify and catalogue the prerequisites for development of a consistent and coherent policy and regulatory framework for offshore Aquaculture in the E.U. and the European Economic Area (comprising 25 Member States and members of the EFTA).
- An increase in public awareness, understanding and acceptance of the technologies concerned and the benefits accruing to the wider public through their appropriate deployment.

7

The International Perspective of the Exclusive Economic Zone (EEZ)

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The Exclusive Economic Zone (EEZ), as recognized by the Law of the Sea, is a zone over which a country or state has special rights for better control over its maritime affairs. The Zone, in most cases, extends for 200 nautical miles (370 km) beyond the territorial waters of the country or state, which may be between 3 and 12 nautical miles from the coastline.

In 1930, the principle of the "freedom of the seas" defeated a conference of the League of Nations to extend national claims for protecting shore-side resources. In 1945, however, the United States extended its control unilaterally to cover all the natural resources of its continental shelf which extended to about 200 nautical miles, and within five years it was joined by the four nations on the western seaboard of South America to enable them, through the Santiago Declaration, to get control over the fisheries resources of the Humboldt Current. Within the next 20 years, about 66% of the nations had established territorial waters to 12 nautical miles, and 8% to 200 miles. Some 25% continued with the old 3 nautical miles.

Between 1956 and 1967, there were United Nations Conferences that tried to propose and establish a Law of the Sea. The first Conference at Geneva resulted in four treaties or conventions, although the breadth of the proposed territorial waters was not decided. The second, also at Geneva, failed to result in any international agreements, but a third initiated a conventional force that took 15 years to mature.

The Third Convention finally got underway in New York in 1973 and lasted until 1982. It defined limits for five baseline areas, namely:

- Internal waters, which the nation has all rights to use and to which no foreign vessels have rights,
- Territorial waters, which extend to 12 nautical miles with the coastal state free to set laws, regulate any use, and use any resource,
- Contiguous zone, 12 nautical miles beyond the territorial waters where laws can still be enforced,
- Exclusive economic zone, which extends for 200 nautical miles from the baseline, and provides the coastal nation with sole exploitation rights, and
- Archipelagic waters, which are both territorial waters and an exclusive economic zone that can be identified as part of a state's territory and territorial waters.

In this paper, the maritime affairs are confined to the exploration and permitted use of the fisheries resources and fish production within the EEZ of a country. This includes any economic, social, and environmental benefits. Despite the potential simplicity, however, of defining the EEZ of a nation or state, with or without any agreements with neighbors, the exact extent of an EEZ and its marine resources are a common source of conflict between them.

On the other hand, the interest of the international organizations is predominantly environmental, rather than economic or social. For example, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has had risk assessment of marine aquaculture as one of its priorities. Both the International Council for the Exploration of the Seas (ICES) and the North Pacific Marine Science Organization (PICES) have working groups on aspects of marine aquaculture, most of which are environmental or ecological. International delegates to the 2004 FAO/Committee on Fisheries, Sub-committee on Aquaculture identified the preparation of guidelines for the ecological risk assessment of offshore aquaculture as a priority for members. The guidelines were published by Nash et al. (2005).

The Open Ocean or Non-Tidal Waters

Offshore waters and their living and non-living resources are owned by their respective coastal nation. Consequently, the coastal nation has to have control and management of their use. Coastal nations, however, may differ in their recognition of these resources.

Countries license individual fishing groups and register vessels to harvest natural and enhanced resources from public waters. Natural and enhanced resources include fish, crustaceans, mollusks, and seaweeds. In sum, the natural harvesting or stock recovery is paid by the private sector, and enhancement is paid for by the government at the appropriate level. The catching technology is then determined by the zoning of the habitat.

Marine Fishing

Governance is fundamental to fisheries, because it determines the manner to which power and influence are exercised over the management. Institutions also play a range of roles in fisheries governance and they affect whether or not fisheries can continue to provide economic, food security, and livelihood benefits.

Economic contributions of industrial-scale fisheries are visible and include exports and revenues from licensing. In contrast, the economic importance of a small-scale fishery may only be recognized if it collapses and the resulting costs of food substitution and unemployment are felt. Developing countries face decisions about how best to realize the potential of all their fisheries. For example, do they develop their own fishing industry, or allow foreign fleets to exploit their resources? Do they prioritize resource rent from industrial fisheries, or the socioeconomic benefits of smaller-scale fisheries? Competing demands for resources and access can lead to conflicts and overexploitation of fisheries, with negative impacts on food security. Management of fisheries that ensures their sustainability is essential to maintain their contributions to food security.

In a summary of papers by the Fisheries Management Science Programme (2005), fishing can be a full time engagement, a part of a mixed fishing-farming livestock, or a seasonal fall-back. Although fishers are often poor, the cash income generated by the sale of the fish can give them access to basic goods and services such as education, health, and other assets. Fisheries can reduce economic and food vulnerability, but they are themselves vulnerable to external influences such as environmental degradation and climate change. To implement effective management, decision makers have to recognize the roles and importance of fisheries to livelihoods, and ensure fisheries are sustainable.

Fisheries systems are therefore complex and dynamic, and fisheries management institutions must take account of a range of information types, as well as changing policy priorities in the sector. Many institutions, however, face severe human and financial constraints and there is a great need for capacity development and improved governance, particularly in developing countries.

Marine Ranching

Marine ranching is the licensing of individuals and groups to plant, manage, and harvest resources from public waters in which they have been raised, released, and subsequently recovered. The private sector pays for all activities and assumes all the risks.

Implementing an effective marine ranching program requires not only the regular release of numbers of aquatic animals and plants but also actions that take into account their biological, ecological, and genetic needs (Bartley 2002). These actions may be the creation of artificial habitats, improvement of coastal areas, and even removal of predators. They may also include releasing fish trained to respond to specific feeds and remain in one area. On the other hand, an effective marine ranching program can increase employment in the local industry and create an efficient production activity.

Of course, in the short term, the national or regional planning of marine ranching programs requires more research information on the economic, environmental, and social effects. Research strategies may include, among many others, studies on the effects of carrying capacity and stock densities that can impact survival and growth; the composition and diversity as a result of release density and exposure; and studies on genetic interactions between sea-ranching strains and local stocks. In the long term, the strategies are specific for the studies of various species individually or in association, but they also include collections of background information to provide a valuable basis for future evaluations of the environmental and ecological effects of sea ranching.

The difficulties of undertaking the majority of discussions of sea ranching recognize undertaking activities which are certainly about the sea ranchers rights, and have a number of environmental and ecological considerations.

Marine ranching and hatchery production of early life stages of fish and shellfish are important management tools. For example, these may be to rebuild a fishery like the red sea bream (*Pagrus major*) fishery in Japan or the orange roughy (*Hoplostethus atlanticus*) in Australia; to maintain a fishery in the face of habitat degradation or loss like the sturgeon (*Acipenser* spp.) fishery in the Caspian Sea or flatfish in the North Sea; to increase the value of a fishery like the chum salmon (*Oncorhynchus keta*) enhancement in Japan; or to create new fisheries like the striped bass (*Morone saxatilis*) in western North America.

Marine Farming

Marine farming is the licensing of individuals and groups to plant, manage, and harvest a resource from private waters. Private waters are areas of public waters that can be identified and leased for private use that is designated and limited. The private sector also pays for all activities, and assumes all the risk.

The demands for more seafood in the marketplace are fuelled in part by the changing scenes in traditional marine capture fisheries and the onset of modern aquaculture, which began just over a century ago. For the most part, early aquaculture activities began as extensive systems in coastal ponds for subsistence, relying on little more than stock enhancement and transplants. These made some contributions, but there were no real advances until the 1940s and 1950s, when some modern semi-intensive and intensive systems were successful for marine fish with the raising of brine shrimp in the hatchery.

Current efforts in aquatic farming development have been increasingly progressive for many years, and have risen to an order of 35% – 45%. The diversity of the cultured species, however, has been very limited and certain production very biased. For example, in addition to the freshwater fish in Asian countries, the dominant species of fish (salmonids) are anadromous. The dominant marine species are prawns, shrimps, oysters, and clams – and not marine finfish species.

Apart from these early and successful practices, the costs of modern marine fish culture are distinctly high. A good aquaculture site is a balance of selected EEZ waters that are good to access, together with a land-based site to provide all the necessary services. These include, for example, the storage of resources, such as vessels, fuel, and feed ingredients, and operational investments, such as labor, food disposition, and energy. A minimum number of industrial subsidies is required, such as coastal rentals, or the exposure to a number of environmental risks, such as areas for pollution or grounds for schooling whales.

The long-term outlet for the production of seafood in the EEZ is encouraging, but there is no question that it requires a great deal of expensive effort because of the innumerable details and the logistics of movement and management. Nonetheless, many solutions have already been found. For example, utilizable offshore waters of the EEZ are greatly different from nearshore waters and they require monitoring of dissolved inorganic nutrients, total volatile solids, the redox potential, and soluble hydrogen sulfide. All four can be quickly measured on any day, and cheaply. In offshore waters, many technological solutions are now being found, including the increased reduction in the dealing with residual drugs and the overuse of feed.

Positive Development Themes

The environmental and ecological elements in the topic of Offshore Aquaculture are very important but need not dominate any workshop programs. The following is proposed as a list of topics for discussion:

- Concepts and species
- Legal and business issues
- Research and development
- Environmental and ecological risks
- International case studies

Concepts and Species

This section can be an introductory overview of what constitutes offshore aquaculture. It can include stock enhancement (e.g., harvest and grow out young fish, such as tuna) or it can be true culture from start to finish.

It is interesting to get the perspective of a representative of an international organization (e.g., the Food and Agriculture Organization of the United Nations, FAO), an imaginative fisheries manager, or fisheries scientist to conceptualize on how far offshore aquaculture might complement or compete with commercial fishing. The session could be extended further if the offshore concepts were divided into the views of both fishing and shell-fishing industries. This session can be a broad-ranging but strong opening lead to all discussion, which would then be followed sensibly by the legal and business issues.

Legal and Business Issues

The second section illustrates the legal rights of a business to operate and have protection offshore. There are the issues of the jurisdiction of immediate coastal waters and waters further offshore (vis-à-vis large countries like Australia, Canada, and the United States, all with powerful states and provinces), and the rights to have possession of species being farmed, which for commercial fishermen might be illegal and/or undersized, harvesting out of season, etc. – in other words, control by sets of laws that were framed for another industry altogether.

In Japan, Yokoyama (2003) established indicators as criteria for the Law to ensure sustainable aquaculture production, and MARAQUA in Europe (Read et al. 2001) described the processes adopted by partnerships when reviewing current practices in relation to licensing, regulations, and monitoring procedures.

Research and Development

Obviously, offshore aquaculture is still very much in embryo, and therefore, a great deal of research and development is taking place all over the world. This could be easily summarized, say, on a continental basis (Asia, Australasia, Europe and Scandinavia, and the United States), or on a marine basis (Atlantic, North and South Pacific, Mediterranean).

That being said, the research and development topic could be usefully divided into two areas: (a) biological engineering and (b) biology (species and husbandry).

Nonetheless, substantial progress has been made with the research and development of some marine fishes and their environments, and there are successful reports by Mazzola et al. (1999) for the western Mediterranean, by Angel et al. (2002) in the Red Sea, and by Karakassis (2001) in the Mediterranean. Similarly, there are encouraging reports on effluent conditions in papers by Nordvarg and Johansson (2002), Islam (2005), and Desa et al. (2005).

Environmental and Ecological Risks

Together with the Modelling-Ongrowing fish farm-Monitoring (MOM) papers (Ervik et al. 1997; Hansen et al. 2001), the collection summarized the findings of five topic groups established to analyze the scientific and socioeconomic basis of current environmental practice in marine aquaculture and it identified the key recommendations for the best environmental practices in relation to marine aquaculture.

Rogers and Greenaway (2005), for example, reviewed the suite of marine ecosystem indicators currently in use or under development in the U.K. to support the major national and international biodiversity and ecosystem policies. They criticized the lack of indicators for the pressure of human activities on the environment, or the socioeconomic response to the pressures.

An in-depth and realistic view of what might be the environmental risks of open ocean aquaculture would be useful. According to Nash et al. (2005), of the 10 principal risks, the two most important were increased organic and inorganic loading. Other risks of lesser importance were residual heavy metals, residual therapeutants, transmission of disease organisms, and interactions with wild fish populations following escape. Further down the list were two interactions with marine wildlife, and marine habitat. The lowest ranked risks were harvesting of juveniles for grow-out and the increased harvest of industrial fisheries for fish meal and fish oils for manufacturing feed, both of which were judged not to be aquaculture issues but fisheries managers' issues.

International Case Studies

The session can finish with international case studies given by individuals who have been trying to implement commercial offshore aquaculture, all the problems that they can identify, the good things, and their forecasted projections.

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Commercial Open Ocean Aquaculture Operations and Their Future Prospects

8

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Key questions that will determine the future prospects for open ocean aquaculture (OOA) are the attitude of government, the technology that is developed to enable development, and the market for seafood products.

In many ways, government attitude and regulation is the most critical of these, because governments have to allocate space in public waters for marine aquaculture to take place. Thus, there must be the political will to enable the industry to develop, which, in turn, requires acceptance by voters that it is a wise and necessary use of the resource. Such acceptance is not guaranteed and depends on a nation's economic imperatives. China, which is by far the leading aquaculture nation in the world, has clearly determined that aquaculture is an economic imperative. Chen (2006) pointed out that "cage fish farming" saves water, land, and energy. By contrast, in the United States, people have not yet accepted these benefits or that aquaculture is a wise or necessary use of the resource. In many cases, it is thought that floating aquaculture will get in the way of other activities that are considered more important. Moreover, OOA is not really necessary in the United States because the country can afford to import all the seafood it needs.

The future prospects for OOA in the United States are not good until or unless a way can be found to make the case more strongly favorable. There are three levels on which such a case can be presented:

1. *Focused:* Create new businesses in coastal communities that need and want economic development.
2. *Broad social and economic:* Provide more affordable seafood and reduce an $8 billion U.S. seafood trade deficit.
3. *Visionary:* Farm the sea as we farm the land, thereby using the vast ocean resource more effectively than is the case presently, thus relieving pressure on the land.

The visionary approach has not yet been given sufficient attention by the OOA industry or by its critics. Much criticism of OOA is based on a presumed lack of sustainability, and a longer term visionary goal puts such criticism in perspective. For example, it is expected that by 2030, the world population will increase from 6.0 billion to 8.3 billion; food calories consumed per person will increase from 2,800 kcal/yr to 3050 kcal/yr; and there will be a need for an additional 1 billion metric tons of cereal crops, requiring 120 million ha more farmland to grow them. The sources of land and freshwater required for such an expansion remain uncertain. Currently, 24% of the Earth's land is cultivated, and most of the rest is desert, ice, mountains, or cities. Top soil is eroding as deforestation takes place to clear more land for farming. The food supply is being further reduced by the increasing use of agricultural crops to produce biofuels. Aquifers are being depleted in China, India, and the United States.

It seems that the world and its people are set on a course that is unsustainable, with little to suggest a political will to do anything about it until the crisis strikes closer to home. Thus, the "Visionary" goal may present the strongest and most profound reason for the development of OOA because: (a) the oceans could offer a solution or serve as a relief valve; (b) current attempts to farm the oceans, albeit easy to criticize, could be the start of a change in ideas about ocean productivity and the Earth's capacity to support increasing human demands; and (c) development of a broad based marine agronomy could rescue humanity from its presently unsustainable trajectory.

Presently, capture fisheries produce less than 2% of total weight of the world's food, 6% of the protein, and about 16% of the animal protein. Notwithstanding that in some parts of the world, fisheries are essential for the nutritional wellbeing of local people their contribution to our food supply in general is modest. In fact, relative to the 68.6% of the world's surface covered by oceans, capture fisheries contributions could be considered wholly inadequate. In contrast to the land, where only about 24% is cultivatable, almost the entire ocean surface is potentially productive without the need for fresh water.

The idea that the oceans may one day be farmed to supply man's needs is not new, although no one has yet provided an answer. If the oceans are to be farmed like the land, production must be based on farming plants as the primary source of biomass, which may then be processed into value added products ranging from human food to industrial chemicals. Ideas on how this might be done include the following:

- Fertilizing ocean waters with iron (Fe), which is the limiting nutrient in many ocean areas. This would increase primary productivity and, in turn, secondary and tertiary production that could be harvested.
- Increasing nutrient levels by artificial upwelling of deep, nutrient rich ocean waters using wave actuated pumps or Ocean Thermal Energy Conversion (OTEC) systems.
- Farming of macrophytes (seaweeds) could be greatly expanded. Presently, there are almost 14 million mt of seaweed farmed globally each year in coastal waters, mostly in China and other Asian countries.
- Farming of floating seaweeds (e.g., *Sargassum* spp.) would eliminate the need for attachment structures and therefore be possible in deep ocean water. Some *Sargassum* species fix atmospheric nitrogen, thus reducing or eliminating the need to apply fertilizer.

In the same way as yesterday's family farms provided the basis for the development of modern agriculture, today's OOA farms should be seen as the first stages in a more intelligent use of the sea that will one day lead to a much larger and more broadly based marine agronomy. These pioneering new businesses provide the physical, commercial, and technological platforms on and around which future developments will occur.

9

AquaModel: Comprehensive Aquaculture Modeling Software

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AquaModel is a sophisticated, PC-based simulation program that provides data needed to evaluate the performance and ecological effects of proposed fish aquaculture farms. It is the first truly comprehensive model for net-pen aquaculture that simultaneously accounts for both water column and benthic effects. Interlinked submodels of fish physiology, hydrodynamics, water quality, solids dispersion, and assimilation were designed and preliminarily validated using field and laboratory data.

Decades of experience reveal a widespread confusion and misunderstanding of the effects of floating marine fish farms in the United States and elsewhere. The public, the news media, some government regulators, and even many scientists do not understand the basic principles of organic waste discharge and assimilation by marine food webs that permit well-sited fish farms to operate with little adverse effect and some marked positive effects on the aquatic ecosystem. AquaModel may also be used as a tool to graphically demonstrate how this occurs.

The system provides the user a 3-dimensional simulation of growth, metabolic activity of caged fish, associated flow and transformation of nutrients, oxygen, and particulate wastes in adjacent waters and sediments (Fig. 1). Often, other models deal only with benthic effects, run on mainframe computers and in sequential modules, do not allow the users to easily change key parameters, and do not allow interactive display of results for short and long time periods. In contrast, AquaModel runs on personal computers and describes benthic and water column effects concurrently. It has additional features not found in other models such as oxygen deficit plume modeling, sediment oxygen perturbation, phytoplankton stimulation, and zooplankton growth results from nutrient addition. A few options are shown in Figure 2.

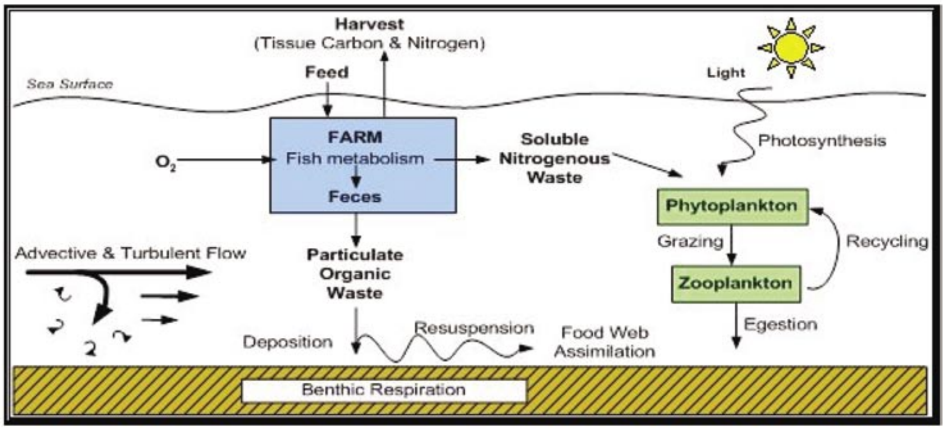
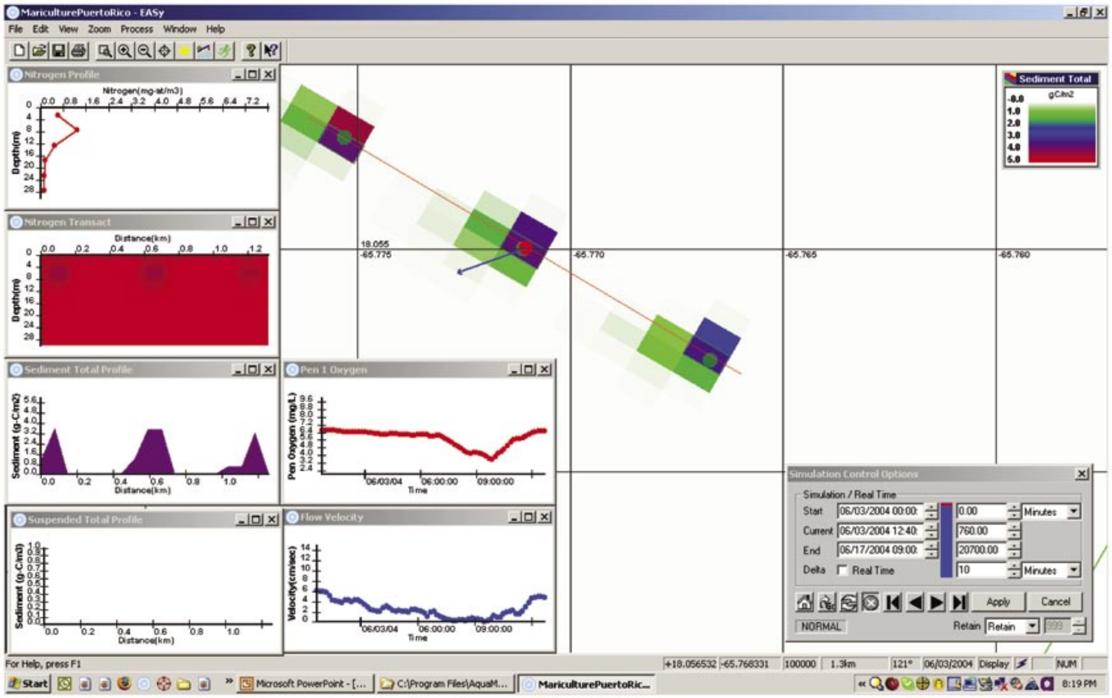


Figure 1. Overview schematic of AquaModel components and dynamics in the marine ecosystem.



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Current 06/03/2004 12:40: 760.00
End 06/17/2004 09:00: 20700.00
Delta ☐ Real Time 10 Minutes
NORMAL
Retain Retain 999
+18.056532 -65.768331 100000 1.3km 121° 06/03/2004 Display NUM

Figure 2. Example screen print of submerged fish farm model run, with main scene showing deposition state of carbon on the sea bottom near three fish farms of differing fish biomass. The dot in the center farm is to position a vertical profiling point, and the diagonal line is a horizontal transect line through all three farms. The X-Y plots show the results of the profile and transect from top to bottom, left to right: nitrogen profile, nitrogen transect, sediment carbon profile, suspended layer carbon profile, oxygen within the center cage, and relatively slow current velocity plot. The box in the lower right contains time step control options.

AquaModel uses Windows® PC operating systems, has drop down menus, uses data from a current meter, tidal cycle, or output from other hydrodynamic transport models, and it includes dozens of easily varied settings (e.g., fecal sinking rates, water temperature, feed rate, feed loss rate, etc.). It allows simulation of the effects of culture of a variety of fish species including salmonids and marine fishes. It resides within a 3-D Geographic Information System (GIS) program known as EASy[1] that was designed for oceanographic use and is compatible with other commonly used 2-dimensional GIS software. State data from user selected locations in the model runs can be exported to spreadsheets to evaluate compliance with sediment or water quality impact zone boundaries. The model allows the viewer to compute, visualize, and store data describing the distribution, transport, transformation, and assimilation of dissolved nutrients and carbon-containing solids. The user can also concurrently evaluate oxygen-deficit plumes, sediment oxygen content, phytoplankton nutrient uptake, and growth and resultant zooplankton grazing.

AquaModel provides a user-friendly means to expedite aquaculture planning and permitting as well as providing a guide to target monitoring over appropriate spatial extents. This comprehensive system supports administrators in evaluating proposed sites or performance standards, provides operators with data needed to obtain permits, and provides investors with information needed to assess risks and opportunities. It is also provides a basis of a future

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[1] For more information about AquaModel and links to EASy GIS software see *http://netviewer.usc.edu/aquamodel/index.html*

expanded systems for regional assessment of multiple farms. When it is equipped with real-time sensor input, it provides a means to optimize fish production, minimize impacts, and integrate shellfish and seaweed culture appropriately.

Physiological submodels for Atlantic salmon (*Salmo salar*) have been developed and preliminarily validated for relatively high velocity sites. A cobia (*Rachycentron canadum*) submodel for use in offshore waters of tropical areas has also been developed and data on other marine fish species are being collected. Extensive additional validation and tuning studies for several species are currently being planned, and the developers of the model and software are actively seeking tropical and temperate water fish farms to participate in cooperative monitoring, validation, and research.

10

Environmental Observations around Offshore Cages in Hawaii

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Concern for possible environmental damage constrains development of the aquaculture industry in the United States. Potential environmental interactions, including degradation of water quality, introduction of exotic species, pollution of the seafloor, adverse interaction with the seafloor benthic community, adverse interactions with protected species, and genetic interactions of potential escapees are all generally viewed as negative interactions, and thus are of substantial concern to the public and to regulators. Certainly, the culture of finfish in cages can be detrimental to the local water quality and the benthos beneath the cages when the fish are overfed or when too many production units are located in an area of limited carrying capacity or restricted circulation, as has been demonstrated by numerous published reports (see Black 2001 for a summary).

The focus of the Hawaii Open-ocean Aquaculture Research Program (HOARP) (Ostrowski and Helsley 2003) was to establish which, if any, of the above concerns are real in open circulation tropical conditions. Routine observations of water quality, health of the ecosystem outside the cages, interactions with protected species, and changes in the benthic assemblage were made to assess these potential impacts of open ocean aquaculture in tropical oceanic settings.

Observations over the past 6 years demonstrated that there was no measurable change to the water quality at the site. Observations of chlorophyll-a and turbidity suggest there was no important change in phytoplankton abundance near the cages, or that the change was so small that it could not be distinguished from the natural background variability.

The only change in the benthos was an increase in the abundance *Capetella capitata* and *Neanthes arenaceodentata*, known indicator species of organic enrichment. The increase in abundance of these two species, rarely observed in the oligotrophic sediments of the offshore, suppresses the abundance of the more common organisms that characterize the normal assemblage. This change in abundance provides evidence for a local species diversity change under the farm operational site. This change, however, was shown to be entirely reversible in time periods of less than a year of production, and thus it should not be considered to be a long-term detrimental impact.

Observations of environmental variables were made around a research site at the Cates International, Inc. offshore fish farm, about 3.22 km (2 miles) south of Ewa Beach, Oahu for the past 6 years. Initially, these were simply water quality measurements and assessment of changes in the micro-benthos beneath the cages and at control stations some 400 m up and down stream that were made as part of a set of proof-of-feasibility experiments. The research at the experimental site was transferred to the farm site in 2001 when the farm commenced operation.

Technically, these are two separate observational series, but because the water quality and benthos studies have continued at the CII farm site a few hundred meters from the initial research site using the same methodology, for the purposes of this paper, they are treated as one set of observations. Episodic sediment trap studies of the flux of particulate material emanating from the cages were added in an attempt to elucidate more clearly the causes of the changes that were observed in the micro-benthos beneath the cages.

The initial focus on water quality was because this was the item of most concern in the public hearings held during the initial development of the farm. All of the parameters required by the Hawaii Department of Health for discharge into public marine waters were measured. These constituents were measured near the cage and at progressively greater distances from the cage out to distances of 1 km. Table 1 provides a synopsis of the observations made during this work and includes both near cage and far-field measurements. The only parameter that was observed to vary outside the bounds of normal variation of marine offshore waters in Hawaii was the concentration of the ammonium ion (NH_4^+).

Table 1. Water quality observations relative to specific criteria

Parameter	Water quality requirement		Observations[a]
	Geometric mean not to exceed the value below	Maximum not to be exceeded more than 10% of the time	Maximum value observed and Number of occurrences ( )
Total Nitrogen (µg N/L)	150	250	>150 to 250 (2)
Ammonia Nitrogen (µg NH_4/L)	3.5	8.5	>8.5 to 69 (9) >3.5 <8.5 (32)
Nitrate + nitrite N µg (NO_3 +NO_2)/L	5	14	Always <5
Total Phosphorus (µg P/L)	20	40	>20 <31 (1) >40 (0)
pH: 8.2 ± 0.05; Temperature: ± 0.5 C from ambient; Salinity: 35 ± 0.5; DO:[b] >80%			

Note: Based on Hawaii Administrative Rules, Title 11, Department of Health, Chapter 24, Water Quality Standards.

[a] Total number of observations: 373.

[b] DO, Dissolved oxygen.

Initially, the water quality observation program focused on changes both in the cage and just outside the cage. The NH_4^+ concentration rapidly declined to that of background seawater. It was assumed during these early observations that this was due to the lack of adequate biomass in the cages to provide a signal that was above background. As the farm grew in size and the resident biomass increased to more than 50,000 kg, with feeding rates up to 2000 kg/day, an intensive effort to examine the NH_4^+ discharge plume downstream of the cages was initiated, but the plume was unobservable beyond a few hundred meters. The mixing due to turbulence downstream of the cage (see Helsley and Kim 2005) was deemed sufficiently large to preclude observation of elevated NH_4^+ at distance. Thus, after three years of observation, research water quality measurements were suspended, because no readings higher than the ambient ocean values were observed at distances greater than 200 m from the cage. Measurements just outside the cage did show elevated NH_4^+ concentrations a few hours after feeding that rapidly decreased to ambient levels as distance from the cage increased.

To satisfy the National Pollution Discharge Elimination System (NPDES) monitoring requirements, however, water quality measurements continue to be made regularly by the farm operator at sites near the cages and on a quarterly basis at the boundary of the NPDES zone of mixing. No values exceeding the water quality standards have been observed at the zone of mixing boundary. The seafloor under the cages was photographed, videotaped, or both at approximately monthly intervals throughout the 6-year period. No visible change in appearance of the seafloor was seen in the photographs (Randy Cates, personal communication, August 2006).

A formal program for the health of Mamala Bay, the broad reentrant in the south coast of the island of Oahu lying between Diamond Head (Waikiki) and Barbers Point (the southwest corner of the island) was begun a number of years ago as part of the compliance program for sewage discharge from the City of Honolulu. The protocols for this monitoring program are summarized in Bailey-Brock (1996) and Bailey-Brock et al. (2002), and which formed the basis for the assessment of impact on the benthos beneath the aquaculture farm.

The benthic biota residing in and on the seafloor was examined under the cages, at distances of about 80 m, and at distances of 200 and 400 m, by analysis of the infauna at more or less quarterly intervals for the past 6 years. A progressive change was noted for the stations under and near the cages. Organisms tolerant of a high nutrient environment became abundant at the expense of those adapted to a low nutrient condition typical of tropical open ocean environments (See Bybee and Bailey-Brock 2003 and Lee et al. 2006 for details). This nutrient enriched condition of low species diversity initially only affected the area under the cages. The station 80 m from the cage later showed the same trends as those observed under the cages. The stations at 200 and 400 m from the cages showed no changes in the diversity of the benthic assemblage.

The opportunity to conduct an interesting experiment arose after a hatchery failed to produce fingerlings in 2005 through 2006. The lack of fingerlings resulted in a progressive decrease in farm output over an 8 month period and was followed by a period in which there were no fish in the cages. Because no feeding was taking place on the farm, there was no added discharge during that time, although the cages were still in place awaiting a new batch of fish. Bottom samples continued to be taken for benthos assessment. After a period of approximately 9 months with low or no production, the seafloor essentially re-established its initial species diversity (Julie Brock, personal communication, October 2006). This was the same type of response that occurred during the experiment in which assemblage changes were observed while feeding was taking place and a recovery to pre-existing conditions a few months after the harvest was completed (Bybee and Bailey-Brock 2003). After 3 years of continuous production, the recovery period was about 9 months rather than the 3 to 6 months previously observed.

Sediment traps deployed under and shoreward of the cages were used to examine the flux of debris shed from the cage and the flux of waste material from the fish culture. Initial observations indicated a sharp drop off in the amount of particulate flux as one moves away from the cages. Moreover, the flux beneath the cages appeared to be higher than expected, suggesting that the assimilation of the feed by the fish was less than optimal. Further studies are currently underway to try to identify the reason for this higher than expected flux of waste material.

Many species of fish are now abundant external to the cages, indicating that the cages may be performing as fish aggregating devices. During the initial surveys at the site before the experiment began, no fish were observed. After the experiment, fish were abundant outside the cage. Three protected species are potentially present at the farm site: humpback whales, sea turtles, and monk seals. During 6 years of operation, no monk seals were seen, but whales and turtles were seen frequently. Neither type of animal seemed concerned about the presence of the cages. In fact, the turtles seemed to find the cages a preferred feeding and resting place.

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11

Environmental Deterioration of Fish Farms in Japanese Enclosed Bays and Measures for their Environmental Management

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Fish farming using net pens in some Japanese enclosed bays started in the late 1950s and was referred to as "the conversion of catching fisheries to rearing fisheries." Net pen aquaculture has increased rapidly in popularity in the enclosed coastal areas of Japan since the 1970s. Total yields from net pen aquaculture recently reached approximately 270,000 metric tons, the majority of which is contributed by the culture of yellowtail, salmon, and red sea bream (Shirota 1990, MAFF 2005). A major problem of using net pens that has yet to be solved is that the fish are reared at extremely high densities with limited space and they require large amounts of food. Dissolved oxygen (DO) tends to decrease in the water in the net pens during the night due to respiration of the fish and the cessation of photosynthetic activities of phytoplankton (Hirata and Kadowaki 1990). Only 10% - 20% of the food fed to cultured fish contributes to their somatic growth. The remainder tends to be discharged as waste in the form of organic particles and inorganic nutrients outside the net pens, often causing organic enrichment of the sediment just below the fish farm and eutrophication of the water in the coves and bays where the fish farms are located (Tsutsumi and Kikuchi 1983; Hirata et al. 1994).

The organically enriched sediment that is formed on the sea floor in the enclosed coves and bays with restricted water exchange often causes depletion of dissolved oxygen in the bottom water, production of hydrogen sulfide in the sediment during the warm season (Tsutsumi et al. 1991; Pawar et al. 2001; Yokoyama 2003), and often results in a catastrophic disturbance of the benthic community (Tsutsumi and Kikuchi 1983; Tsutsumi and Inoue 1996; Yokoyama et al. 1997). The eutrophication of the water and organic enrichment of the sediment due to net pen fish farming raises concerns not only about the management and development of fish farming, but also over the environmental disturbance of the ecosystem in the enclosed bays or coves where the fish farms are established.

Measures to decrease the negative impacts of fish farming on the surrounding environment have been studied since the 1970s. Initial measures conducted in Japan were mostly based on civil engineering techniques, including dredging the organically enriched sediment from the sea floor, digging the sea floor of the mouth of the bays or coves to increase the water exchange, creating sand covers over the organically enriched sediments, etc. (Kawai et al. 1990; Kimura 1990). These measures were shown to be ineffective and too expensive.

A micro-bubble generator was utilized to increase the DO supply to oyster, pearl oyster, and scallop farms (Onari 2001). This device produces tiny air bubbles several µm in diameter, with an extremely large surface area relative to their volume, due to their small size and high dissolving efficiency in water (Onari 2001; Sadatomi et al. 2005). Advantages of this device over conventional bubbling devices include efficient introduction of dissolved oxygen into the water and in reduced costs and energy consumption for aeration of the water. The use of this device, however, is now restricted for temporarily aerating the water in shellfish culture. Its power supply is generated by a fishing boat engine. Use of the device on an offshore fish farm would require continuous monitoring from a raft set beside the fish farms, because of the higher rate of oxygen consumption by cultured fish compared to that of shellfish.

A micro-bubble generating system with an independent electric power supply was developed in a joint research project with Tashizen TechnoWorks, Co. Ltd. (Srithongouthai et al. 2006) (Fig. 1). Treating the organically enriched sediment deposited on the sea floor just below the fish farms requires decomposition of the organic matter in the sediment. With previous techniques, bacterial agents and some chemicals were created and marketed. Unfortunately, they had a very limited effect on only the surface of the sediment.

In this study, decomposition of the organic matter was promoted by utilizing the biological activities of a small deposit-feeding polychaete, *Capitella* sp. I (identified by J. P. Grassle), and its closely related sibling species. These species are common in the benthic communities found in organically enriched sediments throughout the world (Pearson and Rosenberg 1978). They have a life cycle of only 4-6 weeks, and they multiply very rapidly in the organically enriched sediment when the bottom conditions are favorable (Grassle and Grassle 1974; Tsutsumi 1987, 1990). During the process of rapid population growth, the *Capitella* tend to quickly consume the organic matter in the enriched sediment by their feeding activities and stimulation of bacterial activities in the sediment (Chareonpanich et al. 1994; Tsutsumi et al. 2002).

Figure 1. Micro-bubble generating system developed by Tashizen TechnoWorks Co., Ltd.

Tsutsumi and Montani (1993) proposed a bioremediation method for the treatment of the organically enriched sediment with artificially cultured colonies of the *Capitella* species. A joint research project of the author with marine bacteriologists, engineers of the microscopic bubble generator, and fish farmers was initiated in 2002, to improve the water quality at the fish farms using a microscopic bubble generator (Srithongouthai et al. 2006) and artificially mass-cultured colonies of *Capitella* species and bacteria associated with this species (Tsutsumi et al. 2005; Wada et al. 2005). Mass-cultured colonies of *Capitella* that had been generated by the team were spread just below net pens of red sea bream in a bay in Amakusa, Kyushu, in western Japan in the autumn of 2003 and 2004. The *Capitella* population increased very rapidly, reaching densities of approximately 130,000 individuals (ind.)/m^2 and 530,000 ind./m^2 in the sediment within three months in the winter of 2004 and 2005, respectively. As the *Capitella* population increased, the organic matter content and acid volatile sulfides of the surface layers of the sediment decreased markedly (Fig. 2). Thus, spreading the artificially cultured colonies of *Capitella* was shown to be an effective technique for treating the organically enriched sediment and preventing further progress of the organic enrichment of the sediment below the fish farm.

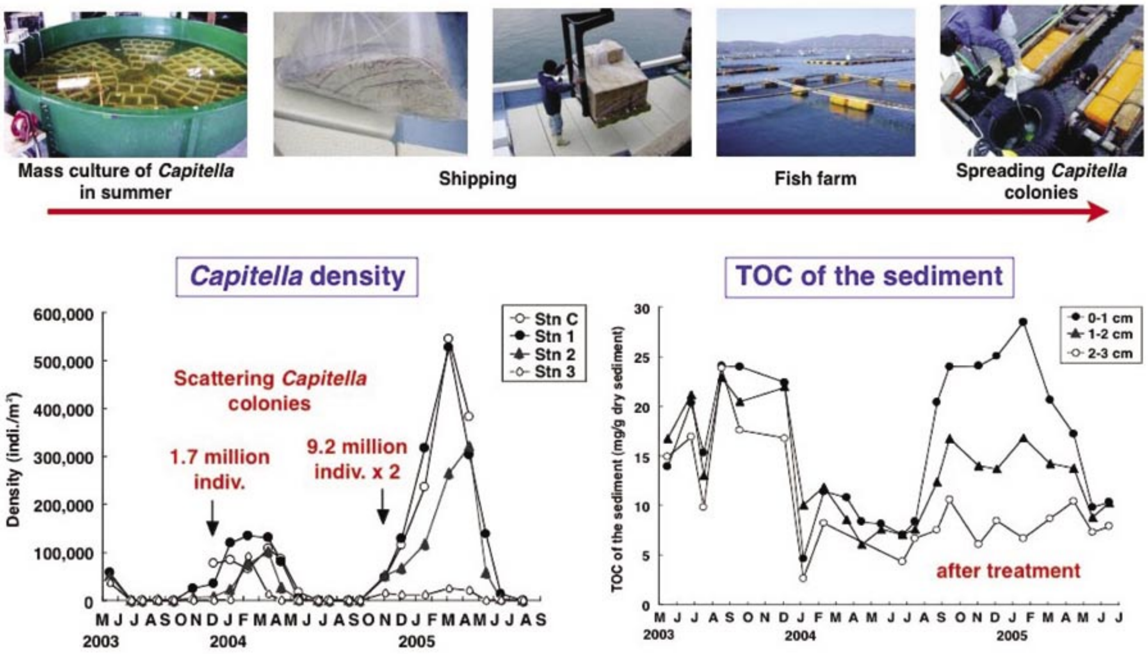

Figure 2. Mass culture of *Capitella* sp. in a factory and spreading of the culture just below a net pen of a fish farm and the effect of the bioremediation experiment for the organically enriched sediment using *Capitella* sp. colonies. Left: Density of *Capitella* sp. population in the bioremediation experiment just below a net pen. Right: TOC of the sediment treated by *Capitella* sp. colonies just below a net pen.

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12

Environmental Research for Finfish Aquaculture in Australia

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Finfish aquaculture in Australia is presently dominated by two species: *Thunnus maccoyii* (southern bluefin tuna) in South Australia and *Salmo salar* (Atlantic salmon) in Tasmania. Other species farmed include yellowtail kingfish (*Seriola lalandi*), snapper (*Pagrus auratus*), and barramundi (*Lates calcarifer*) with others, such as striped trumpeter (*Latris lineata*) and mulloway (*Argyromonas holoepidotus*), in development. The finfish industry in Australia is comparatively small by world standards, but in the regional areas where the farms are located, it contributes hundreds of millions of dollars to the local economy (Table 1). Southern bluefin tuna (SBT) farming is unusual in that it relies on farming fish that have been obtained from wild capture of a quota-limited stock subject to international regulation.

Table 1. Australia's main finfish aquaculture industries.

Species	Location(s)	Tonnes (HOGG[a])	Value (AUD)
Atlantic salmon *Salmo salar*	Tasmania	17,600[b]	$217M[b]
Southern bluefin tuna *Thunnus maccoyii*	South Australia	9,290[c]	$151M[c]
Yellowtail kingfish *Seriola lalandi*	South Australia	2,000[b]	$17.5M[b]
Barramundi *Lates calcarifer*	Queensland, Western Australia, Northern Territory, South Australia	1,250[d]	$11.2M[d]

[a] HOGG: head on, gilled, and gutted.

[b] 2005/2006.

[c] 2003/2004. The dollar value for SBT represents a dramatic decline on previous years due to a drop in price and exchange rate changes.

[d] 2001/2002.

The responsibility for regulating aquaculture in Australia lies primarily with the States and Territories, but the Federal Government has responsibility for off-shore waters beyond 5.556 km (3 nautical miles) to the edge of the Exclusive Economic Zone. A framework has been developed to harmonize regulations and responsibilities between the States and Commonwealth.

Each State and territory has its own set of regulations for aquaculture; the Tasmanian approach is presented here as an example. In Tasmania, the finfish aquaculture industry is subject to regulation through two key pieces of legislation: the *Marine Farming Planning Act 1995* and the *Living Marine Resources Management Act 1995.* Marine Farming Development Plans are statutory documents, developed pursuant to the legislation, that specify marine farming zones, maximum lease area, and management controls for that region (Crawford 2003). Marine farming leases can be issued for 30 years with provision for renewal. The issue of a lease is conditional on the completion of a baseline environmental survey of the lease area. This includes the collection of baseline biological, physico-chemical, visual, bathymetric, and current flow data. Marine farming licenses are issued to leaseholders on an annual basis. Lease-specific environmental monitoring requirements are stipulated in the marine farming license.

In Tasmania, in relation to Atlantic salmon farming, license conditions state that there shall be no significant visual, physico-chemical, or biological impacts at, or extending beyond, 35 m from the boundary of the lease area. Visual impacts include the presence of any of the following: fish feed pellets, bacterial mats (e.g., *Beggiatoa* spp.), gas bubbling arising from the sediment, either with or without disturbance of the sediment, or numerous opportunistic polychaetes (e.g., *Capitella* spp., *Dorvilleid* spp.) on the sediment surface.

Unacceptable impacts *within the lease area* include visual evidence of excessive feed dumping, extensive bacterial mats on the sediment surface prior to restocking, or spontaneous gas bubbling from the sediment. License conditions require routine annual video surveys of the lease site to be performed to ascertain compliance with the above. More detailed biological and physico-chemical assessment may be required in the event that a visual impact is detected at or beyond 35 m from the lease boundary. In these cases, biological and physico-chemical parameters must not exceed specified limits or be significantly different to levels at reference sites.

Heavy metal, antibiotic, and chemical residues within or outside the lease area cannot exceed levels specified by the government. Other generic issues covered in licenses include the requirement for ecologically sustainable waste management practices, mesh size limits for bird netting, the reporting of seabird and mammal interactions, fish disease, mortality, and escapee events, chemical usage, introduced marine pest, and monthly feed input and stock management data.

The effects of SBT farming on the seafloor are much less evident, largely because whole baitfish are fed and consumed with minimal wastage and because farming zones are in high energy, wave-exposed environments.

The Australian Federal Government becomes involved in aquaculture when development actions come under the ambit of the Environment Protection and Biodiversity Conservation (EPBC) Act of 1999 (revised November, 2006). The EPBC Act relates to protection of the environment and heritage with a focus on matters of national environmental significance (NES) and ecologically sustainable development. Any action likely to have a significant impact on a matter of NES requires the approval of the Environment Minister. Matters of NES include world heritage properties, Ramsar wetlands, migratory species, threatened species and ecological communities, the Commonwealth marine area, nuclear actions, and national heritage. A 3-stage process is used involving referral, assessment, and approval. A decision by the department on whether approval will be required must be made within 20 business days. The implications for offshore aquaculture are described in a policy statement (Australian Government 2006).

Aquaculture research is carried out within university departments, State research laboratories, and Commonwealth research agencies around Australia. Much of this research is carried out more or less independently. To better meet the research and development needs of the finfish industries, the Australian Government agreed to the establishment of the Aquafin Cooperative Research Centre for Sustainable Finfish Aquaculture (CRC) in 2001. The CRC represents an investment of around $72 million Australia dollars (approx. $58,032,000) over 7 years from the Commonwealth, key industry sectors, and selected Universities and State and Federal research agencies. This coordinated multidisciplinary approach and sharing of expertise, skills, and facilities was deemed to be essential for the sustainable growth of finfish aquaculture in Australia given the wide geographic spread of research expertise and finfish farming locations.

The Aquafin CRC programs provide a research and development capability to address health, nutrition, and farming technologies including a broadly based environmental program essential to sustainable finfish farming (Cheshire and Volkman 2004). Details and research reports can be found on the Internet (*http://www.aquafincrc.com.au/*). These programs support the ongoing commercial development of the finfish industries while ensuring that they continue to perform in an environmentally sustainable manner.

Some of the environmental issues associated with finfish aquaculture world-wide include:

- Habitat and sediment degradation
- Reduced water quality and possible eutrophication
- Cultured fish escapees leading to genetic or disease transfer to wild stock
- Navigational hazards and restrictions to access
- Possible interactions with predatory marine species including entanglement and predators displacing protected species
- Chemical usage (e.g., net antifoulants) and therapeutic medicines
- Visual and noise impacts

Depending upon the location of the aquaculture operation, e.g., near-shore within 3 nautical miles of the coast versus offshore, the effects may vary and society's concern about these effects may differ.

Any aquaculture management framework has to recognize that unimpacted (natural) conditions are spatially and temporally distinct, and as a consequence, benthic (and system-wide) assimilative capacity varies. Unfortunately, many regulations attempt to define a one-size-fits-all baseline against which to measure effects. With increasing enrichment with organic matter, the chemistry and ecology of sediments under net pens becomes more similar, but for a given total input, the rates of change vary depending on sediment type, temperature, and composition (feeding mode) of the biota. Sediments can take a very long time (years in some cases) to recover completely to pre-farming conditions, but by monitoring sediment condition during the stocking cycle, most farms can use production schedules that enable the extent of recovery to be sufficient for re-use within months. Monitoring sediment condition allows farmers to effectively manage lease areas because there is usually a clear relationship between management practices on-farm and the scale of benthic impact.

Research by Macleod et al. (2004a, 2004b) for the Aquafin CRC has defined a 9-stage scale of impact, with six stages for increasing benthic impact and three stages for the recovery phase. This approach uses video scores that have been calibrated against more detailed benthic faunal counts. Alternatively, research for the SBT industry has resulted in the development of gene probes for specific benthic animal groups (*infauna*) as well as an innovative score-card reporting scheme, which promises to greatly speed up the annual tuna environmental monitoring program undertaken by this industry sector as a requirement of their license to farm fish issued by the relevant government regulatory agency, Primary Industries and Resources South Australia (PIRSA).

One key finding from the CRC research that is relevant to offshore temperate finfish farming is that the assimilative capacity of sandy organic-lean sediments can be quite low compared to organic-rich near-shore sediments dominated by silt and clay. A mitigating factor for benthic organic enrichment can be the presence of scavenger organisms such fish and crustaceans that quickly take advantage of any food arriving at the sediment. Thus, identical organic loads onto a sandy sediment may dramatically change the biogeochemical cycling, local flora, and fauna, while it may have much less effect at another location. This aspect is often insufficiently appreciated when interpreting simple nutrient budgets.

Within the Aquafin CRC, the general approach has been to establish detailed nutrient budgets for the ecosystem, including all significant natural and anthropogenic (including aquaculture) sources (Volkman et al. 2006). This is important in most Australian waters, because nutrients are often the limiting factor for phytoplankton growth in spring, summer, and autumn. The first stage is to develop a hydrodynamic model of the water body and then to capture ecosystem knowledge in linked biogeochemical and sediment transport models. The models require calibration and validation over several seasons. Finally, some ongoing monitoring is needed in conjunction with an adaptive management strategy. The monitoring is to inform not only the regulator and farmer about environmental effects, but also the modeling so that the models can be continuously improved. These models can also provide vital information about how natural environmental events, such as phytoplankton blooms, might impact on the industry and whether the aquaculture or other anthropogenic activities might affect these occurrences. A great advantage of the modeling approach is that it allows scenarios to be run to examine likely effects due to changing environmental conditions, including those related to climate variability or changing farming practices such as location of leases or stocking densities.

In Australia, and around the world, increasing inputs of organic matter and nutrients from agricultural runoff, sewage plants, urban inputs, etc. have created eutrophication problems and put the normal functioning of aquatic ecosystems at risk. There is a fundamental need to determine how sensitive the ecosystem might be to any additional nutrient loading. Symptoms of increasing eutrophication may include an increasing frequency or magnitude of algal blooms, increasing concentrations of ammonium in the water column, and decreasing dissolved oxygen (DO) in the water and sediments. Many indicators are available. A good indicator must be predictive (i.e., it indicates change before the change becomes too extreme). Indicators should provide information about issues of particular concern or about aspects of the ecosystem that have high conservation value. Chlorophyll *a* is good indicator of phytoplankton biomass. It can be rapidly measured by using vessel-mounted fluorometers or in the laboratory by spectrophotometry or high performance liquid chromatography. In many regions, the composition of the phytoplankton is also of interest due to the occurrence of harmful algal bloom species. Dissolved oxygen provides a direct indicator of water quality. Moored instruments are available to monitor DO continuously in the field with data telemetered back to a base station. The usual problems of biofouling, instrument drift, and potential tampering of moorings need to be considered. Measurement of the major nutrients (nitrate, phosphate, silicate) are essential for calibrating and validating models, but may not be a good predictor of problems apart from ammonia, which is directly excreted by fish and can be an indicator of high benthic remineralization. Given the natural variability of most ecosystems, careful assessment of the temporal and spatial frequency of sampling will be important to minimize the cost of monitoring while ensuring it has sufficient power to detect a specified degree of change.

A key element in any regulatory framework is the adoption of an adaptive management framework. This recognizes that current ecological knowledge of marine systems is imperfect and that ecosystem changes may be subtle and hard to detect among interannual variability. This approach includes formulation of an agreed set of environmental variables (including protected value indicators and system state indicators) and appropriate trigger values. These may be set relative to historical data or in comparison with control sites. The particular choice may vary from one ecosystem to the next. This is rather different from a regulatory regime where exceeding a specified value (e.g., of a contaminant in an effluent stream) leads to fines or even industry closure. If a trigger value is exceeded, this is a prompt for further measurement and evaluation to understand how the ecosystem is responding to the environmental challenge. The monitor and respond aspect of the adaptive management cycle may be quite short, perhaps after an annual review of the monitoring data or in response to a particular event. The process of formulating an agreed set of indicators also needs to be adaptive, but on a longer time scale. Achieving agreement is complex, because it requires cooperation across a range of agencies, companies, and other stakeholders with different roles and different priorities. In practice, it can work by having a team of scientists prepare a draft of a set of indicators and trigger values that is then negotiated with regulators, industry, and other stakeholders. Another approach is to carry out a risk assessment involving a broad stakeholder group, although sometimes this can fail to arrive at a common position.

Finally, research also needs to consider the possible effects of climate change on the environment and the aquaculture industry. Climate change will lead to variations in seawater and atmospheric temperatures, frequency, magnitude, and location of rainfall, and the frequency and magnitude of extreme weather events (e.g., winds). All of these can impact aquaculture operations. Possible environmental effects include changes in the frequency, magnitude, and composition of phytoplankton blooms, changes in the geographic ranges of temperature-sensitive species, changes to hydrodynamics and water circulation, increased rates of biological reactions (e.g., remineralization of organic matter) as temperatures rise, changes to river flows and surface run-off (system-flushing), and changes to water quality (e.g., turbidity) and salinity. This can have important effects on the productivity of species that are being farmed close to their environmental limits, as is the case for Atlantic salmon in Tasmania.

My thanks to Jane Campbell, Lesley Donohoe, Catriona Macleod, Karen Wild-Allen, Mike Herzfeld, Peter Thompson, Sue Blackburn, Andy Revill, Wes Ford, Colin Shepherd, Anthony Cheshire, Steven Clarke, Jason Tanner, Ian Nightingale and many other colleagues for information and comments. This work was funded by the Aquafin CRC, FRDC, and participating organizations.

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13

Results of Environmental Monitoring at an Experimental Offshore Farm in the Gulf of Maine: Environmental Conditions after Seven Years of Multi-Species Farming

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The University of New Hampshire, in partnership with local fishing cooperatives and a commercial marine fish hatchery, and with collaboration from several regional research institutions, established an offshore aquaculture research and development facility in the Gulf of Maine in 1999. The offshore platform, located 9.66 km (6 miles) off the New Hampshire coastline in 56.39 m (185 feet) of water, is fully permitted for commercial production. It consists of a submerged grid mooring system that can accommodate four submersible cages for finfish culture, two submerged longlines for suspended molluscan shellfish culture, and surface structures that include remotely operated feeders, acoustic biotelemetry systems, and oceanographic instrumentation. The facility serves as the field site for applied research and technology development, evaluation, and technology transfer for the Open Ocean Aquaculture Project funded by the National Oceanic and Atmospheric Administration. The goal of the project is to stimulate the development of an environmentally sustainable offshore aquaculture industry, thereby increasing seafood production, creating new employment opportunities, and contributing to regional and national economic and community development. To date, fish species cultured at the site have included summer flounder (*Paralichthyus dentatus*), Atlantic halibut (*Hippoglossus hippoglossus*), haddock (*Melanogrammus aeglefinis*), and Atlantic cod (*Gadus morhua*). In addition, blue mussels (*Mytilus edulis*) and Atlantic sea scallops (*Placopecten magellanicus*) have been grown on the adjacent submerged longlines.

Aquaculture, similar to all other methods of food production, will have some effect on the surrounding environment. The past three decades of development of nearshore cage culture for finfish has shown that if done correctly, the effects are localized and negligible. There is also evidence that poorly sited and poorly managed fish farms can result in environmental impacts. These include deposition of uneaten feed and feces on the seafloor that can alter bottom sediments and benthic communities, enrichment of the water column with dissolved nutrients that can stimulate increased primary productivity, escapement of captive fish, and negative interactions with marine mammal predators. In the past decade, environmental conditions in the vicinity of farms has greatly improved due to changes in husbandry practices and feed formulations, better fish health management through vaccine development, and more robust engineered systems have reduced catastrophic fish escapes. These issues, however, continue to be raised by opponents of sea cage culture. In addition, critics also cite overexploitation of lower trophic levels of fish for feed ingredients, transfer of diseases and parasites from farmed to wild fish, and genetic pollution and competition with wild stocks by escaped fish as the negative consequences of sea cage culture, though the actual risk and impacts of these issues are subjects of continuing debate within the scientific community. Regardless of whether the severity of the effects are real or exaggerated and whether some are even relevant to native marine fish farming in offshore environments, these issues must be addressed and successful management of environmental impacts must be demonstrated for open ocean aquaculture to gain "social license" to operate in the United States.

The approach adopted by the Open Ocean Aquaculture Project includes implementation of management practices that are designed to minimize potential impacts and a rigorous environmental monitoring program to measure any changes to the surrounding environment. To address escapes, the project has developed a suite of engineering tools to design and evaluate mooring systems and cages that can withstand extreme environmental conditions and avoid catastrophic losses due to storm damage. Sea cages are submerged 12-15 m below the sea surface to reduce the risk of ship collisions. A containment management plan, based on the principles of a Hazard Analysis and Critical Control Point risk analysis program, includes frequent inspection and maintenance as well as procedures to prevent escapement during stocking, sampling, harvesting, and transport operations. All fish cultured at the site are native to the area, and to date, all juveniles stocked in the sea cages have been the offspring of wild parents. Therefore, any escapees would be genetically identical to local stocks. Waste feed is managed by the use of remote, real-time video monitoring and control of feeding operations, so that feed delivery can be stopped when the fish are satiated. While the project's location in the Gulf of Maine is a low risk area for enrichment from dissolved nutrients, the adjacent culture of extractive species such as mussels and scallops is used to balance the inputs of nitrogen and phosphorus from fish culture. Fish health is managed using vaccination prior to stocking, and by maintaining optimal environmental conditions (e.g., temperature, dissolved oxygen, etc.) to minimize stress. Dead or moribund fish are promptly removed to reduce the risk of developing any reservoirs of pathogens resulting from decomposition. To date, no antibiotics or parasite treatments have been administered.

Eighteen months prior to stocking the first production run of fish in 1999, a detailed hydrographic and environmental assessment of the site was conducted to establish reliable reference conditions[1]. Using high resolution side scan and multi-beam sonar, underwater videography, multi-parameter in situ instrument packages, and traditional water column and benthic sampling and analytical methods, a baseline of seafloor, oceanographic, and environmental conditions for the proposed site was established. Numerical models were used to predict the dispersion and deposition of particulates and dissolved constituents, and 20 monitoring stations were established to represent impact (4), mixing (6), far field (5) and distant far field (5) zones. The parameters measured include benthic community characteristics (e.g., density, biomass, species diversity, and evenness), sediment organic content and redox potential discontinuity (RPD) layer, and water quality (dissolved oxygen, dissolved inorganic nutrients, and chlorophyll). A towed video camera is used to further assess sediment characteristics and provide data on epibenthic fauna. In situ instrumentation at a fixed location at the farm provides continuous measurements

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[1] Grizzle, R., L.G. Ward, R. Langan, G. Schnaittacher, J. Dijkstra, and J.R. Adams. 2003. Environmental monitoring at an open ocean aquaculture site in the Gulf of Maine: Results for 1997-2000. Pages 105-119 *in* C.J. Bridger and B.A. Costa-Pierce, editors. Open Ocean Aquaculture: From Research to Commercial Reality. The World Aquaculture Society, Baton Rouge, Louisiana, USA.

of temperature, salinity, dissolved oxygen, turbidity, and fluorescence at three depths (1, 20, and 50 m), wave height and period, and current velocity and direction throughout the water column using Acoustic Doppler Current Profilers (ADCP) current meters.

Though analysis of environmental data has been conducted annually since 1999, only the data collected in late spring 2005 (Ward et al. unpublished report) was used in the analysis presented here to examine the worst case scenario in terms of organic loading. The 2005 water column and benthic sampling was conducted when the farm was stocked at maximum fish biomass with three sea cages stocked with cod, haddock, and halibut, respectively, containing approximately 25,000 kg of fish. Fish had been fed daily rations of pelletized feed formulation at a rate of 1.5% to 2% fish weight per day, therefore during this period, 500 kg of food was dispensed daily.

Analysis of sediment organic content (loss on ignition), showed very low organic content (1.2%-1.4%) and no differences as determined by one-way ANOVA between projected impact, mixing, and farfield zones. RPD analysis was incomplete due to difficulty recovering undisturbed samples from all stations. For those, however, that were recovered, there were no differences by one-way ANOVA in the depth of oxygenated sediments between impact, mixing, and farfield zones.

Univariate statistics were used to assess differences in density, biomass, and diversity (number of taxa) of infaunal benthos, and no differences (by one-way ANOVA) between the four zones were found. In addition to univariate community assessments, potential changes in taxonomic composition of the infaunal communities that might be pollution-related were examined in two ways. First, ratios of the densities of "pollution tolerant" taxa (oligochaetes, capitellids, cirratulids, ampeliscids) and "pollution intolerant" (nuculids, paraonids, ampharetids) taxa were calculated and compared. Pollution intolerant taxa were in the majority at all 20 sites, with no differences between zones. These data suggest that the infaunal benthic communities in all four zones were dominated by taxa that are relatively intolerant of organic pollution, providing additional evidence of no detectable impacts on the seafloor.

The second taxonomy-based approach involved calculating ecological indices of diversity (e.g., Shannon-Weaver, Simpson) and evenness (relative distributions of taxa, e.g., Pielou, Marginet). Each index distills the community taxonomic composition data into a single number that represents a measure of community characteristics. No differences in the calculated indices for diversity or evenness were found for samples from all four zones, again, suggesting that there were no detectable impacts on the infaunal benthic community.

Epibenthic fauna were sampled using bottom video that captures images of seafloor features such as surficial sediments, sediment texture, bedforms, and borrows for qualitative analysis; and generates quantitative data for epifauna. The video from each station is analyzed by clipping the video to isolate the highest quality segments, subsampling the video frames from ~30 to 1 per second to match the GPS positioning information, and subsequently analyzing each scene in the video for bottom characteristics (sediment type, roughness), visible burrow characteristics (size, density), and epifauna (taxa, density). The inclusion of laser beams at known distances apart in each scene allows the total area of the bottom viewed to be determined. The results of the video surveys in 2005 indicate no differences in density or taxa for benthic epifaunal communities located at stations within the predicted impact, mixing, and farfield zones, therefore, no indication of pollution effects on the seabed were detected in the epifauna data.

The water column was sampled in each zone at three depths (1, 20, and 50 m) and analyzed for suspended particulates (TSS), dissolved nutrients (NO_2, NO_3, NH_4, PO_4), and chlorophyll a. Simultaneous measurements of temperature, salinity, turbidity, fluorescence, and dissolved oxygen were obtained by vertical Conductivity-Temperature-Depth (CTD) casts. "Downstream" sampling locations were determined by the direction of flow at each depth by an ADCP current meter. Analysis indicated no differences (by one-way ANOVA) in any of the measured water column parameters between impact, mixing, or farfield zones.

Collectively, the sediment, benthic community, and water quality data suggest that there are no detectable effects of the offshore fish farming on the seafloor or water column at the level of production at the site. The project will continue to increase production levels and continue monitoring to determine the level of production at which environmental changes may occur.

Risk and Risk Management for Feed and Seed for Marine Fish Raised in Offshore Aquaculture

14

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For open ocean aquaculture of marine fish, the provision of feed and seed occurs externally to the actual fish culture operation. How these external activities are conducted and applied determines the potential ecological impact for the industry as a whole. Ecological risks associated with marine aquaculture may be addressed using a framework similar to that used for assessment of risks in other areas of our lives. The use of a framework developed for the World Health Organization (WHO) for assessment of risk to human health from various threats has been proposed for assessment of risk to the environment from marine aquaculture[1]. The identification and characterization of risk are the first steps in determining what risk management strategies might be the most productive in developing supplies of feed and seed for offshore aquaculture that are low risk and will be stable and dependable over the long run. For each risk, the WHO risk assessment framework may be applied to focus research and development on strategies that could be used to reduce or eliminate risk. In most cases, multiple options exist for risk reduction. Risk management strategies that improve economic gain and reduce or eliminate multiple ecological risks, however, are preferred and they have a much higher chance of resulting in meaningful improvements. Furthermore, strategies that allow improvement, or change over the long term, provide more flexible and ultimately sustainable solutions. In most cases, research is needed to develop better risk management strategies. Up-front costs associated with research, development, and implementation often limit application of risk management strategies to industries large enough to afford these costs even if there are long-term economic benefits associated. This is especially true when governments do not fund this type of research and development.

Potential up-stream ecological impacts associated with feed and seed from culture of marine fish include over-fishing due to demand for wild juveniles for grow-out, and harvesting industrial fisheries for feeds[1]. Stated as a simple equation, risk of over-fishing (R) is a function of fisheries management (M) with the effectiveness of management subject to demand [$R = f(M)$]. On some low scale of harvest (low demand), fisheries management has been shown to be effective. Management, however, can only produce some fraction of what exists naturally, and wild fisheries are not able to increase production beyond naturally set limits. At harvest levels higher than those from which a stock can recover, over-fishing occurs. When there is a high demand, fisheries management becomes increasingly difficult, so alternatives need to be found that reduce

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[1] Nash, C.E., P.R. Burbridge, J.K. Volkman, editors. 2005. *Guidelines for ecological risk assessment of marine fish aquaculture.* NOAA Technical Memo No. NMFS-NWFSC-71. National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA. 90 pp.

or eliminate demand for both wild feed and wild seed. Management to reduce the risk of over-fishing due to feed includes the development of alternative protein and lipid sources (especially long chain n-3 fatty acids) and for seed, the development of hatcheries. In both cases, complete replacement leads to elimination of the risk due to activities associated with offshore aquaculture, and partial replacement leads to demand reduction potentially to sustainable levels, at least until the industry grows again. In addition, hatcheries and alternative feedstuffs can provide economic benefits (in the way of lower prices and better quality) and thus have a greater potential for adoption by industry once a critical size of an industry is reached.

Potential downstream ecological risks associated with feed include organic loading and benthic impacts. In this case, risk (R) is a function of the quality and quantity of feed used (F), the organism under culture (O), and management (M) within the context of the specific site chosen for offshore aquaculture [$R = f(F \times O \times M)$]. Activities that improve (a) the efficiency of the diet (e.g., moving from wet fish to pelleted feeds, defining nutrient requirements, improved pelleting technologies, better feed formulation, feedstuffs processing, etc.), (b) the efficiency of the organism (species choice, selective breeding, improved husbandry, etc.), and/or (c) the management systems (optimal feeding regimes, improved fish health management, protection from predators and diseases, better husbandry, improved systems engineering, etc.), will reduce environmental risks. In most cases, these efforts will also improve economic return once a critical level of production is reached by the industry.

Downstream risks associated with seed are associated with the potential ecological and genetic impacts of escapes on conspecific wild stocks if the cultured fish is native or ecological impacts on native species if the escapees are non-native. This paper covers only the first risk. Risk (R) associated with the escape of a native species is a function of the number of escapes relative to the number of wild conspecifics (Pe/Pw), the differences in genetic structure between the wild and escaped organisms (ΔG), and the fitness (Fe) of the escapees to reproduce in the wild [$R=f(Pe/Pw)(\Delta G)(Fe)$]. Risk associated with escapes can be managed at the hatchery by several strategies, e.g., raising fish with the same genetic make-up as wild stocks (where $\Delta G = 0$), or by domestication of the farmed species which reduces escapees' fitness (Fe) in the wild. In this case, economic gains would favor domestication and not maintaining a wild stock genotype. Risk can also be reduced by raising sterile fish (where $Fe = 0$), which may or may not be economically beneficial, or by maintaining a low number of escapes (e.g., by better engineering or management practices) relative to the size of the wild population. Note that the converse is also a possible strategy. Risk can be reduced by maintaining wild stocks at high levels relative to the number of escapes. This may be addressed by industry by raising a portion of the species they produce under stock enhancement protocols for release (likely to have negative economic implications). An approach that combines several of these strategies may be the most effective.

Risks can be interactive and need to be viewed as a set for a given activity to guide management and research. Often, new risks can be created when a different risk is solved, or the choice of a risk management strategy that reduces or eliminates one risk may or may not also reduce or eliminate another risk. For example, the development of a hatchery to reduce the risk of over-fishing to provide seed potentially creates the genetic risk of escaped fish on their wild conspecifics. If wild fish were used, then $\Delta G = 0$ and the genetic risk from escapees would not exist. This has led some to call for only using local fish as broodstock for hatcheries producing seed for offshore aquaculture and actively maintaining a wild-like genetic make-up in the hatchery. This, however, would be to forgo the positive ecological risk reduction that selective breeding can produce in terms of seed that uses feed resources more efficiently, that makes better use of alternative feedstuffs, has better disease resistance, and so on. Maintaining a wild genotype for fish used in offshore aquaculture would also forgo economic gains and put environmental and economic goals at odds, reducing the chance for adoption and meaningful environmental risk reduction.

Governments can create win-win situations by fostering research and development where ecological risk management and economic gains are in line and both considered. In the case of feed and seed, this would include development of high quality compound feeds from alternative feedstuffs, and hatcheries with associated selective breeding programs for new and existing marine fish industries. Governments can hasten and improve the potential for the adoption of preferred risk management strategies by first identifying those strategies that provide the best overall options and then by funding the up-front research and development costs to put those practices in place.

15

Discussion Summary: Open Ocean Aquaculture—Moving Forward

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Introduction

In addition to the presentations given by the invited experts at the "Open Ocean Aquaculture—Moving Forward" workshop, valuable information was exchanged during the four discussion sessions held during the workshop. Discussion topics included current definitions of open ocean aquaculture, the non-environmental challenges to its further development, the business aspects, environmental monitoring, and the potential further expansion of open ocean aquaculture. At the end of the workshop, participants listed the main research gaps and strategies for moving open ocean aquaculture forward. We would like to express our thanks to John Corbin, John Forster, John Volkman, and Richard Langan for serving as recorders during the discussions and for their contribution to the content of this summary, which represents a compilation of their notes, a summary of the discussion transcripts, and written comments of the participants. We would also like to extend our appreciation for funding support from the Office of Oceanic and Atmospheric Research of the National Oceanic and Atmospheric Administration (NOAA, Grant #NA05OAR4171169) to Oceanic Institute. The views and opinions expressed in this article do not necessarily reflect those of the National Oceanic and Atmospheric Administration, Oceanic Institute, or of all of the participants at the workshop.

Definitions

Several substantially different definitions of open ocean aquaculture from various sources were discussed. At the "Farming the Deep Blue" conference in Limerick, Ireland (October 6-7, 2004), open ocean aquaculture was divided into four classes based on conditions in the Northeast Atlantic,[1] but which do not necessarily apply in other parts of the world. Some participants at this workshop considered it important to point out that open ocean aquaculture takes place in the pelagic realm, which has moderate or greater rates of circulation that is not entirely tidally-driven and is likely to be exposed to high-energy wave conditions. The pelagic environment in some areas of the U.S. Exclusive Economic Zone (EEZ) may also be nutrient poor and with low wild fisheries production. One participant emphasized site exposure to high-energy wave regimes as a necessary characteristic. Others focused on geographic boundaries or distance from the coast (3 to 200 miles), or an absence of coastal influences at the site, i.e., "….the rearing of marine organisms under controlled conditions in exposed, high-energy ocean environments beyond significant coastal influences."

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[1] See Ryan, J. 2004. Farming the deep blue. Accompanying report, Farming the Deep Blue, Limerick, Ireland, 6-7 October 2004. Marine Institute, Dublin, Ireland. 67 pp.

After discussion of the applicability of the various definitions to various situations, it was suggested that defining open ocean aquaculture for all situations would be very difficult. Although some sort of place-based or location definition was required for regulatory purposes, as well as for legislators and politicians, it was questioned whether a precise definition was absolutely necessary at this workshop. Several participants suggested it would be more practical to focus on the goal of "farming the sea."

For the National Oceanic and Atmospheric Administration (NOAA) to have governance at the U.S. federal level, offshore or open ocean aquaculture must be strictly defined as that which takes place within the EEZ, i.e., 3-200 miles offshore from U.S. coastlines. On the other hand, NOAA recognizes that there are aquaculture operations in state waters that would also generally be thought of as open ocean aquaculture. Participants from Asia and Europe pointed out that defining open ocean aquaculture in terms of EEZs has already led to several conflicts between neighboring countries, so the use of the term "EEZ" should be avoided for countries in their regions.

The issues of the distance from shore, the exposure, current velocity, depth, and the relative importance of those factors is going to vary, depending on the type of aquaculture. Because of the complexity of interactions, a matrix might be used as part of the legal definition used by regulatory or permitting authorities to decide whether or not an aquaculture activity would be allowed. Having a series of parameters for open ocean aquaculture would also allow people involved in the industry to better understand each other and to distinguish open ocean aquaculture from that which takes place near shore.

Non-environmental Challenges

A list of challenges, based on reports in the literature and suggestions from various experts, was presented for discussion:

- Fingerling supply
- Government support
- Public perception
- User conflicts
- Status of technology
- Permit and regulatory environment
- Start-up capital
- Market competition
- Species selection

Many of the items on the list were found to be interconnected. For example, fingerling supply is impacted by the status of hatchery technology. Government support and market competition influence the permit and regulatory environment and start-up capital. Public perception is connected with user conflicts, and these aspects directly impact government support and, perhaps, market competition, to a certain extent.

Many of the challenges listed would require another 10 years to arrive at solutions. To make progress in moving aquaculture into the open ocean, it was suggested that specialists in each of the areas work on all of the challenges in parallel, rather than sequentially.

Fingerling supply

Fingerling supply is a key issue for U.S. open ocean aquaculture. The government can develop and build hatcheries to provide fingerlings for the industry at the beginning to expedite expansion, but there should be an agreed upon and reasonable transition period where government phases out of hatchery production for a species as private hatcheries scale up production to support expansion. This is a very difficult issue of what comes first and how to do it so that unfair and constraining competition from government sources is avoided. In other words, the federal government should develop and support the transfer of certain key components of the technology to the private sector to assist them in building hatcheries and growing the fingerlings that they need. Hatchery sites and skilled labor to operate a large-scale hatchery were identified as the constraints in Hawaii.

The United States has much to learn about commercial hatchery operations from other countries. Fish farmers in Asia and Europe can order fingerlings from one of several private hatcheries. Fish producers select fingerlings from whatever hatchery has the best fingerlings for the best price, an integral part of market competition among the hatcheries.

Government support

Participants understood why a private business would want to have a ready supply of its own fingerlings to control stocking and production, but a question was raised about who would be charged with establishing the hatchery technology itself. A lot of the work for the U.S. salmon industry was done with government funding, through government facilities given to the developing industry, both domestically and foreign. For example, government researchers working with public funds established the nutritional requirements of fish and the technology used to make the feeds, which are now used worldwide. Many of the advances that would be considered a requirement for industry development would require a public resource as a basis, because the private open ocean aquaculture industry lacks the financial and technical capability for doing everything that needs to be done to move the industry forward. Government funding agencies may question the economic sense of producing a fish product domestically as opposed to overseas because of higher labor costs and environmental regulations.

It was pointed out that a lot of opportunities have been missed to engender government support to further develop aquaculture. When the coastal fishing communities in the State of Washington went out of business, hundreds of millions of dollars were spent to retrain people to do other things, but they were not retrained to be fish farmers. Retraining unemployed fishermen to produce fingerlings in hatcheries and grow fish out in cages could have provided them with appealing alternative employment opportunities and generated income for the state.

Public perception and user conflicts

Some participants thought that public perception would be the most important factor in generating momentum to move open ocean aquaculture forward. When Maine salmon farming started in East Port in the early 1970s, everyone was happy, because the industry came to an area where there were no jobs. Since that time, however, land in East Port has become high-priced waterfront real estate. Open ocean aquaculture faces opposition because of a viewscape issue among the local community.

Public perception and user conflicts were probably the same challenges that many countries faced when they first started aquaculture. A futuristic vision of open ocean aquaculture that captures people's imaginations is needed to get the momentum going. Once the industry has that type of unified vision, government support is likely to follow. Moving further offshore to get out of view and beyond the area of greatest concern of the permitting authorities and the community at large, however, is not sufficient for addressing user conflict issues. A planned scenario, with appropriate monitoring and safeguards, is needed, because what is not measured cannot be managed.

Status of technology

Because most of the species being cultured in open ocean aquaculture are new to aquaculture, a whole range of technologies, from feeds to vaccines, will need to be developed in addition to technologies unique to the open ocean. Containment technology has advanced substantially in the past decade, but the technology needs to be extended to allow farms to exist farther away from shore and in more challenging marine conditions. Feeding, harvesting, and cleaning technologies also need to be advanced so that more automation can be deployed, thus enabling higher labor cost areas to compete more effectively with low labor cost areas.

There was some disagreement over whether overseas experts should be brought in to improve the status of U.S. hatchery technology. It was pointed out that the United States has not developed a large labor pool with the necessary expertise. On the other hand, because open ocean aquaculture uses a public resource, employing local people was seen as a way to build a more positive public perception. Participants agreed that long-term investment in education is needed in the United States to develop skilled workers who are trained in hatchery technology and fish diseases.

Permits, Start-up capital, and Market competition

For one participant, the crucial challenge was the permit and regulatory environment that allows open ocean aquaculture to take place outside of State waters. The concern was that much of the open ocean aquaculture industry is already taking place outside the United States, a situation that will be exacerbated if the U.S. permit and regulatory environment is not established soon.

It was suggested that open ocean aquaculture start with high-end niche market products so that producers would get their capital back in a reasonable amount of time. In Hawaii, start up capital was not a big constraint because of the research tax credits given by the state for every dollar that a venture capitalist invested in new technology such as open ocean aquaculture.

Advertising fish as locally grown can be a big selling point, but producers should be careful not to imply that if a product is not grown locally, then there is a problem with it. Most of the U.S. seafood industry imports most of its seafood, and they would not want people saying that imported seafood is bad. Growing seafood locally has a huge long-term benefit due to the distribution advantages and lower freight costs. Farming fish also offers the opportunity to address certain animal welfare concerns by being able to actively manage stock growout conditions and product harvesting, handling, and processing.

Species selection

Species selection can be thought of as overlapping circles of different factors. One circle is the biology or cultivability of an organism. Cultivability a given species can change with advances in technology. Overlapping that circle is an economic circle, i.e., the species has a certain value. If the goal of open ocean aquaculture is to produce affordable seafood, the focus should be on large-scale production of low cost seafood. In that case, the species would be the marine counterpart of tilapia and carps. If the goal is high-value products for niche markets, the focus would probably be on development of multiple species and multiple markets to diversify the products available while maintaining profitable pricing. Overlapped with the economic and cultivability circles is a politically correct or socially acceptable circle that may make a species appropriate or not appropriate (e.g., it is a favorite game fish, or other fishers are dependent on that species). Some participants suggested that candidate species for open ocean aquaculture should perhaps be limited to those that are not currently being cultured in land-based operations or near shore cages.

It was suggested that species selected for open ocean aquaculture should all be high value species. Operators of commercial open ocean farms in Hawaii stated that the main reason for targeting and producing high-value, tasty, carnivorous fish was due to the high cost to produce them in that way. It is not cost effective to produce a low-value species in a 2600 m^3 flipper cage that currently costs $150,000, plus the cost of mooring.

An agricultural industry that is dependent upon a single species is extremely vulnerable to a number of factors, including disease or a change in market conditions. Sustainability is a function of the ability of that industry to change and the diversity of cultivars on a farm. On the other hand, culturing exotic species adds a complexity to open ocean aquaculture development from environmental and other standpoints, because it opens up a plethora of issues such as complications associated with escapes that make the offshore industry objectionable to far more people than would otherwise be the case.

As the open ocean aquaculture industry evolves in the next 10 or 20 years, it will become more efficient. Perhaps one or two species will be identified to become "the salmon of the open ocean," but there is going to be a lot of trial and error to get to that point. At this stage, research should focus on developing more candidate species for open ocean farming.

Additional challenges

Land-based infrastructure, a key component of siting and supporting an offshore fish farm, is required at the right location. The economic imperative to develop open ocean aquaculture was also seen as an important challenge in the United States, where a very different set of circumstances exist to what existed in Chile, Scotland, and Norway during the 1970s and 1980s, when their aquaculture industries experienced rapid growth.

Challenges that have not yet come up because the open ocean aquaculture industry is still in its infancy include the problems of scale and scaling up, and medium-term issues, such as breeding and diseases, which will not hit until the industry reaches a certain scale. Managing 40 open ocean aquaculture cages at one site will be considerably more difficult than managing 10 sites with four cages each. Maintaining different strains of the same species, bred for different characteristics (e.g., growth, disease resistance), is going to be a major issue in each of the species after 10-20 generations. Also, as the industry grows, the issues of disease management and feeds (including alternate protein and lipid sources) are going to increase with it.

Business Aspects

Whether aquaculture operations take place offshore or inshore, many major costs are the same (e.g., the cost of feed and fingerlings, marketing, and shipping). The added costs are the containment systems, transportation, and perhaps, skilled labor. These are balanced by lower building costs and for energy and land. In broad and general terms, most of the costs of an open ocean aquaculture facility are fairly fixed. At a certain point, the fish farmer can control only some of these costs. For example, the manufacturing costs of feeds continue to go up, even though the amount of fishmeal used in the feeds has been greatly reduced. A fish farmer can invest in an expensive advanced technology and justify it in terms of a 15-20 year life, but within 5 years, that technology might be out of date, and the farmer would have to adopt another type of technology. As a result, the business cost calculation becomes quite complex.

Two other costs to consider are location and the cost associated with monitoring the environment. Where to site a farm is directly related to cost. If open ocean aquaculture is to grow into a bigger industry at depths where cages are currently located, there is an associated cost for environmental monitoring that is likely to increase. On the other hand, moving the cage to a deeper site would require more money initially, but the costs of environmental monitoring may decrease because of fewer monitoring requirements. It would be an important factor in deciding whether or not to select a site at a greater depth. As open ocean cages get larger, a realistic notion about the requisite associated costs is necessary.

Producing affordable fish does not necessarily have to be one of the initial goals of open ocean aquaculture. Many successful farmed species started at much higher prices ($4 to $5 per pound, i.e., $9-$11 per kg) and then dropped down to $2 or $1 per pound ($4.50 to $2.25 per kg). Salmon was an expensive fish in Europe before salmon farming started. Now it is the most common and affordable species. The cost of cultured red sea bream in Japan was $15/kg in the 1970s, but it currently sells for about $5/kg. A similar consequence is expected with other species. It was predicted that if open ocean aquaculture of high-value species became highly successful, supply and demand would take care of its affordability for more consumers.

A basic problem for moving aquaculture further offshore in Japan is the cost of transportation. If open ocean culture technology would not allow producers to ship their product for less than $5/kg, it would be seen as an impractical move. Diversification has helped to create jobs and buffer the aquaculture industry against fluctuating product costs in the northeastern United States. In specific markets, live cod sells for $11-12/kg, while mussels sell for about $3/kg. Mussels are relatively cheap to grow in this area, and this type of product diversity addresses the conflict with other users and people who lost their jobs in the U.S. commercial fishing industry because of declining wild fisheries.

A common way to look at product prices is to think of demand as a stable "pie" that is always the same size, and that once that demand is satisfied, then prices fall to zero. In reality, however, marketing has repeatedly been shown to create a larger pie and to make demand increase. Thus, the survival of a business is not really a matter of managing supply, but of keeping supply slightly behind the demand curve. Low mortality rates and better growth efficiency would allow the fish farmer to survive in the highly competitive market.

The open ocean aquaculture market is going to go worldwide, and the United States will be competing for markets at a global level. As the industry develops, it is important, from a marketing standpoint, to think about what makes one product unique and distinguishable from similar products being produced everywhere else. A native species fits that criterion much better than is often the case with introduced or exotic species. At this point in the development of the industry, the focus should probably be on a few endemic species that have good economic potential to allow the industry to move forward. Introduced species and selective breeding are scientifically complex and controversial issues and may be politically difficult to resolve, given current information.

Several participants thought that branding of fresh fish would help keep open ocean aquaculture producers out of the "commodity" pit for perhaps a 5-15 year period, but not forever. An example was given of the very successfully branded and marketed Copper River salmon. An individual corporate brand, however, is difficult and expensive to maintain. The producers received considerable funds from the federal government to support the marketing campaign for Copper River salmon, and there is a finite supply of the product. A much better approach was thought to be working within a larger framework when branding a product. A country-of-origin or a state-of-origin brand, such as "Hawaii Seafood," would be a powerful brand, and it would bring aquaculture producers and wild-caught producers together. In addition, it is likely that some state funds would be available to support it. Branding might also help to create new markets. The Korean government recommended that aquaculture producers unify the offshore premium brand, to create a new market that would not compete with that of the inshore farmers.

A very positive way of making people feel that the industry belongs at a particular site is to bring them out to the operations site to see for themselves. In Europe, an entire bay is taken up by massive rafts with mussel ropes attached to them. A tourist industry has been built up around bringing tourists out to visit those rafts and giving them some mussels to eat.

Environmental Monitoring

There was general agreement that a range of potential environmental interactions, which have been documented or implied for near shore finfish cage culture, must be addressed for offshore culture. These include:

- Benthic impacts: sediments and benthic communities
- Water quality: increased nutrients, phytoplankton
- Disease and parasite transmission
- Escapees: genetic pollution, competition with native stocks, predation on protected species
- Exploitation of lower trophic levels: fishmeal and fish oil
- Increased biomass of wild fish external to the cages
- Seaweeds and biofouling organisms

Some of these interactions have positive aspects, such as biomass and diversity enhancement from spreading wastes in nutrient poor pelagic and benthic ecosystems. Whether positive or negative, the degree of impact may be different for aquaculture in the open ocean from that in near shore areas, as will society's perceptions. Scientific knowledge of possible offshore effects is not, as yet, well known. Existing knowledge and standards, however, that have been developed for ecosystem protection in countries including Australia, Ireland, and the United Kingdom (particularly, Scotland) as well as for U.S. state waters in Maine and Washington, have many common features and provide a good starting point for addressing environmental concerns.

The workshop participants agreed that an expectation of "no effects" was unrealistic and not achievable. Some environmental effect within the lease area due to aquaculture is to be expected. With upscaling, the additive effects need to be considered and the scale of the ecological footprint must be assessed relative to the size of the ecosystem in which farming takes place.

Models play a major role in synthesizing knowledge and understanding processes. They enable scenarios to be simulated for predicting possible effects due to different management strategies. A variety of models are available, ranging from those that address aspects of fish physiology, nutrient fluxes, hydrodynamics and sediment processes, to full ecosystem models. Farm-focused models such as AquaModel and DEPOMOD that simulate water column and benthic effects can be used to evaluate the effects of changing parameters using a Windows™ PC operating system. A different modeling approach is to put aquaculture in the context of the whole ecosystem, which requires much higher computing power, depending on the number of trophic levels and degree of complexity involved. A 3-dimensional hydrodynamic model can be used to examine dispersion of wastes from the farm and how the physical environment varies on seasonal to inter-annual timescales. This type of modeling is especially useful for offshore aquaculture. In Australia, CSIRO researchers within the Aquafin CRC have coupled a full 3-dimensional hydrodynamic model to a sediment model to examine the role of sediment resuspension in dispersing the organic matter and to a biogeochemical model for defining the relationship between nutrients released into the water column and effects on phytoplankton abundance.

All participants agreed that efforts must be made to minimize negative effects of aquaculture, both spatially and temporally. The degree of environmental impact is greatly influenced by a number of factors, including the following:

- Site selection
- Assimilative capacity
- Appropriate engineering
- Management practices (feeds, feed management, containment management, cage maintenance)
- Effective monitoring and assessment
- Strategies for corrective action

Aspects of the ecosystem that are of high value and potentially vulnerable (sometimes called protected ecosystem values) need to be identified so that monitoring strategies can be developed to ensure positive environmental outcomes. This process needs to be transparent and involve a wide range of stakeholders. It must also recognize that the list of concerns may vary from place to place. Science plays a vital role in informing this process, but ultimately, the decisions will be made by the designated regulatory authority.

Monitoring at offshore locations has its own set of restrictions. Detailed enumeration of benthic species obtained from sediment grab samples may be required during the initial site assessment and during the first few stocking cycles, because these types of analyses provide detailed information about sediment conditions and perturbations. Video or photographic systems that have been calibrated against this information may be adequate for on-going monitoring.

The importance of establishing baseline conditions for water column and benthos (sediments, fauna) and the use of circulation (dispersion and dilution) models and model verification to locate monitoring stations were discussed. The effects of annual variability also need to be understood to ensure that the site is suitable for aquaculture and to provide a framework for understanding any measurable changes in the ecosystem.

There was a strong view that an assessment of environmental interaction and some on-going monitoring would be required, to ensure that environmental standards can be appropriately established and then are being met. In this manner, any cumulative changes over the longer term can be discerned. This is important information for the fish farmer, because fish health is strongly influenced by environmental conditions. It is also vital to make this information available to the general public to allay any concerns that some might have about the aquaculture operation. With time, the frequency of monitoring can usually be reduced as more information is obtained, regional-specific standards are set, monitoring methods are refined and simplified, and uncertainty about possible effects is reduced.

For water quality assessment, automated sensing systems that relay information from sensors back to land in real-time are particularly important. These can be sited at the farm, but they require on-going maintenance and periodic calibration to be effective. There was consensus that, while possible in some ocean environments, water column pollution, such as eutrophication of coastal areas by dissolved nutrient discharge, was unlikely in the open ocean. Also, while the risk of benthic pollution from deposition of uneaten feed and feces may be reduced in the open ocean, the risk is site specific and must be managed as such. It is also necessary to consider positive impacts, such as increased habitat for local fish and lessening of fishing pressure on stressed local fisheries.

The process for establishing environmental standards for benthic conditions was a topic of lengthy discussion. Monitoring methods to determine the degree of organic enrichment vary in cost, precision, clarity of interpretation, and the ability to standardize methods and establish meaningful performance standards. Monitoring under and around the cages by visual inspection (e.g., divers, remote photography) requires a good database on benthic fauna to act as an indicator of more subtle changes in sediments or benthos. Total organic carbon (TOC) in sediments is generally a good indicator of organic enrichment, but this type of monitoring requires a qualified laboratory facility. Organic content by loss on ignition (LOI) is similar to TOC, and it is generally well correlated with changes in the benthic community, but it is a less accurate measurement of carbon than TOC. Depth of the Redox Potential Discontinuity (RPD) layer (Eh) is good measure of sediment oxygen/sulfide and it is generally well correlated with changes in the benthic community, but it is difficult to gather the data in deep water because of high spatial variability and it requires an undisturbed sediment core. Benthic faunal community monitoring can consist of measures of biomass, species diversity, number of taxa, the presence and ratio of pollution tolerant/intolerant organisms, or a combination of these variables. This type of monitoring is very expensive and time consuming. Interpretation of the results may be somewhat ambiguous, making it difficult to establish performance standards.

There was some discussion about the potential to use tools such as multi-beam sonar for inspection of submerged infrastructure (cages, mooring lines, anchors), broad scale seafloor site assessment, and for monitoring cage inventory (biomass and numbers). The usefulness of such observations, however, has yet to be verified.

How "impact" is actually defined and quantified was briefly discussed. For example, at what level would an increase in the abundance of *Capitella* spp. constitute an impact? This led to a discussion about the need for effective performance based standards. There was broad agreement that some change would take place directly beneath the cages. It was suggested that changes within the zone near the cages be accepted as necessary. Thus, monitoring should be directed to establishing the amounts of change (if any) at the edge and outside the sediment impact zone (the National Pollutant Discharge Elimination System zone of mixing in the United States). The difficulty and cost of benthic monitoring in deep water was also discussed, but the participants did not arrive at a definite conclusion. Integrated aquaculture (co-culture of plants and bivalves) was mentioned as means of mitigating wastes from finfish. For fish farmers, however, it would create a level of complexity that could be difficult to manage.

Expansion of Open Ocean Aquaculture

Technology is one critical factor for the expansion of an open ocean farm. Experience and knowledge gained from the salmon farming and other seafood industries, including the wild-caught sector, have provided open ocean aquaculture with a jump start on technology. Open ocean fish farmers know the minimal number of cages and market value of their target species required to keep their operations economically viable. Their challenge as an industry is to keep up with the technology, whether it is hatchery technology or the technology offshore. Their survival as an industry will depend on making production more cost effective to operate in an offshore environment. For example, with automated technology for cleaning the cages and automated feeders, the number of cages to be handled under one operation can increase considerably.

Basic research that needs to be done on the physiology of cultured fish species can have a huge impact on the ability of fish to express their genetic potential. Funding for feed manufacturing technology development is also needed for reducing feed costs, improving feed conversion ratios, and controlling diseases.

Scale issues become a major consideration unless the product has a very high premium. A general rule for one open ocean salmon aquaculture site would be 10 cages, each producing 1,000 tonnes. The 1,000-tonne production unit is believed to be the viability limit for salmon farming under ordinary conditions. This prediction was based on existing offshore operations. The 10,000-tonne limit, however, does not apply to all types of open ocean aquaculture. If the culture species are scarce, at a production scale for a niche market, the prices should remain stable. On the other hand, the prices would start to drop when producers expanded their products and competed with each other.

It is expected that the deeper the site, the easier the permit would be to acquire, and the more the business would expand and be successful in the long term. Open ocean aquaculture of the future may not be just one huge fish farm, but a complex of 10 large submerged cages, each growing 1,000 tonnes. With a 10,000-tonne business, a producer could afford to have his or her own feed mill and provide the supporting infrastructure for this type of large-scale activity.

Research Gaps and Strategies for Moving Open Ocean Aquaculture Forward

At the end of the workshop, research gaps and strategies for moving open ocean aquaculture forward were elicited informally from the invited speakers. Although the result was not a comprehensive list of the research gaps, it provides the readers with a collective overview of the ideas expressed by the participants on the research needs and strategies for moving open ocean aquaculture forward to the next level.

Research Gaps

Engineering

- Deep water containment systems
- Design and development of fully integrated farming systems, free floating and other more open water systems, matched to specific environments that maximize production efficiencies and minimize risk to personnel and specific environments.
- Development of large semi-stationary systems as distinguished from drifters
- Increased automation of routine operations such as inspection, cleaning, mort removal, stocking and harvesting to reduce diver time and improve production efficiencies
- Improved structures to reduce escapes through prevention of predator interaction
- Develop new materials to replace netting that will reduce biofouling and minimize escapement
- Synergistic possibilities for aquaculture with other areas, e.g., energy development or other offshore industries

Environment

- Key component characterization of bioenergetics for environmental assessment and optimization of growout to maximize economic gain and minimize environmental impacts
- Assessment of relative magnitude of environmental potential risks to allow prioritization of monitoring efforts
- Development of site recovery strategies and bioremediation methods
- Development of criteria and assessment of cumulative impacts for multiple farm placement in an area
- Potentially beneficial effects of organic enrichment on an environment that is nutrient poor, i.e., pelagic and benthic.
- Better understanding of the interactions of escaped fish with wild stocks
- Cost effective methods for monitoring benthic conditions at deep water sites
- Area specific development strategies that balance fed species with extractive species
- Standardize monitoring methods and interpretation of data
- Develop thresholds for water quality and benthic condition indicators
- Develop Hazard Analysis and Critical Control Point- (risk-) based containment management plans

Management

- Risk assessment protocols to identify specific social values worth protecting
- Development of risk management strategy for open ocean aquaculture
- Identification and system development of protocols for stock management
- Operating procedure development, including staff safety
- Management protocols for treatment of the farm as an ecosystem

Technology

- Seaweed farming technology
- Feeding, cleaning, monitoring, and harvesting technology development for large cage systems
- Predator and protected species monitoring and deterrents
- Establish effective technology transfer infrastructure (including personnel) for all technologies
- Video products to provide imagery of the condition of the environment before and during operations
- Cost effective tools for site selection and site assessment, before, during, and after operations
- More dependable and large scale hatchery production technology

Feeds

- Alternative feed ingredients from diverse sources (e.g., land plants, byproducts, and ocean based alternative feed stuffs)
- Improved feed and feeding efficiency

Health

- Improved disease resistance of stock by nutrition, development of high health seed, or both.
- Basic immunological research on target culture species
- Integrated health management plans for each species

Strategies for Moving Forward

- Consider a workshop to create a vision for this industry (both United States and international).
- Create a critical mass of industry participants to move development forward.
- Look at a variety of scenarios for the future marine protein production that features open ocean aquaculture technology.
- Make risk assessment transparent to allow contrasting the inshore with the offshore and offshore technology versus fishing technology.
- Hire a professional to set the framework for making open ocean aquaculture a sustainable industry.
- Provide comments and language for the U.S. Offshore Aquaculture Bill that makes it more acceptable to all parties.
- Bring in the seafood industry as a partner.
- Bring the nongovernmental organizations and various groups into a cooperative dialogue on the open ocean aquaculture opportunity.
- Meet with the environmental groups that want to have a constructive dialogue on sustainable open ocean aquaculture development.
- Develop consistent, easy to understand messages to educate the government and the public on open ocean aquaculture issues.
- Develop greater international cooperation and exchange of information for research, industry, development, and effective policy formulation for sustainable open ocean aquaculture.
- Develop aquaculture as a community social event (social marketing).
- Form a marine aquaculture association with responsibility to:
    - Advocate for open ocean aquaculture
    - Advocate a legal framework for open ocean aquaculture
    - Increase interaction and cooperation among research programs
    - Coordinate public education strategies
- Coordinate and increase public and private funding for multidisciplinary open ocean aquaculture research.
- Conduct market research for open ocean aquaculture products in general.
- Improve the quality of on-farm research.
- Develop several successful pilot projects to demonstrate the economic and social value to the public.

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Graphic design by BLC Graphics.com

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