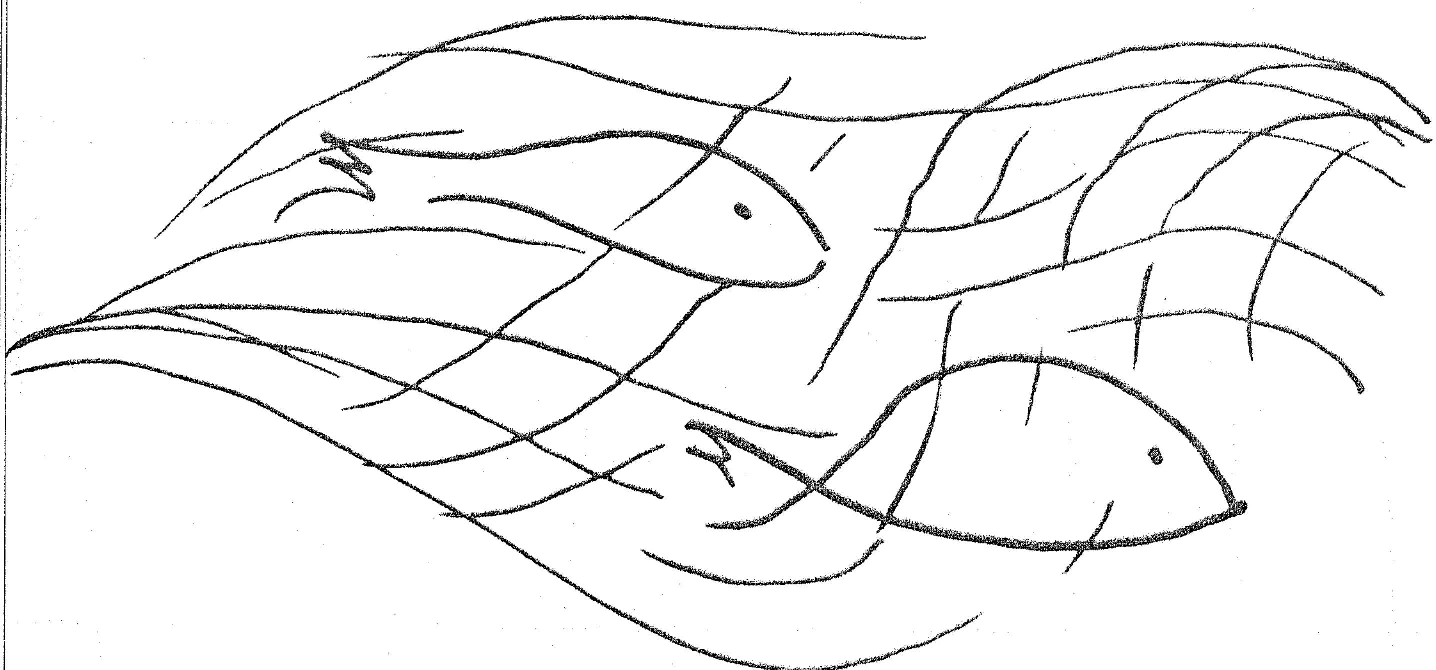
OPEN OCEAN AQUACULTURE

From Research to Commercial Reality



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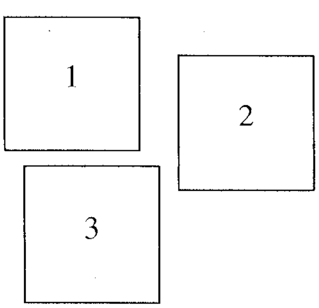

1. Red hind grouper larvae (related to Quintero-Fonseca et al., this volume).
2. Offshore cage in the Gulf of Mexico (Goudey et al., this volume).
3. Mussel longline systems used in Norway (Fredheim and Lien, this volume).

THE HAWAII OFFSHORE AQUACULTURE RESEARCH PROJECT: CRITICAL RESEARCH AND DEVELOPMENT ISSUES FOR COMMERCIALIZATION

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ABSTRACT

Hawaii and the affiliated Pacific islands offer a tremendously fertile ground for exploring the objective of commercial offshore aquaculture. The region has extensive experience in marine finfish culture, sufficient seedstock for testing, consistent warmwater growing conditions, and the ability to reach deep waters near to shore. The University of Hawaii Sea Grant College Program and Oceanic Institute have been working with governmental and private organizations in Hawaii since 1999 to examine the biological, environmental, and economic feasibility of offshore aquaculture in the Pacific region. Under the NOAA-funded Hawaii Offshore Research Project Phases I and II, these efforts led to the first successful demonstration in the U.S. of offshore grow-out of a tropical marine fish species in a single, commercially sized sea cage, operated under completely submerged conditions. Since 1999, over 130,000 Pacific threadfin (*Polydactylus sexfilis*) have been harvested in two very successful sea cage trials. Biological performance compared favorably against that of control populations raised in onshore tanks. Market distribution to the U.S. mainland, Asia, and Europe indicated market acceptance and provided initial pricing information for this species for economic analysis. In addition, preliminary water quality information was acquired that is essential to establish zone of mixing requirements for National Pollution Discharge Elimination System permits for future commercial offshore operations. Several areas of research could lead to increases in overall profitability and long-term sustainability of a potential offshore industry. Lessons learned and needs for the future are discussed based on the experiences of this joint research effort.

INTRODUCTION

The U.S. Department of Commerce has recently enunciated a policy to encourage aquaculture development in the United States. The National Aquaculture Plan envisions the growth of the aquaculture industry to $5 billion in the U.S. by 2025, five times the current value of $900 million (Anonymous 2000). This increase is desired to reduce the seafood import deficit and to stabilize world seafood supplies. However, it requires both acceptance by consumers and the rapid removal of administrative impediments currently present in the permitting process. It also requires the development and implementation of sustainable, new production technologies including a considerable expansion into the offshore waters of the United States.

National Oceanic and Atmospheric Administration (NOAA) and the National Sea Grant Office have identified demonstration of the feasibility of offshore aquaculture in the U.S. as a high priority to address issues of sustainability of U.S. fisheries. Capture harvest of wild fisheries are at or near maximum sustainable yields (NMFS 1999), and expansion of land-based aquaculture in coastal zone areas is limited due to high land and water costs, environmental issues, and competing interests, such as urban development, recreation, and tourism. The captive raising of fish in large, offshore containment structures has been viewed as a means to supplement increasing regional and global demands for fish and fishery products.

Great strides have been made in recent years in the technology of these containment systems, and several nations have adopted offshore aquaculture at either commercial or experimental levels (McVey 1998). Development of offshore capabilities in the U.S. has been hampered by restrictive permitting processes in coastal regions and lack of demonstrated feasibility in critical areas, such as engineering of containment structures to withstand open ocean conditions, adequate hatchery technologies, and efficient offshore production management and harvesting methods. These broad issues, as well as more regionally specific issues such as marine construction and environmental regulations, need to be addressed before offshore aquaculture production can develop.

Hawaii and the affiliated Pacific Island nations are particularly suited to explore the objective of offshore aquaculture research and commercialization. Technologies for mass culture of several indigenous species exist (Lee and Ostrowski 2001), and the topographical relief of volcanic islands assures that deep water can be reached near to onshore support and processing centers. These deep waters are also inherently oligotrophic and create a laboratory for examination of the effects of aquaculture activities and effluents on the surrounding environment, and reduced burden on the economics of production because of reduced cage fouling. Moreover, recent partial closures of the local longline industry and new restrictions to traditional fishing grounds have highlighted the need for new economic opportunities in the region.

The Hawaii Offshore Aquaculture Research Project (HOARP) is a joint research effort between the Oceanic Institute (OI) and the University of Hawaii (UH) Sea Grant College Program, in partnership with state governmental agencies, commercial farmers, and seafood processors. The ultimate goal of the project is to provide a scientific basis for evaluation of the biological, environmental, and economic feasibility of offshore aquaculture in the Pacific region, and ultimately, the entire U.S. Further, bottlenecks and areas critical for improvement would be identified.

PROJECT COMPONENTS

Permits

The primary constraints to conducting offshore aquaculture in Hawaii are environmental compatibility and the physical constraints of weather, oceanographic conditions, and port access. To minimize these constraints, several sites along the south and west shores of Oahu were evaluated. A site was identified about 13 km west of Honolulu Harbor about 3 km offshore in water about 30 m deep. The site had a sandy bottom, ideal for the type of anchors targeted and was also 800 m away from the nearest coral reef ecosystem.

All offshore lands in Hawaii are classified as a conservation district. As a result, special permits were required for any activity within 5 km of shore (State of Hawaii waters). Rather than go through the lengthy full permitting process required by the regulations governing an offshore lease, the project chose to avail itself of the simpler procedure of applying for a permit to do research within a conservation zone. Consultations were required with many agencies or divisions of those agencies including five divisions of the Department of Land and Natural Resources (DLNR) (Aquatic Resources, Land, Boating and Recreation, and the Aquaculture Development Program), the Department of Health, the Department of Economic Development and Tourism, the Office of State Planning (particularly its Office of Environmental Quality Control), the U.S. Coast Guard, the U.S. Army Corps of Engineers, and the U.S. Navy. Eventually, three written permits were required (DLNR Conservation District Use Permit, Army Corps of Engineers, DLNR-Boating and Recreation Mooring Permit). Even for a limited research permit, more than 9 mo elapsed between the start of the process and the issuance of the final permit.

Cage System

A totally enclosed, semi-submersible cage produced by Net Systems, Bainbridge WA (Ocean Spar Sea Station™ 3000) was chosen for the project. Several types of cages were considered but the perceived need for a cage that could be maintained in a fully submerged condition was thought to be an important, and perhaps even critical, parameter in a predominantly tourist industry driven state.

The cage was bi-conical in shape, approximately 24 m in diameter and 15 m in depth with a working volume of about 2,600 m^3. The netting of the cage consisted of a hexagonal mesh of Spectra™ with an opening of 2 cm. The cage was moored on a four-point anchor system with a working anchor scope in excess of 5:1. Each anchor was larger than required. The smallest anchor had a mass of greater than 3 tons. Each anchor was attached to the cage with Spectra™ mooring line and a short piece of heavy anchor chain. Subsurface floats were attached to the Spectra™ line approximately 20 m from the chain to provide a compensation system that assured that the anchor lines remained taut, yet shock absorbing, at all times. All anchors and cage deployment activities were constrained to be within 300 m of the permitted location. The cage remained fully submerged throughout, with the very top of the cage about 12 m below the surface. All stock introduction, feeding, and harvesting were done from this fully submerged position.

Offshore Nursery Cage

Several innovative designs were required to scale efforts to use a single cage and to ensure operations went smoothly. One key tool developed was a nursery cage within the Sea Station™. The purpose of the nursery cage was to reduce residency of fish onshore and conserve resources, and to adapt fish quickly to improved water conditions and the offshore environment for better overall biological performance. The inner nursery net was constructed of nylon (0.5 cm mesh) and deployed around the central spar inside the main net. The nursery net was about one-third the volume of the main net. Fish were transported from the onshore hatchery directly into the nursery net at sizes smaller than 10 g, and released from the nursery net into the main portion of the cage when they reached approximately 40 g in size.

Species of Culture

The species of fish chosen for culture was the indigenous Pacific threadfin (*Polydactylus sexfilis*), known locally as moi. This fish has been highly regarded in Hawaii since ancient times when it was known as the food of the ali'i, only to be consumed by members of Hawaiian royalty. Moi was commercially fished in the past but overfishing and over-regulation effectively removed it as a commercially exploitable stock. Today, annual commercial catch from the wild averages less than 1,000 kg. Pacific threadfin is considered heavily depleted and is being used as a key species in a stock enhancement research program.

In the 1970's the UH Sea Grant College Program supported research into the life cycle of this species. Over the last seven years OI has developed mass culture technologies appropriate for the Pacific threadfin through the USDA's Cooperative State Research, Education, and Extension Service making it the newest commercially grown species in Hawaii. The species grows well in captivity, reaching a market size (350–450 g) at 6–8 mo of age. It sells in the round for about US$10/kg at the farm gate because of current, limited supply. The full market potential of Pacific threadfin has not been analyzed.

Pacific threadfin was the only marine species being cultured in Hawaii in numbers sufficient for the demonstration project. Ostrowski and Molnar (1998) described methods for hatchery production of fry. The parents of the cultured threadfin were captured from the indigenous wild stock of Hawaii, and genetic mapping has indicated that fish are of one genetic stock (Tringali et al., in press). Pacific threadfin from the same parents are currently being grown for release for stock enhancement research purposes by OI. Thus, an accidental release of fish from the cage would have no adverse genetic impacts on wild populations. A cooperative export market plan was devised to ensure that local farm producers would not be adversely affected by test efforts.

HOARP PHASE I AND II ACCOMPLISHMENTS

HOARP sought to combine newly developed cage designs from Ocean Spar Technologies, Inc. of Bainbridge, Washington, with technologies of Pacific threadfin mass culture and fish management developed by OI. Furthermore, innovative approaches in fingerling transfer to the cage, daily maintenance, feeding, and progressive harvesting needed to be developed to operate the cage in a fully submerged position. Operation of the cage in a fully submerged position was thought essential to move technology development forward in Hawaii, to ensure that operation of an offshore production farm would be compatible with visual and other concerns of other ocean users associated with a predominantly tourist industry driven state.

Results of the permit efforts and the Phase I 6 mo grow-out of fish in a single 2,600 m^3 bi-conical sea cage indicated that Pacific threadfin can be successfully stocked, fed, managed, and harvested under completely submerged conditions. Phase I identified novel methods of fish transfer and management including: a) use of a nursery cage inside the grow-out cage; b) feed delivery to depths of 12 m; and, c) harvest techniques that did not require surfacing of the cage. Fish in the cage grew as well as fish in onshore reference tanks, although feeding methods paralleled in both systems yielded feed conversion ratios (FCRs) of 1.7–1.8, about 30% higher than historically obtained with this species in land-based systems. A total 17,381 kg of 0.28-0.37 kg fish were harvested (5.8 kg/m^3 maximum density) from the cage at an 82% survival rate, adjusted for high (26%) initial stocking mortality. This resulted in an overall survival from stocking to harvest of 61%. Phase I also provided preliminary water quality and ecosystem information with effects of the cage as a fish aggregation device and benthic biota. An estimated 681 kg of fish were attracted to the cage in a development pattern similar to that seen for artificial reefs. Polychaete community structure underneath the cage changed as a result of a heavy feeding event but recovered to previous structure after feed rates were reduced (Bybee and Bailey-Brock, this volume).

HOARP Phase II sought to address critical areas to further improve and define the technology. Research targeted increased harvest density, transport of smaller (2 g versus 9 g in Phase I) fingerlings to reduce the stress of transport to the cage, and use of discrete feedings to increase economic performance. The project also expanded environmental monitoring to better assess effects of activities on water quality, benthic community structure, and the cage as a fish aggregation device. Importantly, Phase II included efforts to assess the economics of a commercial operation to identify, through sensitivity analyses, key areas of economic importance that would direct future research and development efforts.

Phase II achieved its goal of improving growth of threadfin (0.42–0.48 kg fish were harvested) and doubling harvest density (12.4 kg/m^3 maximum density, with over 34,843 kg harvested), but with little change in FCR (2.1) and overall harvest survival (58%). The latter was due primarily to unaccounted losses of fish (38%), presumably during the nursery stage. It is at this stage when cannibalism is prevalent (Ostrowski et al. 1996) and where natural settling behaviors of juvenile threadfin (Ostrowski and Molnar 1998) expose them to the risks of crowding at the bottom of a bi-conical nursery cage design.

Unexpectedly, routine liver histology conducted on fish during Phase II generated concerns for fish and human health about a month before harvest that nearly interrupted sale of harvested fish. Livers were excessively fatty and cytoplasmic vacuolation was noted in some individuals. After extensive analyses for any toxic insult from water borne or feed contaminants, it was determined that overfeeding was the suspected cause of the problem. Feeding rates were adjusted and the fish were harvested.

The cage also attracted a similar biomass of species (800 kg) as in Phase I, indicating that species aggregation outside of the cage was a habitat (cage dimension) and not a density (biomass in the cage) limited effect. Benthic community structure underneath the cage was no different than control sites (Bybee and Bailey-Brock, this volume). Expanded environmental monitoring revealed significant changes in total ammonia concentrations within a full cage diameter downstream several hours after the first feeding of the day.

The bioeconomic model generated during Phase II indicated improvements in several biological aspects of production were needed to ensue profitability of a commercial offshore threadfin farm. While early transfer of fish offshore optimizes onshore hatchery and support costs, the causes of unexplained losses of fish need to be defined and resolved to reach profitable harvest densities of near 40 kg/m^3. Feeding costs also need to be reduced from an estimated US\$2.77/kg (US\$1.32/kg current feed price x 2.1 FCR) to improve profitability. Furthermore, costs of environmental monitoring and compliance need to be reduced to ensure these do not overly impact the bottom line.

LESSONS LEARNED

While the suitability of Pacific threadfin to offshore production was demonstrated, several areas of research remain critical to establish overall economic and environmental viability, and long-term sustainability of a potential offshore aquaculture industry. The eventual fate of the discharged metabolic products from the cage system is largely unknown and raises questions with regulatory agencies. Moreover, the long-term effects of cage culture on the benthic biota and ecosystem outside the cage must be defined in multi-cage systems. Both survival and harvest density of Pacific threadfin need to be increased. Paramount is the need to optimize the use of the offshore nursery system to minimize early mortality. Key nutrition and feeding issues must be researched as well to reduce unacceptably high feed conversion ratios obtained and improve the overall health of fish and condition of their livers. Improved physical characteristics of the feed for offshore use, nutritional needs, and appropriate feeding regimens for Pacific threadfin need to be developed.

The Pacific threadfin proved to be an excellent model for offshore testing and candidate for commercialization. Importantly however, other species being explored in the region exhibit characteristics that may be economically and biologically more favorable in the long-run, and provide the diversity needed for a budding offshore industry in the Pacific. This is particularly true in Hawaii since the local fishery has been severely impacted by the partial closure of the long line industry and by new restriction to traditional fishing grounds. This suggests strongly that additional effort should be placed on the culture of other species that can replace the fish being lost to the closures and restrictions. One species, the greater amberjack (*Seriola dumerili*), has exhibited exceptional growth and behavioral characteristics for offshore aquaculture (Chambers and Ostrowski 1999). Amberjack culture has been a major focus of research and development in Japan (Tachihara et al. 1993) and the Mediterranean (Grau et al. 1996). OI has made considerable progress in hatchery development as well, and preliminary restaurant and market tests have shown that Hawaii-cultured fish are a desirable sashimi (raw) and cooked product. However, considerable work is required to make mass culture of this species a reliable process. As the parameters for Pacific threadfin are being finalized for commercial application, the amberjack should be examined for its suitability.

FUTURE NEEDS

Future research needs to target enabling technologies that are essential to reduce risk and improve profitability of offshore aquaculture production in Hawaii, the Pacific region, and ultimately, the entire U.S. With the establishment of Hawaii's first offshore aquaculture farm and the potential for others in Hawaii and the affiliated Pacific Islands, several key areas need to be researched sooner rather than later. These include:

1. minimizing the level of environmental monitoring;
2. improving offshore nursery survival and understanding the feeding and nutritional requirements of the fish to be grown in the cages;
3. researching the life cycles of other indigenous species so a greater number of species can be raised if economics warrant; and,
4. beginning a program aimed at animal health and product quality.

Improvements in biological performance of target species, and the development of alternative species are essential. Biological performance directly influences waste production and is essential to maintain a competitive edge for U.S. producers, while ensuring production of wholesome, healthy seafood products. Without development of alternative species to challenge economic assumptions and increase the product mix, offshore production in the Pacific region has little margin for error in profitability, market penetration, and opportunity for growth. The development of alternative species will increase the seafood product portfolio and allow offshore production in the Pacific to realize its full potential.

While research to date has paved the way for commercialization, start-up companies will be limited to 45 metric tons (100,000 pounds) of production until zone of mixing requirements are established for compliance with National Pollution

Discharge Elimination System (NPDES) regulatory standards. An approach to develop these requirements and an associated monitoring plan have been initiated and coordinated with state and federal agencies. However, monitoring methods must be simple and efficient to be cost-effective. Improvements in overall biological performance of Pacific threadfin and modeling of effluents from offshore operations will be necessary to establish environmentally and economically reasonable monitoring requirements for large-scale operations.

Our current (HOARP Phase III) research is targeted to resolve several critical issues that were deemed of primary importance to commercialization based on our previous efforts. These include:

1. improving offshore nursery survival to reach operating densities high enough for commercialization and, with deployment of nursery cages, reduce costs of onshore hatchery support systems. Such nursery cage technologies would be applicable to areas outside Hawaii as well;

2. evaluating the ecological impact and economic value of the developing fish community around a multi-cage facility. This will provide needed information for environmental impact statements and any added value that can be extracted from an offshore aquaculture operation;

3. establishing the effects of the operation of a multi-cage offshore facility on waste discharge and the benthic community structure. This will provide data needed for an offshore venture to establish and meet the environmental monitoring and permit requirements necessary for an offshore operation in the Tropics; and,

4. characterizing the dispersal patterns of water chemistry constituents around a multi-cage facility. This will provide state and federal regulators the appropriate models to evaluate permit requirements, and aid development of appropriate, yet cost-effective tools for collection of data and monitoring by commercial companies.

In addition, there remain several research efforts we believe need to be addressed in future endeavors, but that will be unresolved by the end of HOARP Phase III. These include:

1. development of optimized diet formulation and physical characteristics of the feed to increase production efficiency and minimize waste output from the cage. This will improve profitability and environmental compatibility of the operation through reduced feeding costs and the risk of adverse environmental effects;

2. development of an optimized feeding regimen to increase production efficiency, minimize wastage, and improve fish health and product quality. This ensures the production of wholesome healthy seafood products and a marketing edge for long-term sustainability as concerns for animal agriculture production worldwide are increasing;

3. determination of shelf life and potential for long-term product storage. This would enable development of marketing and distribution tools essential for start-up of a large, seafood production operation and its long-term goals of sustainable profitability. Little scientific information exists on warm-water marine species; and,

4. development of research on other high value species indigenous to Hawaii and the U.S. mainland, including the Gulf of Mexico as alternative offshore candidates. For a healthy industry to develop, it is critical that the seafood product portfolio be augmented to sustain competition. Development of species with sashimi (raw) grade qualities has particular value-added appeal to counter the comparatively high production costs for U.S. aquaculture farmers and maintain international competitiveness.

CONCLUSIONS

There is tremendous potential for offshore aquaculture research and development in the Pacific. HOARP I and II have paved the way for development of a coordinated and cooperative approach to research the key biological, environmental, and economic issues for commercialization of the technology in the region. This technology has focused on the use of submersible cage designs to address concerns of competing uses of valuable ocean resources. The Pacific threadfin holds promise for commercialization, and new species being developed can help expand the seafood portfolio. Several research questions are critical to improving profitability and long-term sustainability of a potential offshore industry. Public perception of offshore aquaculture in the region is positive, and results indicate that this form of aquaculture, conducted with an appreciation for minimizing the real and perceived impacts on the environment, can be a viable business opportunity in Hawaii and the Pacific region.

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